16th Bathurst Meeting

Abstracts Volume

Talks

Theme 1: Carbonate Platforms

Carbonate Factories, Depositional Environments, Architecture and Modeling

T-1 to T-9

Carbonate factories: a model of global carbonate platform distribution

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Carbonate factory, carbonate prediction, global distribution, paleoceanographic model, paleoclimatology

Shallow-water carbonates are a major component of the Earth System but their spatial distribution through geological times is difficult to reconstruct, due to the incompleteness of the geological record, sampling heterogeneity and their intrinsic complexity (i.e. the “conundrum” of Pomar & Hallock, 2008). Beyond this complexity, carbonates are not randomly distributed in the world oceans, neither in the modern nor in the past, and thus, global trends exist. In the present review, we focus on the understanding of the spatial distribution of carbonate production that is controlled by ambient environmental conditions at a global scale. A deterministic approach is used, which focuses on discriminating components, stratigraphic architectures and environmental features to relate shallow-water carbonate production (i.e. carbonate platforms) to sea-surface oceanographic parameters (temperature SST, salinity SSS and marine primary productivity). This approach allows determination of different carbonate factories and classifying sedimentary case studies. The scheme is designed to be applied in the geological record.

The work is based on extensive, mostly unpublished literature reviews on marine carbonate platforms. Ecological niche modelling coupled with deep-time general circulation models (i.e. MITgcm) are used to calibrate a predictive tool of carbonate factory distribution at a global scale. A carbonate factory function is set up that is based on oceanographic parameters (i.e. SST, SSS and marine primary productivity). The model was tested using remote-sensing (AquaMODIS) and *in situ* (GLODAPv2) oceanographic data of Modern times, while outputs of paleoceanographic models are utilized for Lower Aptian (Cretaceous) modelling.

Four marine and neritic carbonate factories were defined that are called the marine biochemical factory, the photozoan factory, the photo-C-factory and the heterozoan factory. The model simulates the global distribution of Lower Aptian and Modern shallow-water carbonates that shows ca. 80 % fit to bibliographic reference points. Carbonate factories appear to thrive for specific ranges along the environmental gradient of carbonate saturation. This conceptual scheme appears to be able to provide a simple, universal model of paleoclimatic zones of shallow-water marine carbonates.

Tectonic processes compete as a regional controlling factor that cannot be predicted at a global scale (e.g. initial topography) and create large heterogeneities in sedimentary profiles and stratigraphic architectures. An exception of this pattern is the biochemical factory for which tectonic processes (e.g. convergence zones) define the sedimentary profile (e.g. homoclinal ramp of a foreland basin) and associated paleoceanographic conditions (i.e. production under relatively restricted paleoceanographic conditions).

Quantifying complex heterogeneities of stromatoporoid/coral build-ups and oncoid shoals from km-scale 3D outcrops, Late Jurassic Hanifa Fm, Tuwaiq Mtn Escarpment, Central Saudi Arabia

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Keywords: Carbonate Reservoir Heterogeneities, Stromatoporoid/Coral Reefs, Oncoid Shoals, Outcrop Analogues, Photogrammetry

Property heterogeneities derived from complex facies dimensions and layer architecture are a common cause for un-even flood advance and sub-optimum recovery in carbonate reservoirs. However, they usually cannot be resolved appropriately in the subsurface because of insufficient resolution of seismic and well data. The objective of this research is to provide high-resolution statistical datasets on 3D facies architecture and facies distribution, from 3D drone-based photogrammetry and field-based surveys of outcrops exposing the Late Jurassic Hanifa Formation at Wadi Birk, Central Saudi Arabia. The Hanifa Fm is one of the major hydrocarbon reservoirs in the subsurface of Saudi Arabia with facies assemblages, which are in many respects analogous to those also found in the overlying super-giant reservoirs of the Arab D.

A 4x4 km^2 area with large mesas and long cliff faces exceeding a total length of 20 km has been scanned with hexacopter and fixed-wing drones to collect a comprehensive high-resolution imagery. A high-resolution digital outcrop model (DOM), which was built using Pix4D software, has been interpreted with VRGS software to extract formation architecture and facies dimensionality. The DOM is anchored by 10 measured stratigraphic sections complete with outcrop gamma-ray profiles.

The DOM reveals a layer cake architecture for the lower Hanifa. However, the upper Hanifa has heterogeneous internal architecture owing to a complex arrangement of 'stromatoporoid/coral reefs and oncoid shoals. The upper interval changes in thickness from 16m to 20m, and displays a high degree of facies heterogeneity both vertically and laterally. On one extreme a section through upper interval is represented by interbedded stromatoporoid/coral biostromes and wackstones/packstones over several meters thickness before being capped by oncoids. On the other extreme, a section only contains wackstone/packstone beds capped by oncoids with no stromatoporoid/coral biostromes. Spacing between stromatoporoid/coral biostromes could be a few meters to several tens of meters with the thickness and width of the biostromes varying from half to three meters. The observations and results provide input into high-resolution static reservoir models addressing the gap in our understanding of inter-well scale heterogeneities for similar subsurface hydrocarbon reservoirs.

Demise signatures in carbonate platforms

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Keywords: carbonate platform demise and/or drowning; sedimentology and diagenetic approach; tectonics, eustatic, clastic and/or nutrient influence

Carbonate systems build amongst the largest edifices on the planet, are able to keep-up with most tectonic or glacio-eustatic induced sea-level rises and consequently the foundering of many platforms is often enigmatic. The cause of demise of platforms and the deposition of potential overlying seal units are critical for understanding thresholds for carbonate platform survival as well as petroleum systems evaluations in better understanding relationships between reservoirs and caprocks.

The paradox of foundering of carbonate platforms has been variously linked to ‘drowning’ via (1) fast glacio-eustatic sea-level rise, (2) tectonic induced sea-level rise (3) nutrient and/or clastic poisoning and (4) subaerial exposure, shut-down of the carbonate factory and a subsequent inability to ‘catch-up’ on subsequent reflooding. Despite better understanding of the foundering of carbonate platforms being critical for their survival, evaluations of the sedimentary, geochemical and petrophysical signatures of each of the potential causes for demise remain understudied.

This study will evaluate the sedimentary, geochemical and diagenetic signatures across key outcrop analogue sections and subsurface reservoirs to understand the impacts of different causes of foundering on reservoir and caprock development. The work to will investigate: (1) both short- and longer-term (~> 1 Ma) transgressive drowning successions of carbonate platforms, (2) nutrient/or and clastic influenced land-attached, nearshore carbonate foundering, (3) carbonate platforms affected by karstification prior to drowning, and (4) volcanogenic smothered systems.

Distribution and growth styles of isolated carbonate build-ups as a function of fault propagation

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Keywords: continental margins; fault growth; fractured reservoir; isolated carbonate build-ups; Northwest Australia.

Abstract

The control of faulting on the position and distribution of isolated carbonate build-ups is investigated in Northwest Australia using high quality 3D seismic and borehole data from the Bonaparte Basin. In detail, we address the relationship between carbonate productivity and fault growth so as to understand what are the primary controls on the growth of isolated carbonate build-ups. Throw-depth (T-Z) and throw-distance (T-D) profiles for normal faults suggest they formed fault segments that were hard linked at different times in the study area. This caused differential vertical movements. Some of the normal faults have propagated to the surface, while others have upper tips 19 to 530 ms TWT below the sea floor, with the largest values comprising faults underneath ICBs. As a result, four distinct zones correlate with variable geometries and sizes of carbonate build-ups, which are a function of topographic relief generated by underlying propagating faults. Relay ramps form a preferred location for the initiation and development of carbonate build-ups, together with adjacent structural highs. Due to the complex effect of fault propagation to the paleosurface and hard-linkage through relay ramps, three distinct models explaining carbonate build-up growth are proposed here: (1) one in which fault throw is larger than carbonate productivity; (2) a second model considering fault throw to be equal or less than carbonate productivity; and (3) a third model in which fault throw post-dates the growth of the carbonate build-up(s). The analysis of fault propagation vs. carbonate build-up growth shown here is important, as the three models proposed potentially correlate with variable fracture densities and distributions within the carbonate build-ups. Based on our results, models 2 and 3 above enhance fracture- and fault-dominated porosity and permeability to a greater degree.

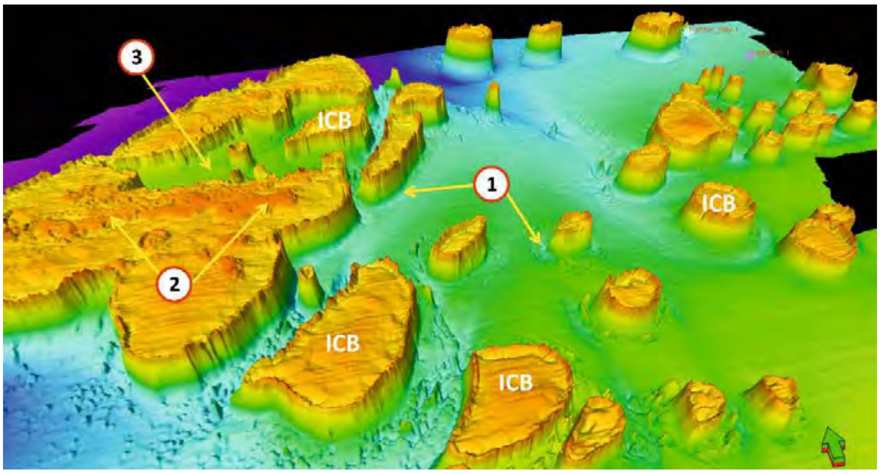

Figure 1. Seafloor 3D map visualisation displaying the Karmt Shoals with several isolated carbonate build-ups. (1) Moat channels surrounding ICBs, (2) interior patch reefs, (3) inner lagoon.

Aragonite depositional facies in a Late Ordovician Calcite Sea; Laurentia

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ABSTRACT

Kingston Ontario Canada is known as 'The Limestone City' because most historic buildings are constructed of beautifully preserved Upper Ordovician limestone. From a geological perspective the numerous outcrops and many quarries in the area expose one of the most important global, Late Ordovician carbonate successions deposited in a subtropical ocean during a postulated calcite sea time. The Black River and Trenton groups are traditionally interpreted as a deepening–upward succession deposited in a progressively subsiding Appalachian Basin margin that contained warm-water, marine, photozoan deposits that pass upward during sea-level rise into cool-water, marine, heterozoan carbonates. This succession is customarily interpreted to reflect an incursion of cold, high-latitude ocean waters into the area. Such a view is herein revised in the light of recent advances in the understanding of cool-water carbonates and calcite-aragonite seas. The strata are instead interpreted as having formed on a thermo-stratified marine ramp whose depositional surface sank with time coincident with sea level rise into deep, cold waters below the shallow thermocline, and remained there until latest Ordovician time when shallow water facies returned during the acioeustatic sea level fall. Cold sub-themocline waters could have been augmented by incursion of polar nutrient-rich waters during highstands. If a calcite sea, shallow tropical facies were, because of high neritic ocean water temperatures and slightly elevated seawater salinities, aragonite-dominated. This interpreted geohistory confirms recent concepts of calcite-sea carbonate polymorph modeling. Alternatively, since all cool-water carbonates are calcitic, it was an aragonite sea, as indicated by shallow-water facies, and this geological period has been misinterpreted as a calcite sea time.

Keywords; Late Ordovician, Limestone, Laurentia, Calcite-Aragonite Sea, , Cool-water Carbonate.

How do intrashelf basins in shallow water carbonate platforms form? Insights from the Cretaceous Arabian Platform

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Key words: intrashelf basin formation, Cretaceous carbonate sequences, source rocks, anoxic events

Organic-rich carbonate sequences filling intrashelf basins (ISB's) form some of the most prolific source rocks of the world (Hanifa, Natih/Shilaif - Arabia; Eagleford – Texas, etc). With new drilling technologies, ISB's have become the target of hydrocarbon production, fundamentally changing the energy industry.

Commonly ISB's and their infill are under- and overlain by layer-cake shallow-water carbonate sequences. So how and why did these ISB's form? Tectonism/differential subsidence? Increased rate of accommodation space creation? Climate change? Carbonate factory drivers? All the above?

Based on the analysis of logs and core from hundreds of wells, time-stratigraphic control, and detailed carbon isotope records, carbonate sequences on the Cretaceous Arabian shelf reveal interacting local and global drivers leading to basin formation and source rock infill. Subtle differential tectonism, climate crisis, the dynamics of the shallow water carbonate factory and accommodation space creation all play a role.

During the Jurassic/Early Cretaceous the northeastern shelf of Arabia was a passive margin facing the Tethys Ocean. For the Early Cretaceous, isopach maps of stratigraphic intervals show small changes in thicknesses without significant lateral facies changes or depositional architecture. This indicates subtle differential subsidence over the shelf area, however without architectural consequence as the carbonate factory was evidently in keep-up mode. At the Barremian/Aptian boundary, a major geochemical disturbance has been reported, probably linked to large scale volcanism, associated CO_2 emission and an ensuing climate crisis (negative carbon isotope spike). At this point an uneven topography developed because the carbonate factory differentiated into keep-up mode in slowly subsiding areas and give-up mode in the parts with higher subsidence. This happens even though the overall rate of accommodation space creation decreased from approximately 40 to 20 m/ma. During the ensuing transgression biota on the shelf becomes dominated by microbial carbonates (Baccinela/Lithocodium) for approx. 1ma. Subsequently, microbial sediments are replaced in the keep-up areas by more normal shallow-marine assemblages characterized by corals, foramifera and rudists, and in give-up areas with fine-grained foramiferal wacke/packstones. The intrashelf basin formation is initiated during a period characterized by rising carbon isotope ratios linked to large scale withdrawal of organic carbon in the deep sea (Oceanic Anoxic Event 1a – OAE1a). With CO_2 being removed from the atmosphere, climate recovered and normal marine conditions returned over the shelf. Continued rapid relative sea level rise leads to the deposition of thick sequences of stacked rudist biostromes near the margin of the nascent intrashelf basin. It is at this stage that give-up areas drown to a depth that is sufficient for the intermittent deposition of organic source rock sequences. With decreasing rate of accommodation space, basin margins prograde and finally the shallow basin fills during late HST and subsequent lowstand. During the next transgression the shelf margin returns to keep up sedimentation characterized by layercake stratigraphy until renewed climate disturbance.

In summary, climate crisis causes OAE's in deep oceans and triggers the creation of intrashelf basins on shelfs with differential subsidence by stressing carbonate factories. Basin fill with organic–rich sediments occurs thereafter and is time-stratigraphically decoupled from OAE's.

Forward stratigraphic modeling of Cretaceous intrashelf basins – insights into highstand system tract basin fill

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Keywords: Forward Stratigraphic Modeling, Intrashelf Basin, Progradation, Rudists

Computational stratigraphic modeling is a powerful tool that allows users to improve confidence in stratigraphic interpretation and prediction in poorly imaged or data sparse regions. This methodology can be especially useful for understanding sedimentation and potential stratigraphic traps associated with shallow, intrashelf basins, where stratal geometries are commonly subtle in legacy seismic data and easily misinterpreted from widely spaced wells. Specifically, where within these intrashelf basins provide necessary depositional elements for the formation of stratigraphic traps. While computational stratigraphic models, such as DIONISOS, can provide single realizations of a stratigraphy, greater value lies in allowing interpreters to quantitatively compare multiple model results to understand the fundamental controls on stratigraphic architecture within a target system. By systematically varying input parameters, a suite of models can be compiled into probabilistic fairway maps of reservoir and sealing facies.

A computational stratigraphy approach was applied to a conceptual scenario based upon the Cretaceous intrashelf basins of the Middle East and West Texas. The relatively shallow (50-100 m), muddy depressions are flanked by low angle ramps with high energy margins that are commonly dominated by rudist communities. Resulting rudist grain dominated deposition form attractive hydrocarbon reservoir targets. The prediction of both the formation and infilling of intrashelf basins have been problematic as they tend to form and fill rather quickly. A series of DIONISOS models were created to mimic the initial bathymetry of a low angle carbonate ramp, from the formation of an intrashelf basin, through its filling and eventual demise. Input parameters for sedimentologic and stratigraphic variables, such as eustasy, facies subdivisions, carbonate production curves, and wave action depths were derived from outcrops and modern analogs. Systematically varying these input parameters allows the user to visualize sedimentation patterns and first principle controls on the distribution of rudist platform margin facies. The forward stratigraphic models indicate that subtle variations in antecedent bathymetry are essential in determining the geographic distribution and evolution of these high energy depositional belts. During transgressions the rudist platform margin facies backstep rapidly to only the highest bathymetric highs where they form aggradational patch reefs or drown and are substituted by basinal mudstone deposition. During regressions, the high energy grainstone belt progrades rapidly, up to 10's km, into the basin to produce large scale reservoir geobodies. Progradational packages are commonly manifested as 60-80 m thick and km scale in length clinoform geobodies that have a relatively flat depositional profile, which is the result of low degrees of down stepping.

Future work will investigate the interplay and specific roles of wave energy, direction and strength, and antecedent topography in the creation of margin rugosity. Investigation into basinal controls on key criteria such as promontory development, progradation distance, and vertical stacking patterns will allow for predictive models to be developed that will highlight the exploration play fairways for a host of stratigraphic trap concepts.

ALBION : a multi-scales 3D dynamic outcrop analogue of Barremian-Aptian peri-Tehyan carbonate platforms

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Key words: dynamic outcrop analogue, urgonian, karst, multi-scales, multi-physics

Building consistent models of carbonate reservoirs requires beforehand a realistic appreciation of their heterogeneity. Typically, the heterogeneity in carbonates originates at different scales and from multi-geological processes. Moreover, various processes related to water-rock interactions and fluids displacements affect the reservoir and enhance the heterogeneity of deposits. In some cases, karst can develop in the formation, leading to a self-organised reservoir. Conventional description of outcrops does not achieve the objective of reservoir characterization because of the variable accessibility and quality of outcrops (surface weathering), a description that rarely allows tackling geological processes, no direct assessment of the impact of reservoir heterogeneity on hydrodynamic behavior.

A new concept has arised from the needs of characterizing carbonates at different scales and from an integrated point of view: the dynamic outcrop analogue. The dynamic analogue is assessed through multi-physics data acquired on outcrops but also on plugs, cores, in boreholes and between wells and in underground passageways. Coupling the hydrodynamic response of groundwater reservoir to a static description of its heterogeneity very early before the building of models provides a key knowledge on the understanding of reservoir architecture. It contributes to improve the way models are populated and to enhance the forecast of reservoir.

The ALBION project focuses on Urgonian limestones from south-eastern France. The studied dynamic outcrop analogue is the Fontaine-de-Vaucluse aquifer mostly developed in the Urgonian formation. 32 field sections have been described and used to build a comprehensive geological model of this area, which covers more than 1000 km^2 (Tendil , 2018). This analogue benefits also from original accesses to the reservoir via numerous caves and the so-called LSBB (www.lsbb.eu) which is an underground laboratory.

In LSBB tunnels, five boreholes spaced a few meters apart enable multi-physics study of unweathered carbonate rock at fine scale. Links between facies, stratigraphic discontinuities and hydrodynamics have been investigated (Cochard, 2018). Next to these wells, three horizontal cores, respectively 240m, 110m and 70m long have been acquired in different directions and allow studying intra-horizon heterogeneity at an inter-wells scale.

The center of the studied area is the Albion Plateau where few outcrops allow geological studies. On the plateau, the karstic network is well-developed with very deep vertical caves. Some of them allowed rock sampling and geological description up to a depth of about 800m, and provided results which contributed to model enhancement.

Through the ALBION dynamic analogue was developed an integrated workflow coupling multi-scales and multi-physics characterization. It provides new insights into karst and paleo-karst genesis processes. Relationships between the development of specific karst features and lithology are proposed and tested through numerical modelling.

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Talks

Theme 2: Diagenesis and Geochemical Markers

Carbonate Precipitation/Dissolution, Diagenetic Processes and Products.

T-10 to T-22

The nucleation of $CaCO_3$ from Neoproterozoic seawater

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Keywords: Neoproterozoic, carbonate geochemistry, supersaturation, inhibitors, homogeneous nucleation

Geologists have long recognized that the varying styles of nucleation and crystal growth preserved in Precambrian carbonates reflect secular changes in $CaCO_3$ production [1]. For example, Mesoproterozoic and early Neoproterozoic carbonates (ca. 1,600–720 Ma) record the progressive replacement of seafloor precipitates, common in Archean and early Proterozoic rocks, by sediment derived almost exclusively from microcrystalline $CaCO_3$ mud (or micrite). Although generally agreed to reflect a shift in the locus of $CaCO_3$ production to water column nucleation [1], the environmental conditions recorded by this transition, and its impact on the global carbon cycle, are unknown.

Here, leveraging recent fluid inclusion constraints on Neoproterozoic seawater chemistry [2] with pH and total alkalinity constraints provided by authigenic Mg-silicates [3], we experimentally examine the nucleation of $CaCO_3$ from Neoproterozoic seawater in the presence of a key inhibiting compound – PO_4. Constant composition experiments show that aragonite consistently nucleates at $\Omega_{Calcite}$ of ~20-30 independently of dissolved inorganic carbon (DIC) and alkalinity. However, when PO_4 is added at concentrations greater than ~12-15 µmol/kg, nucleation of both aragonite and calcite is inhibited. Instead, this leaves amorphous $CaCO_3$ (ACC) as the dominant nucleating phase, occurring at $\Omega_{Calcite}$ of ~50 and above. Because ACC is highly unstable, it recrystallises to high-Mg calcite (HMC) and/or monohydrocalcite, dependent upon Mg/Ca ratio, DIC, and pH.

Our experimental data provide new insight into the processes that generated finely crystalline $CaCO_3$ from late Proterozoic seawater, specifically the enigmatic synsedimentary cement calcite microspar [4]. That HMC is consistently formed through an ACC precursor at solution Mg/Ca ratios >2 is consistent with petrographic evidence for a Mg-calcite precursor. In addition, because the ACC→Mg-calcite transformation proceeds via Ostwald ripening, a distinctive crystal size distribution is preserved in the calcite, which has been recovered in Proterozoic examples. Because ACC is indiscriminate toward trace element uptake, this may also explain elevated Sr associated with microspar. Finally, our experimental data are consistent with independent constraints on the marine carbonate system derived from contemporaneous Mg-silicate-microspar precipitation in carbonates from the Akademikerbreen Group, Svalbard [3].

Together, our data suggest that inhibiting compounds in Neoproterozoic seawater likely enabled non-classical $CaCO_3$ nucleation at high $\Omega_{Calcite}$, producing synsedimentary microspar cement (and sometimes, Mg-silicates [3]). In fact, the stratigraphic abundance of $CaCO_3$ microspar reached its acme in the early Neoproterozoic [4], indicating that seawater repeatedly crossed this $\Omega_{Calcite}$ threshold across multiple marine basins. This uncovers the mechanisms underpinning a shallow water $CaCO_3$ factory that was perhaps the most dynamic and unusual in Earth's history.

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Calcite cement — burial history in a nutshell

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archetypal calcite cement morphology

The morphological development of archetypal cement that fills sediment pores occurs in two stages divided by a transmissivity threshold; after this threshold, cement is erratically distributed. The shape of euhedral crystals at cement's growing front is controlled by fluid chemistry and external factors, while the shape of the anhedral crystals they leaves behind is controlled by geometrical selection; use of shape between these two is often confused.

After nucleation, cement crystals grow by the addition of concentric flat layers, whereas after seeding, growth proceeds first by epitaxy, and then by layered or mantle growth. Epitaxial growth initially is 10 times faster than mantle growth, but decelerates eventually matching mantle's rate. Epitaxy initiates at multiple points on seed crystals with a complex growth surface that, with growth, simplifies and morphs towards the first equilibrium, or wulff surface. The volume of epitaxial growth dominates cement morphology in the confines of pore space and is determined by the properties of its seed crystals; this is especially important in carbonate sediments for their crystals have particularly variable properties.

Pauses in cement growth allow halted surfaces to age; growth from such aged surfaces commonly seed only on high-energy sites, such as emerging dislocations, and at the corners and edges of the halted crystal's surface. Changes in crystal habit often follow pauses in growth; a change from acute to obtuse habit causes the maturation of crystal aggregates to be realigned. Impingement intercrystalline boundaries surround crystals that seed on paused surfaces; these crystals incorporate paused surfaces that are invisible in normal light. When a paused surface does not seed further growth, it becomes a hiatus intercrystalline boundary. Any slice through the line of intersection between an impingement and a hiatus boundary produces enfacial junctions.

A different type of enfacial junction arises at the point where three continuously growing crystals meet and calcite is lost disproportionately along the three intercrystalline boundaries. The calcite released by such a process can source later cement growth and should be integral to cement mass transfer models. Therefore, one type of enfacial junction is associated with pauses in cement growth, a different type occurs when impingement boundaries are modified, and enfacial junctions are absent from some cement mosaics; the significance of enfacial junctions needs reexamination.

The reconstruction and animation of cement examples show a wealth of information on cement's morphological evolution this is at present underused.

The role of viruses in carbonate precipitation:

Viruses are the new frontier in carbonate sedimentology

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Key words: viruses, bacteriophages, nanospheres, experiments, carbonate precipitation

Although it has been suggested that viruses may induce precipitation of carbonate, the exact mechanisms involved and the roles they might play in the nucleation of carbonates are still unknown. Experimental evidence is presented demonstrating that bacteriophages (the phage P1 obtained from infection of the *Escherichia coli* K12 AB1157 strain) are an important factor in mediating carbonate precipitation. Short-term experiments were designed to induce viral-mediated mineral precipitation at different fluid compositions. The $CaCO_3$ precipitates obtained, analyzed with fluorescence and electron microscopes and X-Ray diffraction, and evaluated by statistics, clearly show that bacteriophages strongly affect the processes of carbonate precipitation. Control experiments with no viruses produced crystallites of low-Mg calcite and some micron-sized spheres composed of aggregated calcite scalenohedral crystals, but no larger crystal clusters from particle agglomeration. With phages, precipitated particles randomly agglomerate to form structures of various sizes. The initial precipitates, nanospheres 10s to 100 nm in diameter, do not have a definite icosahedral shape (the typical virus shape), but that may have been lost in the permineralisation of viral capsids. The origin of nanospheres in carbonate sediments, once attributed to nanobacteria (R.L. Folk), could be the result of this virus permineralisation. Importantly, the viral precipitates and clusters coalesce with time to form sheets. The generation of nano- to micron- scale crystalline particles through viral activity, could then lead to further precipitation of carbonate through heterogeneous nucleation. Additionally, in our experiments bacteriophages strongly influence the mineral composition of the precipitates, with vaterite being the dominant form over calcite.

However, the mineralogy of the viral precipitates is likely to be controlled by the fluid chemistry, as well as the viruses themselves, such that the whole range of carbonate minerals could be precipitated, including dolomite, or more likely in the first instance, its very high Mg-calcite precursor.

The results of our experiments clearly show that the presence of viruses affects the precipitation of $CaCO_3$, and they reveal the strong influence that viruses have in terms of the rate, size, shape and mineralogy of precipitates. We provide the first demonstration of how important viruses are to the formation of carbonate sediment. This conclusion has immense implications for the precipitation of fine-grained carbonate throughout the geological record. And in this context, we support the view that the geological history of viruses is likely to be as long as that of bacteria, that is back to the beginning of life, ~ 4 billion years ago, indicating that viruses are likely the agents of carbonate precipitation and thus the formation of many limestones and dolomites throughout time.

The translocation of aragonite during early marine diagenesis: uncertainties and implications

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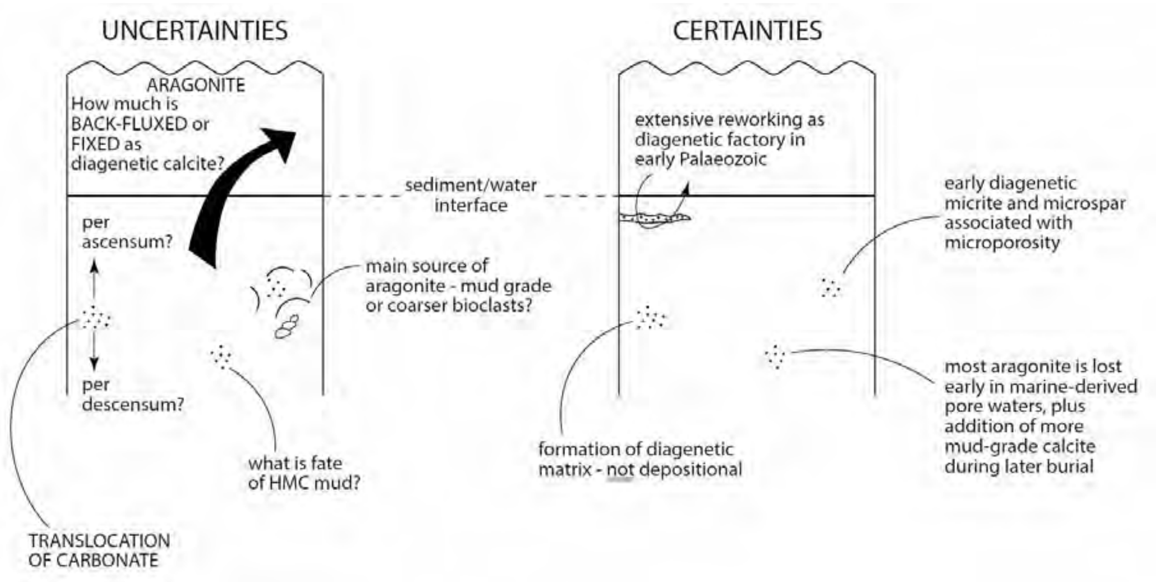
Key words: aragonite, carbonate flux, diagenesis, micrite,

A consensus has emerged that extensive early calcite precipitation due to the remobilisation of aragonite in modified sea water is a common feature of many shale-mudstone successions deposited in low energy, oxic, offshore settings. The result is diagenetic bedding, producing significant limestone units in what were originally largely shale-mudstone hosts. If such effects are characteristic of shale-mudstone successions, why shouldn't they have operated in similar carbonate dominated settings? A strong case for the operation of such processes has been appreciated from deep water including slope carbonates as well as from large scale studies of microporosity (e.g Hasiuk F J et al., 2016 J Sed Res 86, 1163–1178), but is this a universal early diagenetic process in all low energy settings? What is uncertain is to what extent this diagenetic mud had a mud grade precursor and there is no consensus as to what was the main source of the aragonite: mud grade or larger shell material?. Evidence from molluscan taphonomic studies have shown that in low energy settings the bulk of skeletal grains disappear due to aragonite dissolution. This raises the question as to whether what we see as depositional textures are in fact taphonomic ones. For example, could what might have been a bioclastic packstone or wackestone likely end up with a more matrix-rich texture (diagenetic re-texturing)? If non-mud grade aragonite is the main source of this diagenetic calcite matrix do we classify it as allomicrite or polymicrite (but not automicrite)? HMC muds during their replacement do not appear to undergo translocation and produce microporosity (Loucks, R G et al. 2013 JGCAGS, 2: 29–41) while HMC bioclasts do not appear to be dissolved. We know that in shale-mudstone successions diagenetic bedding is enhanced by later cementation likely sourced from chemical compaction. This later burial phase is also found in limestones associated with microporosity.

Other uncertainties exist regarding how this released carbonate is translocated within the sediment: per ascensum or per descensum? It is also possible that little or no translocation takes place with aragonite muds dissolve but with local calcite precipitation (Lucia & Loucks, 2013, JGCAGS, 2: 1–10). A critical uncertainty is how much of the aragonite lost by early dissolution is fixed as early diagenetic calcite compared with how much is back-fluxed into the water column?

The effect of early aragonite removal in shallow marine sediments has varied through time. There is a case that during the early Palaeozoic, when it appears diagenetic mud-grade calcites formed close enough to the sediment-water interface to be readily reworked, it was a significant contributor to the depositional carbonate factory.



What we think we do not know and what we think we do know about diagenetic carbonate muds related to early aragonite dissolution in low energy marine settings

Dissolution processes within the tidal capillary fringe of eogenetic carbonate platforms

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Key words: mixing, dissolution, karst, secondary porosity

Mixing of fresh and saline groundwater is widely cited as the primary driver of cavernous porosity formation in eogenetic carbonate rocks. A growing body of evidence indicates, however, that respiration of dissolved organic carbon at or near water tables may be more important than mixing. Using geochemical and hydrological data collected from San Salvador Island, Bahamas, we suggest that tidally oscillating water tables create ideal conditions for coupling microbial respiration of DOC to dissolution. The thin vadose zone on San Salvador Island facilitates efficient transport of soil organic carbon into the subsurface where it accumulates at or, very near, water tables. High soil organic carbon fluxes fuel respiration within freshwater lenses and generate dysaerobic to anaerobic conditions in groundwater. Tidal oscillation of the water table ventilates the vadose zone and drives oxygenation of the lens top. By measuring changes in the concentrations and relative amounts of CO_2, O_2 and Ar in subsurface gasses collected directly above the water table in uncased monitoring wells, we show that the falling water table during ebb tides pulls oxygenated air into newly exposed, wetted pore spaces in eogenetic carbonate bedrock (the tidal capillary fringe). Depth profiles of dissolved oxygen concentrations in wells indicate rising water tables may physically entrain these air bubbles, as DO concentrations at the water table were at least 5% saturated but declined to near 0% saturation about 1 meter below the water table. This tidally driven, mechanical oxygenation fuels aerobic oxidation of organic matter to CO_2 which, in turn, dissolves carbonate bedrock. Tidal pumping of the water table also facilitates dissolution by flushing reaction products away. Timeseries measurements of specific conductance (SpC) demonstrate small-scale oscillations, on the order of 5-10 $\mu S\ cm^{-1}$ over each tidal cycle. SpC maxima typically occur while water table elevations are increasing, resulting in hysteresis in water table-SpC relationships. We interpret this hysteresis as evidence of tidal pumping of water from less connected to more connected pores, either within the freshwater lens or the tidal capillary fringe. Specifically, increased head in more connected pores as the tidal water table rises forces water with higher electrical conductivity out of adjacent, less connected pores to generate the observed hysteresis. The combination of dissolution and transport within the tidal capillary fringe may establish water tables as hotspots of dissolution, creating laterally continuous, but vertically restricted, regions of enhanced porosity and permeability.

Cryogenian syn-glacial carbonates and implications for a snowball Earth

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Keywords: Geochemical modelling, Cool-water carbonate, Precambrian, snowball Earth, dolomite

The Earth underwent two globally-extensive glaciations during the Neoproterozoic (~717-635 Ma). The 'snowball Earth' theory suggests that during this time the Earth's surface was completely frozen, with marine ice sheets that near-completely sealed off the Earth's oceans from its atmosphere (Hoffman et al., 1998). A central tenet of this hypothesis is that carbonate could not precipitate from syn-glacial seawater due to a lack of alkalinity influxes into ice-covered, isolated oceans. These oceans would instead be dominated by chemical exchange with mid-ocean ridge volcanic systems, developing low pH (resulting in carbonate dissolution) and low Mg/Ca ratios (Hoffman et al., 1998).

However, carbonate sediments are present in both of the Neoproterozoic (Sturtian and Marinoan) ice ages in global glacial successions. Further, Sturtian sediments of the Adelaide Fold Belt, South Australia have sedimentological evidence for dolomite precipitation from syn-glacial seawater. Discrete beds of dolomite and dolomitic silt (with a carbonate content of up to 72 %) are present throughout the Sturtian Yudnamutana Subgroup, including in horizons over 1000 m stratigraphically below post-glacial strata. These carbonates may be deformed by sedimentary processes (e.g. dropstone emplacement) demonstrating their syn-sedimentary precipitation. Euhedral dolomite crystals appear to replace detrital (silicate) minerals and show no evidence of a detrital core, indicating an authigenic origin for the dolomite. The mid-Sturtian Warcowie Dolomite Mb. shows increasing carbonate content towards the upper bed surface, suggesting a seawater source for the dolomitising fluid.

The dolomite mineralogy of these syn-glacial sediments, as well as the post-glacial 'cap carbonates', is inconsistent with 'snowball Earth' Mg-poor glacial ocean conditions and implies that magnesium cycling (i.e. continental weathering) must have been active during the ~57 million year Sturtian glaciation. Based on these observations, a recent Precambrian geochemical model (PreCOSCIOUS) was modified to test the links between Sturtian carbonate mineralogy and environmental conditions. We found that around 9% of present continental chemical weathering during glaciation (i.e. not fully isolated oceans) is consistent with sedimentological observations and further supports the long timescale of glaciation.

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Acceleration of dolomitization by zinc in saline waters

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Keywords: dolomite, kinetics, replacement reaction, saline fluids, zinc

The formation of dolomite, the second most abundant carbonate mineral on Earth, plays a key role in the global carbon cycle. Dolomite stores 14% more carbon per unit volume, and is less prone to chemical weathering, in comparison with calcite. It has proven to be very challenging to form crystallographically well-ordered dolomite in the laboratory under ambient conditions due to the slow reaction kinetics. The chemical mechanisms that catalyze the formation of dolomite remain an enigma. In our study using batch reactor experiments of calcite-to-dolomite replacement and mineralogical and geochemical characterization, we demonstrate an unexpected acceleration of dolomite formation in zinc-enriched saline fluids. Our research hypothesis was based on three main considerations. Firstly, Mississippi Valley-type zinc ores occur commonly in host rocks that are dolomitized. Secondly, zinc ions have a hydration enthalpy that is stronger than that of magnesium ions despite a similar ionic radius. Thirdly, zinc drives mineralization leading to the formation of kidney or bladder stones, and carbonic anhydrase (a zinc-containing metalloenzyme) accelerates the formation of calcium carbonate. Our results show that the acceleration of dolomitization correlates with dissolved zinc concentration, and occurs irrespective of the zinc source tested (i.e. zinc chloride and zinc oxide). The dolomitization rates were modelled using the Avrami equation. Moreover, the experimental data suggest that the addition of dissolved zinc counteracts the inhibiting effect of dissolved sulfate on dolomite formation. Integrating the information from this research with previous studies enables us to develop an understanding of the dolomitization pathway, from calcite to protodolomite by dissolution-precipitation, and then to well-ordered dolomite by Ostwald ripening. Our findings suggest that the fluids' high ionic strength and zinc complexation facilitate magnesium ion dehydration, thus increasing the availability of magnesium for incorporation in the dolomite crystal, which results in a dramatic decrease in induction time. This study establishes a previously unrecognized role of zinc in dolomite formation, and may help explain the changes in dolomite abundance through geological time.

Ediacaran-Cryogenian dolomite hardgrounds and their significance to cap dolostones

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Keywords: Cryogenian, Ediacaran, cap carbonate, dolomite, hardground

Cap carbonates are widespread units (generally dolostones) that form after Cryogenian glaciations. Several thin dolomite units that have features resembling cap carbonates occur within the Cryogenian-Ediacaran succession of the Adelaide Geosyncline. While each of these dolomite units has distinctive features, they also share many similarities with cap carbonates including: stratigraphic thickness ranging from several centimetres to several meters; impure dolomite composition; graded beds with a sharp top that become more dolomite-rich upwards; and evidence of volume expansion in the form of sheet cracks, tepees or other soft- sediment deformation structures.

Sedimentological evidence indicates the graded beds within these thin dolomite units are a form of submarine hardground or firmground. The dolomite appears to be precipitated at the seafloor during periods of little or no sedimentation. The dolomite forms largely as a replacement of pre-existing siliciclastic material (generally clay minerals), with pervasive dolomite replacement occurring down to depths of several centimeters below the sea floor. Volume expansion structures are a product of this near-surface dolomite precipitation, brought about by the high degrees of dolomite supersaturation with a consequent large force of crystallization and unlimited (marine) carbonate source for the precipitating dolomite.

This deepwater marine dolomite precipitation may be a result the dominantly anoxic nature of Cryogenian- early Ediacaran oceans perhaps caused by alkalinity-producing anoxic bacterial reactions. Seafloor dolomite precipitation appears to be ubiquitous in the highly alkaline anoxic conditions that dominate Neoproterozoic oceans. In this scenario, cap dolostones may in part, be the result of slow sedimentation rates following post-glacial transgression. During condensation, marine dolomite replacement, together with reworking of this replacement carbonate may contribute to widespread carbonate deposition following the Cryogenian glaciations. In this scenario, the relatively light carbon isotopic composition of cap dolostones may be explained by mixing of marine and authigenic carbonate in the synsedimentary diagenetic environment. Sedimentary structures typical of cap carbonates like sheet cracks and tepees are likely formed by volume expansion caused by displacive crystallization of the replacement dolomite. This model explains many of the unusual features of Precambrian cap dolostones.

Carbonation of ultramafic rocks as a drive for hydrothermal dolomitization: from conceptual model to field evaluation in Atlin, British Columbia

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Key words: Hydrothermal Dolomite, Listwanite, Ultramafic Carbonation, Atlin, Ophiolite

Whilst thermal conditions are kinetically favorable for the formation of hydrothermal dolomites (HTD), the requirement remains for flux of fluids with a favorable Mg/Ca ratio. Basinal brines, commonly invoked as source fluids for HTD, have low Mg/Ca ratios. Interaction with primary mafic minerals (olivine and pyroxene) provides an alternative source for Mg, but the mechanism for extracting significant volumes of Mg from these minerals is unclear as secondary minerals (chlorite and serpentine) tend instead to sequester Mg from solution. We present a new conceptual model for formation of HTD by release of Mg from carbonation of ultramafic rocks, geochemical simulations of the system and preliminary results from recent fieldwork to test this model in Atlin, BC.

Fluid charged with CO_2 (typically magmatic) can drive carbonation of ultramafic lithologies (listwanization) forming a quartz-carbonate assemblage. Serpentine dissolution is accompanied by simultaneous precipitation of magnesite and quartz. Upon serpentine exhaustion fluid pH drops and magnesite dissolves (replaced by quartz), resulting in a fluid enriched in Mg. PHREEQC simulations indicate this is a potential fluid for dolomitization. However, there is ongoing debate regarding the degree to which listwanitization is an isochemical process or could represent a Mg source.

In Atlin listwanites, formed *in situ* post-orogeny, are exposed immediately adjacent to limestones. These limestones have been significantly dolomitized and silicified, with zebra-fabrics and large breccia bodies. Thick (1cm) pore-lining saddle dolomite cements were analyzed pore-to-rim using EPMA and isotopic analysis of microdrilled samples. The earliest (rim) dolomite is rich in both nickel (115ppm) and iron (48,300 ppm), with light carbon and oxygen isotopes (-0.26 to -0.04 $\delta^{13}C_{vpdb}$ and +1.01 to +1.57 $\delta^{18}O_{vsmow}$). Later (pore) dolomite is relatively metal poor (~10,000ppm iron and undetectable nickel), and isotopically heavier (+1.94 to +1.89 $\delta^{13}C_{vpdb}$ and +2.32 to +3.33 $\delta^{18}O_{vsmow}$). Elevated metal concentrations appear to correlate with bulk rock interpretations of mobility of elements such as Ni, with pore-to-rim trends reflecting sequential alteration in the listwanite, although prior studies of the listwanite report no leaching of Fe or Mg. Isotopic signatures indicate precipitation of dolomite from hot meteoric fluids.

Given the proximity and observations of volumetrically significant quantities of HTD we argue that Mg-rich discharge from the listwanite is responsible for dolomitization and associated silicification. The extent to which this mechanism has dolomitized host-rock proximal to the silicified and brecciated HTD remains to be established. In this case study, the fluids appear to be of meteoric origin, though we suggest no dependency on the ionic strength: seawater or brines are equally plausible. The key driver is a source of high-CO_2 fluid to interact with the ultramafic lithologies to provide Mg-rich fluids. Given an appropriate hydrological drive, these fluids may migrate and dolomitize limestones at some distance from the ultramafic source. The applicability of this model to rift settings is yet to be determined though, if a volumetrically significant quantity of (magmatic/metamorphic) CO_2 is available, this model is geochemically valid for a range of conditions under which listwanitization occurs (150-300 ^{o}C).

Shallow fault-related dolomitisation: is it time to re-evaluate Cambrian dolostone formation in the Canadian Rocky Mountains?

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Keywords: aquifer, dolomitisation, faults

Palaeozoic carbonate rocks often have a complex tectonic history that can obscure their original formation mechanism. Therefore, understanding early diagenesis may help to better understand the impact of subsequent tectonic events. This includes understanding early fluid movement and connectivity between different stratigraphic layers. Here we present our findings on an outcrop of hydrothermal dolomite (HTD) in the Middle Cambrian Cathedral Formation exposed in the Canadian Rocky Mountains, which exhibits a range of typical HTD features, including: brecciation, clast alteration halos, and zebra dolomite textures.

Field observations and petrographic analyses show that differing styles of dolomitisation produce distinct dolostone geometries that formed in two separate dolomitisation events. The first event produced non-stratabound dolostone bodies that exhibit stratabound terminations extending up to 6.5 km in length. These contain euhedral dolomite phases that locally replaced host limestone, with later recrystallisation of precursor dolomite by subsequent subhedral and anhedral replacement dolomite phases. A second dolomitisation event precipitated saddle dolomite that cemented mosaic and chaotic breccias, forming metre scale non-stratabound dolomite bodies proximal to faults. Stylolites crosscut all replacement dolomite phases but are crosscut by saddle dolomite. Stable isotope analyses indicate that replacement dolomite and saddle dolomite cement are more isotopically depleted with respect to oxygen than Middle Cambrian seawater.

Cross-bedded quartz arenites of the Lower Cambrian Gog Group outcrop ~300 m below the dolostones of the Cathedral Formation and are pervasively cemented by replacement and saddle dolomite cement. Fractures in the Gog Group are also cemented by saddle dolomite that exhibits crack-seal textures. Quartz grains typically have point- and long-grain contacts with minor concavo-convex contacts, indicating that the Gog Group underwent little compaction prior to dolomitisation. Authigenic quartz and albite associated with dolostone in the Cathedral Formation would suggest that dolomitising fluids interacted with K-feldspar in the Gog Group.

Replacement dolomite in the Cathedral Formation likely formed from modified Cambrian seawater with a potential contribution of dolomitising fluids from the Gog Group. The presence of saddle dolomite cement supported sandstone potentially indicates that the Gog Group was overpressured during dolomitisation, which may have resulted in the brecciation of the Cathedral Formation due to changes in fluid column heights [1]. These results suggest that the Cathedral Formation was subject to two phases of dolomitisation during shallow and intermediate burial from the Middle to Late Cambrian. This suggested age range for dolomitisation is earlier than other published research [2, 3] indicating that a re-evaluation of these deposits is required.

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New insights into dolomitisation in a rift basin, Lower Carboniferous, Derbyshire Platform

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Key words: Carboniferous, dolomitisation, hydrothermal, seawater, volcanism

Fault-controlled (hydrothermal) dolomitisation (so-called HTD) has received much interest as it is an important host for MVT-mineralisation and hydrocarbons, and an excellent proxy for fluid flow and reaction in carbonate systems. The source of fluids of sufficient volume and the correct chemistry to explain HTD however, is much debated. Since dolomitisation is favoured where there is a precursor high magnesium calcite or dolostone, it is possible that such a process is a critical precursor to the formation of HTD from evolved brines during extension and transpression.

In the Pennine Basin and North Wales, UK, HTD developed on the margins of Mississippian carbonate platforms that grew on the rotated footwalls of normal faults and a basement of Lower Palaeozoic metasediments. Conceptual models for their formation focus on expulsion of fluids from Serphukovian-Bashkirian sediments within adjacent hanging wall basins, by compactional dewatering or rupture of overpressured compartments and seismic pumping. This project aimed to determine the source, composition and drive mechanism of fluids that formed a large (~60km^2), non-stratabound dolostone body exposed within the Viséan sediments on the southern margin of the Derbyshire Platform, through a combined regional sedimentological, diagenetic and structural framework, utilising multiscale, interdisciplinary techniques.

Dolomitisation on the Derbyshire Platform is aligned to deep-seated basement faults and extrusive, intraformational volcanic beds, and five dolostone phases have been identified.

These are present as matrix replacive and cement phases that are spatially and temporally related to deep seated structural lineaments. It is proposed that stratabound, early post-rift dolomitisation resulted from the geothermal convection of seawater that interacted with the Viséan extrusive and intrusive volcanics on the Derbyshire Platform. This previously undescribed model of dolomitisation is key to explaining the anomalously large quantity of dolomitisation observed on the Derbyshire Platform and has implications to other carbonate platforms where dolomitisation is interpreted as fault-controlled.

Subsequent phases of dolomitisation are fault-controlled, with each phase becoming increasingly confined to fractures. Timing of dolomitisation is interpreted to be a Carboniferous event, the result of rapid, episodic, basin de-watering on to the platform via faults/fracture systems and the development of pockets of overpressuring. Illite-smectite clay transformations within Viséan basinal sediments provided the necessary magnesium required within select fault/fracture systems. Consequently, burial calcite cements and MVT-style mineralisation was precipitated within fractures and dissolution-enhanced secondary porosity, with fluids derived from the overlying Namurian succession which also acted as the seal.

This project provides a step-change in our ability to predict the location of HTD in rift basins by demonstrating the importance of early dolomitisation by seawater on platform margins to the localisation of later HTD bodies. It also highlights the complex interplay between basin kinematics, host rock permeability and timing of fluid supply through episodic fault reactivation, connecting platforms to basin compartments, which ultimately controlled the positioning of HTD geobodies on platform margins. This has implications to the exploration of both minerals and hydrocarbon within HTD hosts, and will inform studies of fluid transfer and reaction in carbonate systems.

Cave breakdown and the preservation potential of near-surface formed coastal caves: learnings from subsurface data and geomechanical numerical models

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Key Words: breakdown, burial, caves, finite numerical modeling, preservation

Carbonate rocks often exhibit multi-scale pore networks due to the interplay of depositional, diagenetic, and structural controls. Because carbonate rocks are highly susceptible to dissolution (particularly) at near-surface conditions, caves commonly develop. The development of these dissolutional features are ubiquitous across geologic time, despite differences in factors including depositional environment or setting, facies type/associations, and surface water chemistry. Paleocaves that formed in near-surface conditions have commonly undergone complex diagenetic and burial histories, such as cave breakdown, sediment infill, and repeated phases of mechanical compaction during burial (Loucks, 1999).

The process of cave breakdown is believed to be both a cave forming process (coalescing caves into larger chambers) and destructive process (collapsing caves). It is suggested that breakdown is a process that is common within the shallow vadose zone (Osborne, 2002), where the hydraulic support from the phreatic water is not present (White and White, 1969; Osborne, 2002). While cave breakdown is a process that is recognized to be occurring today, the question remains under what conditions caves can remain open with significant burial depths.

This study investigates the preservation potential of caves that have developed in near-surface conditions and undergo significant burial by constructing geomechanical finite numerical models. We employ physics-based geo-mechanical numerical models to test the factors that affect the preservation potential of caves. We hypothesis that caves that form at or near the surface, and are filled with phreatic fluids prior to burial, can remain open to significant burial depths. Our results suggest that such caves can remain open past burial depths of 10,000 meters. These results suggest that there is a large preservation potential for caves that develop at near-surface conditions to remain open and intact at significant burial depths

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The stable isotope composition of Qatar coastal waters ($\delta^{18}O$ and δD) in comparison to the $\delta^{18}O$ and $\delta^{13}C$ of modern sediments and ancient rocks: Houston, we have a problem

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Isotopic measurements of Qatar coastal waters show that during evaporation to halite saturation both $\delta^{18}O$ and δD rise above values of +12‰ and +60‰ VSMOW respectively, significantly higher than previously reported for marine waters. $\delta^{18}O$ measurements of gastropod shells and aragonitic mud recovered from coastal waters with salinities ranging between 40 and 90 psu show strong correlation with the $\delta^{18}O$ of associated seawater (R^2>0.85; slope ~1), and are as high as +5‰ VPDB. The $\delta^{13}C$ values of these sediments correlate positively with their $\delta^{18}O$ values (R^2=0.43), and range as high as +4‰ VPDB. The positive $\delta^{18}O$-$\delta^{13}C$ correlation likely reflects sequestration of ^{12}C into organic matter through photosynthesis in more restricted settings. Comparable $\delta^{18}O$-$\delta^{13}C$ correlations were previously observed and similarly interpreted in Pleistocene-age gastropod shells and foraminifera tests taken from the arid southern Australian margin. Local variability in $\delta^{13}C$ values of recent sediments from both of these arid settings are similar to that of secular variation during the Cenozoic.

In situ field experiments demonstrate that neither Mg-calcite nor aragonite dolomitize in Qatar coastal waters over a period of greater than three years regardless of grain size, degree of evaporation, and the presence or absence of overlying microbial mats. Measurements of Mg^{2+}/Ca^{2+} ratios in these waters also yield little evidence of dolomitization. In contrast, both underlying Eocene deposits and locally-uplifted Miocene rocks are mostly dolomitic, and based on ongoing Eocene rock studies, appear to have undergone dolomitization in marine waters prior to significant meteoric exposure. Dolomite in rocks of both these ages are locally interbedded with meter-thick gypsum deposits, inferred to be of marine origin. Confoundingly, the $\delta^{18}O$ and $\delta^{13}C$ of such dolomites indicate formation in near-normal seawater. If the chemistry of modern deposits from similar evaporative settings is an indicator, both the $\delta^{18}O$ and $\delta^{13}C$ of the ancient dolomites or their precursor deposits were reset, apparently prior to significant exposure.

In the Eocene rocks of Qatar, general correlation between the presence of dolomite and the inferred depositional environment is non-existent. Such poor correlation calls into question the reflux dolomitization model, which is commonly invoked to explain dolomitization in arid settings. Regardless, early dolomitization of the near-surface ancient rocks of Qatar may be a key to their preservation. Whereas Holocene sediments are plentiful along Qatar coasts, Pleistocene deposits are generally absent, likely deflated and largely removed by winds during lowstand. Whatever the chemical driver, early dolomitization and resulting lithification may be a key to highstand carbonate sediment preservation in arid coastal settings.

16th Bathurst Meeting

Abstracts Volume

Talks

Theme 3: Core to Seismic Interpretation, Upscaling and Pore Systems

T-23 to T-24

Seismic Investigation of Carbonate Platform to Basin Development offshore Jamaica

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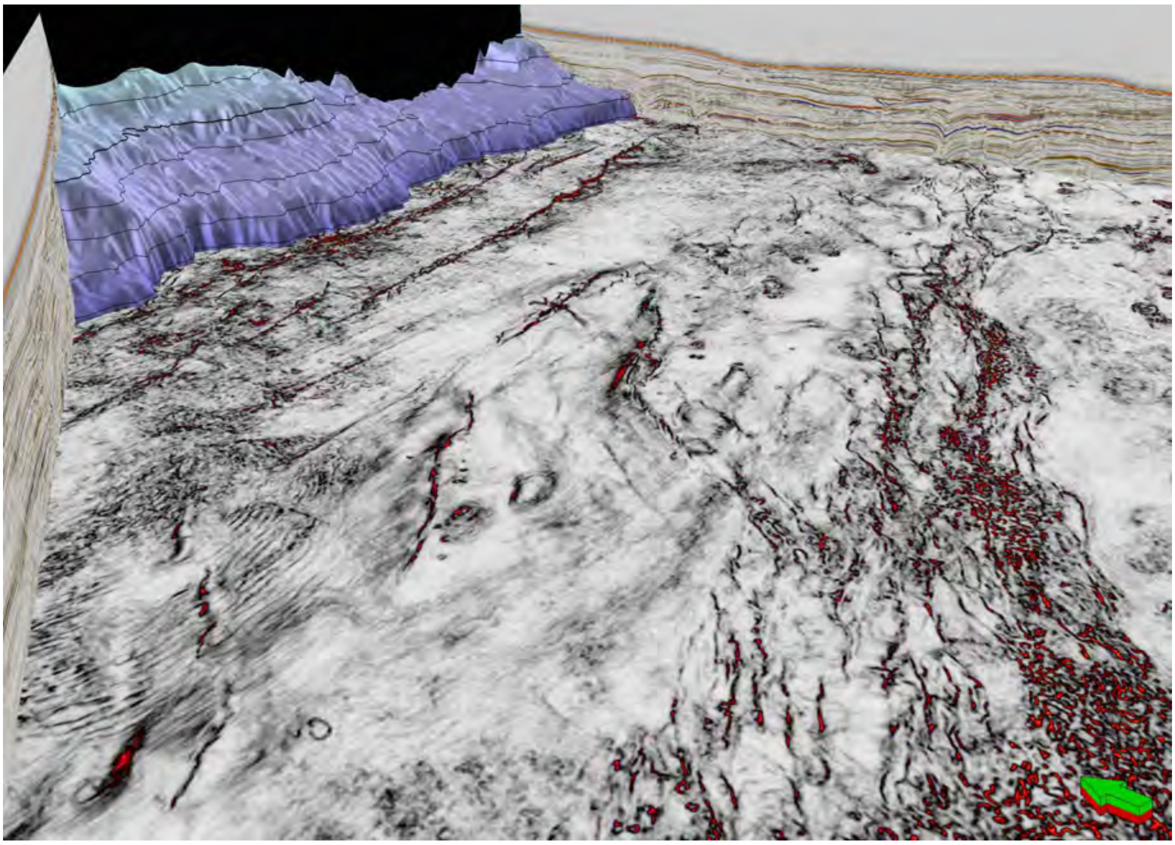
Key words: Amplitudes, Fluids, Seismic, Platforms, Tertiary

In 2018 Tullow Oil acquired the first ever 3D seismic survey offshore Jamaica, in the central part of the Walton Basin. This is a Tertiary strike-slip influenced rift that is surrounded by Mesozoic basement highs, some of which are cored by igneous bodies. The present-day basin has water depths of ~ 500 – 1000 m and is defined by a high-relief shallow carbonate bank to the south and east (the Pedro Bank), a drowned steep-sided carbonate platform to the west (the Walton Bank) and a shelf area to the north bordering the Jamaican coast. The island of Jamaica was tectonically uplifted from the Late Miocene to Recent on a restraining bend of the northern Caribbean plate boundary that passes through the island. Platform and basin carbonates of Middle Eocene to Middle Miocene age are exposed onshore and were likely contiguous with the offshore successions prior to uplift. Younger carbonates onshore have mostly been removed by prolonged karstification and erosion.

The new 3D data set crosses the margin of the Walton Bank and is tied to the Pedro Bank, including the offset Arawak-1 well, and interior parts of the Walton Bank, by a mixed-vintage 2D seismic grid. In the absence of any well data in the Walton Basin itself, interpretation has been guided by field observations of the onshore carbonate facies architecture, supported by published data and collaboration with local specialists. However, many outcrops onshore are limited in size, widely distributed and can be difficult to correlate. The new 3D seismic data give a unique insight into larger scale platform margin to basin geometries and the structural context of carbonate accumulation. They also provide new evidence of a dynamic fluid flow system within the basin. Vertically migrating fluids exploited faults and chimneys, many with suprastratal sags that imply dissolution and collapse in the underlying conduits. Soft amplitude anomalies, frequently associated with faults, attest to porosity enhancement in the basinal carbonates. These might also be related to hypogene dissolution from fluids exploiting relatively permeable, platform-derived, resedimented grain-rich strata. Pulses of tectonic activity are also recorded by the presence of large scale carbonate mass transport complexes in the basin, sourced from the surrounding steep and gullied platform margins. Evidence for active tectonism and fluid circulation largely terminates at the top of the Miocene section, with few faults or pipes reaching the modern sea floor. However, shedding of sediment off the steep-sided Pedro Bank continued, probably under glacio-eustatic control, producing spectacular submarine channel systems and possible megabreccias within the Quaternary / Recent section.

This presentation will summarise the conceptual model for the Jamaica Tertiary carbonates and illustrate some of the key features revealed by the 3D seismic that are feeding into Tullow's geological interpretation of this exciting frontier basin.



Composite PSDM cube with platform margin surface and variance slice through basin fill

Modern Nature: Understanding the Seismic Paleokarst Landscape of the Loppa High, Norwegian Barents Sea.

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Keywords : Paleokarst landscape, seismic attributes, Gipsdalen Group, Barents Sea

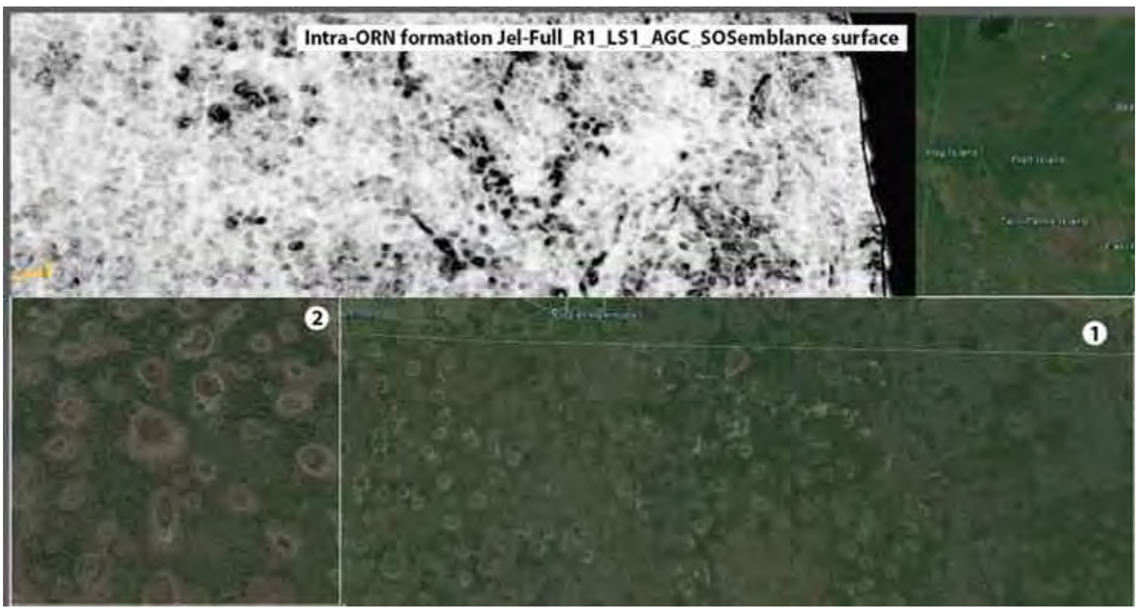
Modern seismic geometric attributes produce 3D volumes that can facilitate the recognition of karst geomorphology by enhancing sub-seismic lateral variations.

In this context, the presentation aims to characterize the paleokarst horizons by presenting the morphology of the associated reflectors recorded on seismic data, together with endokarst features in the underlying carbonate succession such as cave systems and collapsed structures.

The Upper Carboniferous and Early Permian age carbonate units underwent intense karstification associated with subaerial exposure during multiple periods resulting in the development of sinkholes, sinking streams, caves, uvulas or karst valleys, and other characteristic features.

Such complex seismic landscape also requires a review of karst processes and development, which can be beneficially captured via geophysical characterization of near-surface karst landscape features that certainly equate to our better understanding its evolution.

The presentation offers a rich visual journey between the beauty of the natural landscape from Florida, Western Australia, Madagascar, Mexico, Italy compared to the Norwegian seismic examples which can be used in the exploration to constrain geological input, and to de-risk subsurface uncertainties



16th Bathurst Meeting

Abstracts Volume

Talks

Theme 4: South Atlantic Pre-Salt Carbonates, and Potential Analogs

T-25 to T-33

Stratigraphic model for the South Atlantic West margin presalt carbonates

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Key Words – Carbonate Platforms, Continental Rift, Sequence Stratigraphy, presalt, Campos Basin

Abstract

There have been few attempts to apply sequence stratigraphic models to lacustrine carbonates in continental rift settings. Many publications focus on marine settings whilst making assumptions on constant subsidence rates and eustatic sea level fluctuations. In order to further our understanding of the stratigraphy of the non-marine carbonate deposits, Campos Basin, Brazil, we have tackled the challenge of establishing an appropriate sequence stratigraphic model for these subsurface rocks. The goal of this work has been to construct a hierarchical scheme from core-based, high-frequency cycles to seismic scale units that reflects the major controls on the accumulation of these lacustrine carbonates. The study is based on a proximal to distal rectangle of 3D seismic, 23 wells with wireline data and 400m of core through the pre-salt carbonate succession (Coqueiros Formation) of the Campos Basin, Brazil. Four hierarchical levels of cyclicity were identified on the basis of their facies and taphofacies successions, exposure surfaces, gamma-ray trends and stratigraphic geometries.

The identified cycles are correlated to the 3rd, 4th, 5th, and 6th orders (sensu Vail et al., 1992).

The smallest scale units are metre-scale, generally transgressive-regressive (T-R) cycles with low energy facies at the base and higher energy rudstones and grainstones near the top. Exposure features, such as breccias, commonly cap them. Because there are no correlatable stacking patterns to these cycles and considerable thickness changes within the Coqueiros and Macabu Fm, they are considered to be autocyclic, developed in response to local sedimentary dynamics. They generally exhibit thickening and shallowing-up stacking patterns and progradation of lake margins. The accommodation space are tectonically controlled.

The cycles of the others hierarchical levels are Allocyclic. The 5th order cycles range from 10 to 30m thick. The facies successions form symmetrical cycles, strongly expressed in the rise and fall of the GR log values. They are considered to be driven by changes in lake level responses to a higher frequency local and seasonal climate variations. It may also be associated with tectonic subsidence.

The 4th order cycles, is about hundred metres thick. They are controlled by climatic variations and can be correlated regionally. These variations are interpreted as alternation of terrigenous sediments, suggested in more humid periods, showing high values of GR, and carbonate facies, in arid periods showing low values of GR, commonly stacked in shallowing upward.

Finally, the 3rd order cycles are the thickest ones, hundreds of metres thick. They are a result of the tectonic activities, responsible for the creation of the accommodation space and the geometry of the basin. High productivity of carbonates in tectonic quiescence periods can fill or overfill the accommodation space resulting in agradacional or progradational geometries.

The analyses of the sedimentary framework and the stratigraphic organization of the strata into system tracts contribute to the carbonate reservoir facies predictability in exploratory and R & D activities.

Microcycles, T-R trends and high frequency correlation using core data and borehole image logs from lacustrine carbonates

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ABSTRACT

Lacustrine sedimentary deposits are acknowledged for displaying well-defined cycles. Sequence stratigraphy analysis through facies stacking patterns has traditionally been used to propose ideal depositional cycles and help to correlate wells. However, this method does not include very high frequency cycles, which are key features that allow us to understand the dynamics and evolution of the paleolake. In lacustrine carbonate deposits, biological and chemical variations can be registered in a very high frequency, even on a millimeter scale. These laminae alternation is defined as microcycles, being common in varves and rhythmites, but also recognized in shallow water carbonate deposits, such as microbialites, travertines and tufas.

In this study, ideal microcycles were defined for two different lacustrine carbonate deposits: the Paleogene Yacoraite Formation, Salta Basin (Argentina) and the Cretaceous Barra Velha Formation, Pre-salt of Santos Basin (Brazil). The carbonates of the first one show higher influence of biological processes (microbial) when compared to the carbonates of the second one, whose features indicate higher rates of chemical precipitation. Both deposits show exceptional carbonate textures and structures related to chemical, biological and hydrodynamic processes related to environmental changes.

In general, dolomitic layers were considered as the base of each microcycle, here interpreted as biogenic deposits, presenting laminar to columnar structures (typical of microbialite), while calcitic layers were considered as the top of each microcycle, here interpreted as mainly chemical deposits (microbial influence being secondary, but also important), presenting massive to smoothly laminated structures, calcitic shrubs, shperulites and crusts, mostly with crystalline textures. The differences of mineralogical, textural and structural features from base to the top of the microcycles were attributed to climate changes that affected the lake level, water chemistry and hydrodynamics. The similarities between different types of microcycles were used to propose a genetic evolution in terms of Transgressive – Regressive (T-R) trends.

The thicknesses of the microcycles were measured in outcrops (Yacoraite Fm), cores and borehole acoustic and resistivity image logs (Barra Velha Fm), and they were used to perform statistical analysis to identify changes of the depositional pattern through the deposits. Similar trends were traced along tens of kilometers, despite of facies change, what corroborate the stratigraphic framework proposed and validates this new application of borehole image logs data in the study of sequence stratigraphy.

Keywords: carbonate, microcycles, lacustrine, microbialites, pre-salt.

Presalt lake evolution in the south Atlantic: the significance of microbial chert

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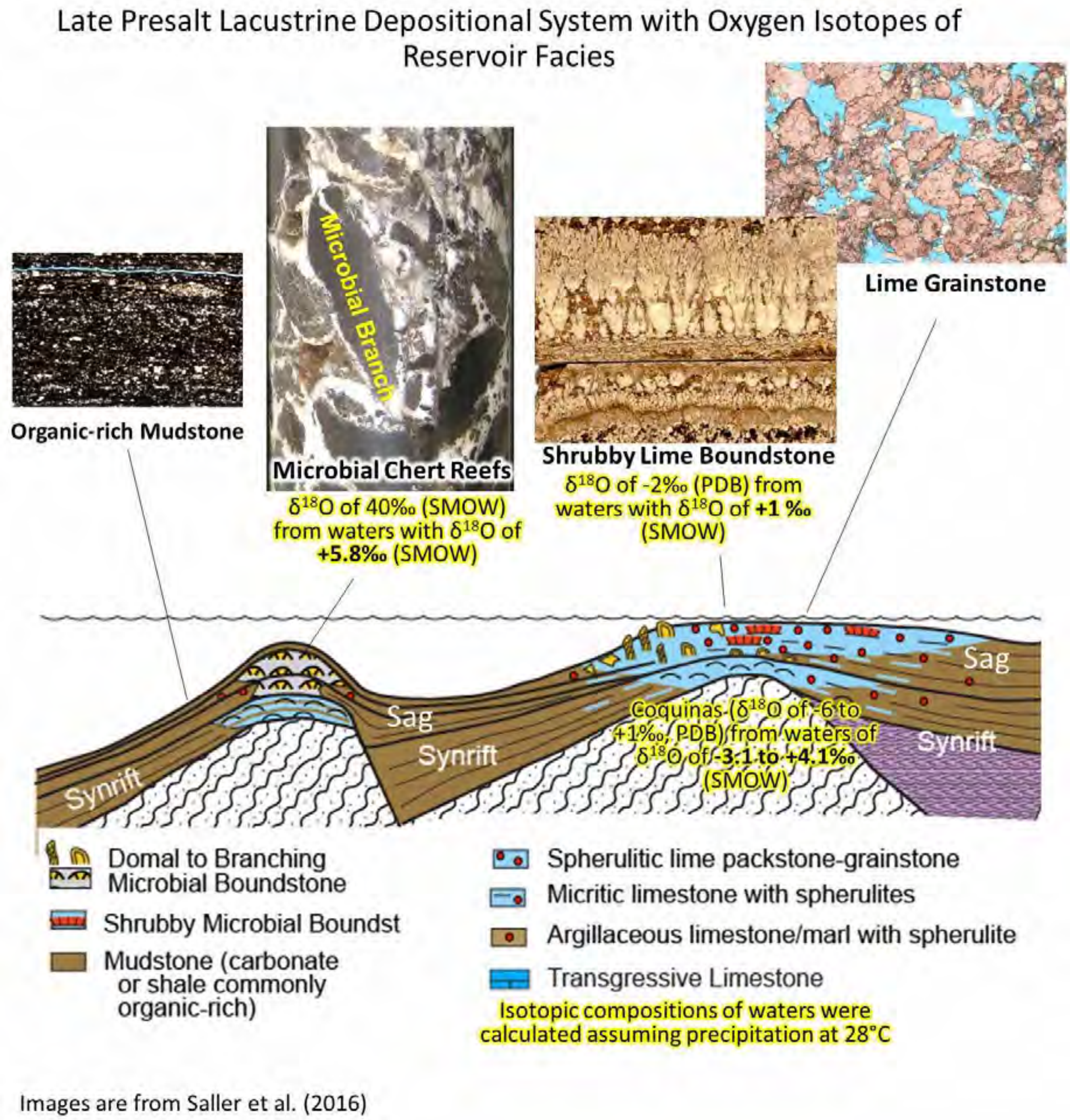
Key words: presalt, lacustrine, chert, microbialite, Cretaceous

Lacustrine deposition resulted in Cretaceous carbonate and chert reservoirs in both offshore Brazil and Angola prior to deposition of the widespread late Aptian salt. During the late Barremian to middle Aptian (lower to middle Cretaceous), presalt deposition changed from coquina-rich limestones to microbial-rich cherts and limestones. Microbial chert reefs grew on platform margins and isolated highs in the basin after coquina-rich intervals and before many microbial carbonate platforms. Four independent observations indicate deposition of substantial chert reefs at surface temperatures and pressures. (1) Cherts with microbial boundstone fabrics have later silica cements growing off them and into adjacent primary pores. (2) Seismically mappable chert mounds (reefs) are 200 m thick and 1-2 km across. (3) Sedimentary chert clasts have early isopachous fibrous chalcedony cements that are truncated at the edge of clasts, indicating deposition of the clasts as chert reef talus. (4) Stable oxygen isotopic compositions of many microbial cherts and chalcedonies are extremely heavy ($\delta^{18}O$ of 38-41‰, SMOW) supporting chert precipitation at surface temperatures from highly evaporated lake water. Late silica cements ($\delta^{18}O$ of 31‰, SMOW) are present, but volumetrically minor (<25%) in the seismically defined chert mounds. Stable oxygen isotope analyses are consistent with coquinas being deposited in relatively fresh to evaporated lake water, microbial limestones deposited in moderately evaporated lake water, and cherts deposited in highly evaporated lake water. Assuming all three reservoir types were deposited at similar tropical surface temperatures (28°C), lime coquinas ($\delta^{18}O$ of -6 to +1‰, PDB) would be precipitated from waters with $\delta^{18}O$ of -3.1 to +4.1‰ (SMOW), calcites in shrubby fabrics ($\delta^{18}O$ of -2‰, PDB) would be precipitated from waters with $\delta^{18}O$ of +1 ‰ (SMOW), and microbial cherts ($\delta^{18}O$ of 40‰, SMOW) would be precipitated from waters with $\delta^{18}O$ of +5.8‰ (SMOW). Although temperatures of precipitation of these phases may have been different and diagenetic alteration occurred, this generalization suggests that microbial cherts precipitated from the most highly evaporated lake waters. See Saller et al. (2016) for more details.

Reference

Saller, A.H., Rushton, S., Buambua, L., Inman, K., McNeil, R. and **Dickson, J.A.D.** (2016) Presalt stratigraphy and depositional systems in the Kwanza Basin, offshore Angola. *American Association of Petroleum Geologists Bulletin*, **100**, 1135-1164.



Late presalt lacustrine depositional system with oxygen isotopic compositions of reservoir facies. Images are from Saller et al. 2016.

Where have most of the carbonates gone? Silicified Aptian pre-salt microbial (?) carbonates in South Atlantic basins (Brazil and Angola).

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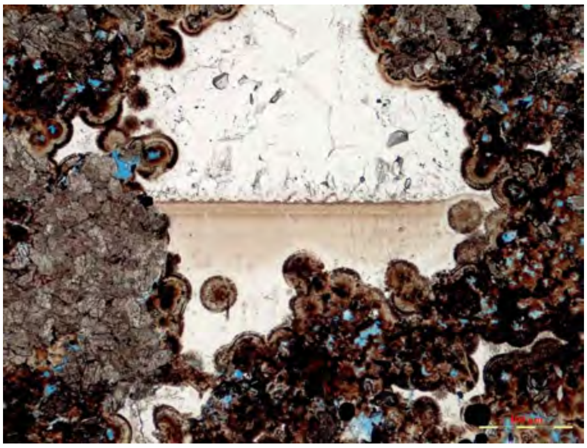
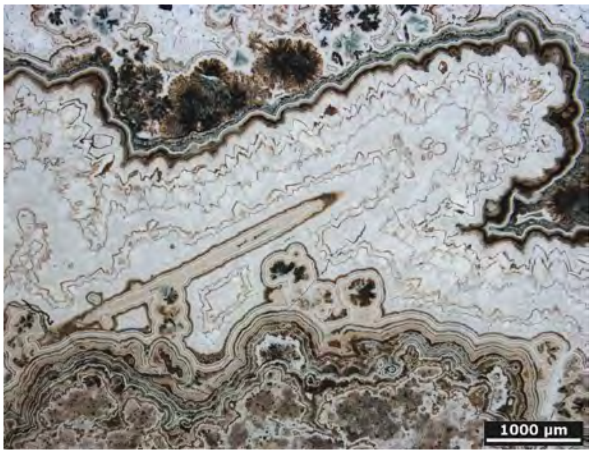
Key words:
Angola, Brazil, hydrothermalism, microbial carbonates, pre-salt, silicification.

A series of Aptian rift-sag basins successions formed during the opening of the South Atlantic Ocean in both the American (Santos, Campos and Espiritu Santo basins) and African (Kwanza) sides. On top of altered tholeiitic volcanic highs, shallow lacustrine, microbial (?) carbonates, fine siliciclastics and chemical sediments deposited in alkaline lacustrine environments. These carbonates, though initially comparable, underwent different diagenetic transformations, among whom partial-to-full silicification processes played a major role on creating, modifying and preserving their present-day reservoir characteristics. Silicified pre-salt carbonates have been found in at least three of five Aptian pre-salt basins (Campos and Santos in Brazil; Kwanza in Angola).

Former lacustrine carbonates formed in shallow-bench to proximal-bench slope ambients and were pervasively silicified. These silicified carbonates alternate with profundal lacustrine laminated calcisiltstones/dolosiltstones. Occasionally the original protolith is still recognizable partially preserving former calcitic allochems (ostracods, pellets, encrusting algae and eukaryote cells). The profusion of ostracods and the scarcity of high-alkalinity mineral markers (talc-stevensite) suggest that the original carbonates formed in a moderate alkaline lacustrine ambient.

An early silica event (*limnic silica-1*) is represented by direct lacustrine precipitates as discrete, fine-grained opaline crusts (now porous microquartz) covering topographic paleo-surfaces, thought to occur during alkalinity crises and silicic acid destabilization.A syn-sedimentary-early diagenetic (Aptian) silicification event (*pond silica-2*) post-dates early carbonate corrosion. Silica textures vary from fine-grained, fabric-preserving silica cementation to almost fully- replacive (fabric destructive) silicification, with scarce intensely corroded patchy calcitic/dolomitic resisters. Syn-sedimentary silica cementation textures include (1) dominant opal-chalcedony-mega-quartz cement passive filling sequences, thought to represent phreatic (hydrothermal pond) ambients; (2) scarce opal-cemented geopetal filling structures cementing corroded and rubefied thrombolithic/estromatolithic pores in vadose ambient; and (3) fully pseudomorphosed bladed or raft calcites by silica (opal and/or chalcedony), indicative of hydrothermal boiling in a sub-lacustrine sinter ambient, probably near or around discrete vents. Massive, fine grained (opaline, cherty) silica eventually can preserve original biotic structures with exquisite detail. The main silica diagenetic process consists on the transformation of opal-A to microcrystalline quartz, passing through a series of intermediate phases (opal-CT, opal-C, moganite), with concomitant microtexture destruction, porosity changes and geochemical alteration. Primary biogenic silica presence cannot be overruled but its presence, preservation and recognition are problematic; most of the possible biotic silica structures can be explained as artifacts after silica diagenesis.





Left: micro-karst cavity cemented by vadose geopetal opal and late phreatic mega-quartz; Right: silicified bladed calcite crystal indicative of non-isothermal hydrothermal boiling.

Late hydrothermal silicification (*hydrothermal silica-3*), including quartz veins, stockworks, hydrothermal breccias and vugs, overprinted the already silicified horizons. Late silicification is caused by the inflow of high temperature (90-170ºC), medium-to-high salinity (10-20wt% NaCl eq.) hydrothermal brine plume, with coeval hydrocarbon migration (black-oil to condensate-bearing fluid inclusions). The hydrothermalism accounts for: (1) hydraulic fracturing, porosity formation and late mega-quartz cementation; (2) recrystallization of former *silica-2*, obscuring or erasing original textures; (3) corrosion and silicification of the remaining carbonate components; (4) *in-situ* generation of pyrobitumen after thermal degradation of liquid hydrocarbons. The age of the hydrothermal plume in Campos basin spans between 107.0±1.0 to 104.3±0.8Ma (Ar-Ar adularia dating). The hydrothermal plume also hydraulically fractured the upper tight, thin kerolite-rich healing phase causing hydrothermal dedolomitization.

A Pre-Salt – like carbonate environment within the Post-Salt sequence in the Namibe Basin (Angola): understanding controls on facies occurrence and diagenetic pathways for South Atlantic reservoirs.

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Keywords: Continental carbonates; Diagenesis; Namibe Basin; Post-Salt; South Atlantic.

The Namibe Basin is the southernmost basin in Angola, located just north of the Walvis Ridge, and developed as part of South Atlantic rifting in the Cretaceous. It is characterised by syn-rift to sag continental/lacustrine facies and post-rift marine sediments, separated by Aptian evaporites. However, a lacustrine environment is temporarily re-established in the Late Cretaceous, with deposition of carbonate facies similar to those encountered in the Pre-Salt reservoirs. This system is now exhumed and represents a very good analogue for South Atlantic Pre-Salt reservoirs as geometric relationships between carbonate facies and geo-bodies are perfectly preserved. Facies include sub-lacustrine hydrothermal spring mound complexes with silicified botryoidal vent-top fabrics, travertine-rich slope systems and distal water-lain deposits of bivalve-gastropod coquinas, as well as stromatolitic and thrombolitic ostracod-rich build-ups. This system occurs within a graben defined by synthetic and antithetic faults and directly overlies Santonian igneous rocks. Igneous activity was coeval with faulting and was responsible for the fluid flow that formed the spring mound complexes. Individual carbonate bodies can be tens of meters thick and they often occur along fault trends, and the geometric relationships between these complexes and faults provide a predictive tool when exploring for similar systems.

Microscopy shows that the carbonates underwent several diagenetic modifications mostly related to circulation of fluids during hydrothermal activity. Facies are pervasively dolomitised, with dolomite replacing the original matrix and precipitating as cement overgrowths. Silicification is significant in the vent-top areas, occurring as anhedral and chalcedony replacive mosaics and as large blocky crystals in pores. Multi-stage brecciation is mostly affecting the vent-top areas, with breccias being infilled by dolomite cement and silica. Dissolution is also evident, mostly affecting the mound slope and the water-lain distal areas, occurring as primary porosity enhancement and preferential dissolution of organism shells. Porosity in the vent-top facies is mostly related to the inter-botryoidal spaces when preserved from cementation. Within these facies silica cement also provides an overall rigid framework against compaction and a way for fracturing to develop, typically exploiting the inter-crystal boundaries. Porosity in the travertine slope facies is typically a combination of primary porosity and early dissolution enlargement, while the water-lain distal facies are mostly characterised by mouldic porosity.

Effectiveness of this system as good oil reservoir analogue is confirmed by presence of bitumen across different sectors and within different facies types, suggesting potential for oil to charge and flow through the pore networks. This study has important implications in the exploration and development of Pre-Salt continental carbonate reservoirs as it provides a facies and diagenetic model in relation to structures, also characterising porosity trends. This study could also provide the ground for continental carbonate plays to be explored within Post-Salt sequences.

Biogenic spherulites forming with Mg-clays in modern hypersaline and alkaline lakes on Rottnest Island, Western Australia: a new biosignature?

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Key words: lacustrine thrombolites, microbialites, Mg-clays, spherulites, pre-salt reservoirs

Radial-fibrous carbonate spherulites are a common component in the economically important Lower Cretaceous “pre-salt” lake carbonates of the South Atlantic, and have been reported in Paleozoic strata and a number of modern marine, lacustrine and vadose environments. However, a biotic role in their formation remains a topic of debate, due to poor preservation of the microbial component (if it existed) and a paucity of suitable modern analogues. Here we report conical thrombolites featuring spherulitic fabrics, forming in close association with coccoid-dominated microbial mats, within hypersaline, alkaline and Si-poor lakes on Rottnest Island, Western Australia, suggesting a biogenic origin for some spherulites in the rock record. Two spherulitic fabrics within the cones can be recognised and formed asynchronously based on textural and chemical differences. In both fabrics, extracellular polymeric substances (EPS) mineralized first as honeycomb-like polyhedrons composed of an Mg-silicate phase. Silica was most likely sourced from the dissolution of diatoms present in the microbial mat. The younger spherulites formed as Mg-calcite, within Mg-silicate polyhedral voids left by coccoid cells, and have micritic nuclei resembling smaller coccoid fossils. Pores between spherulites were subsequently in-filled by

microcrystalline aragonite and the Mg-silicate dissolved and/or replaced. The older spherulites comprise 100–500 µm wide radiating aragonitic spheroids, variably intergrown, nucleated on a micritic centre containing coccoid cyanobacterial moulds mineralized at various stages of cell division. The coccoid moulds combined with high δ^{13}C values suggest abundant oxygenic photosynthesis and rapid mineralization. The matrix comprises Mg-silicate spherical nanocrystal (100–300 nm) aggregates that contain coccoid moulds and are interpreted as recrystallized Mg-silicate from mineralized EPS. Under a transmission electron microscope, the spheres are revealed to be faceted, and resemble scaled-down versions of the polyhedrons present in the younger spherulitic fabric. The two spherulitic fabrics present in conical thrombolites on Rottnest Island both appear to be bio-induced, whereas the polyhedral spherulite morphology is controlled by the structure of mineralized EPS. The Rottnest Island spherulites provide a potential analogue for similar features in the geological record, suggest that Mg-silicate minerals in ancient spherulite matrices may have a biogenic origin, and that polyhedral spherulites may indicate the former presence of mineralized EPS, thus representing a new type of biosignature.

Forward stratigraphic modelling of continental carbonates. Coupled simulation of deposition in aerial, lacustrine and hydrothermal settings.

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Keywords: Forward stratigraphic modelling, Continental carbonates, Lacustrine, Travertine, Lattice gas

Forward stratigraphic modelling has proved to be a very efficient technique for simulating the deposition of sediments and analyzing the influence of the environmental parameters on the architecture of depositional systems. However, continental carbonate systems develop in such a wide range of depositional settings - from aerial to subaqueous environments -, that they cannot be integrally modelled by existing softwares. A new and very disruptive technique has been developed in SED-RES™, an in-house TOTAL solution, by coupling forward modelling for sedimentation in subaquatic conditions with a cellular automaton for hydrothermal and aerial settings.

In lacustrine conditions, the development of carbonates is driven by several geological processes such as climate change, fluid flow and water chemistry. As an example, microbial occurs in stratigraphic intervals characterized by specific climatic and geodynamic conditions. Consequently, many parameters impact the lacustrine carbonate factory and the distribution of the carbonate facies within this factory: lake level oscillations, subsidence along active normal faults, paleo-topography of the lake margins, carbonate production rates, sediment transport... All these parameters play a leading role on the development of the factory, and on the way sedimentary features are preserved. Consequently, the key issue for a successful forward modelling of lacustrine carbonates is the capability of the soft to manage these parameters. Thanks to such a management, SED-RES™ produces very realistic sedimentary architectures and distributions of carbonate facies as expected from field observations.

However, classic stratigraphic modelling doesn't allow to simulate carbonate build-ups in sub-lacustrine or aerial conditions. The parameters which control spring mounds, hydrothermal travertine mounds, fissure ridges, dams, lacustrine or fluvial crusts… are different from those which drive the regular lacustrine sedimentation. In continental build-ups, carbonate precipitation results from a continuum of abiotic and biologically influenced processes among which faulting, thermal water discharge, substrate topography and gradient, together with climate and vegetation, constitute the prevailing parameters. The modelling of these complex processes requires the possibility to handle water flows during the numerical simulation. In order to represent this flow, a cellular automaton has been developed in SED-RES^{TM}. As it mimics the process, the cellular automaton is a solution which preserves the efficiency of the algorithm. Based on a lattice gas, it determinates both the advection and diffusion components of the transport process. In the model, water incomes from (hydrothermal) springs can be driven by the location of the faults. The way build-ups are created depends on their location, above or below the lake level. In the case of terrestrial domes mostly composed of thermogene travertine, water runs on the topography from a spring orifice. The precipitation of carbonate is dependent on the dipping of the slope. According to the gradient, cascades and dams deposits are associated to fluvial crusts. Because of the oscillations of the lake level, the form may change and a terrestrial dome can be submerged after a water level increase. Associated to the modelling of the regular lacustrine carbonate sedimentation, the simulation of continental build-ups numerically generates the very complex sedimentary architectures observed in continental carbonates.

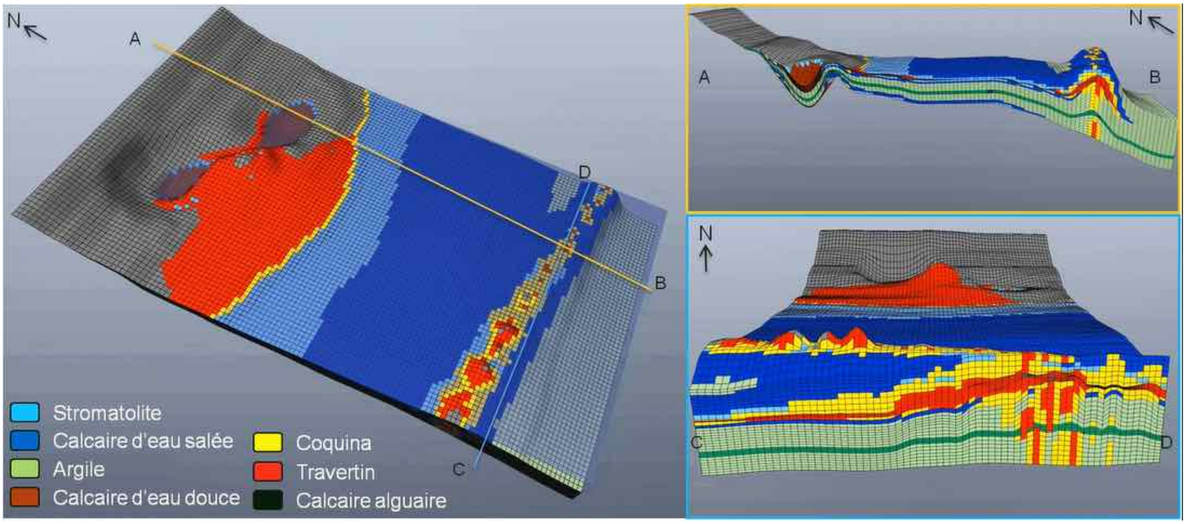

Figure 1: *Aerial view, longitudinal and transversal cross sections in a SED-RES^{TM} model of continental carbonates.*

Acknowledgements
The authors thank TOTAL for funding the R&D project and giving permission to publish this paper.

The hydrochemical evolution of alkaline volcanic lakes: a model to understand cyclothems evolution and mineral paragenesis in the South Atlantic Presalt lakes

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Keywords: Calcite, Lacustrine, Magnesium-rich clay, PHREEQC model, Silica

Understand the origin of the exotic Sr-rich spherulitic calcite/ Mg-rich clay/ silica deposits accumulated in the South Atlantic Cretaceous Presalt lakes is challenging our ability to comprehend the chemical evolution of alkaline volcanic lacustrine systems. Here we present a new hydrochemical model based on an open basin concept, thermodynamic equilibrium, and chemical data from Lake Baringo (East African Rift) to shed light on the mechanisms facilitating carbonate-clay-silica precipitation in alkaline lakes, with an emphasis on the Presalt mineral associations. This model explores the effects that the leakage to underlying aquifers, the combination of lake evaporation and lake recharge (with river, hydrothermal and marine waters), and the bathymetric effects of the CO_2 partial pressure have in the stationary precipitation of Presalt lacustrine mineral assemblages. Sediment thickness calculations suggest that the facies and mineral heterogeneities recognised in Presalt cyclothems are likely reflecting temporal fluctuations in the type of waters sourcing the lake, and in the degree of leakage to aquifers over multiple evaporative-freshening cycles. A plausible link between enhanced strontium uptake into Presalt calcite allochems and $[Ca^{2+}]/[CO_3^{2-}]$ lake water stoichiometries allows to infer two contrasting scenarios for Sr-rich spherulitic calcite formation. The first scenario is characterised by limited hydrothermal inputs to the lakes, and broader leakage ratios encouraging the formation of calcites in the

absence of Mg-clays; the second scenario arises from reduced seawater inputs to the lake and extensive leakage ratios to aquifers promoting the simultaneous precipitation of calcites and Mg-clays. Our conceptual model allows to quantify, for the first time, the role that hydrology (groundwater charge, discharge to aquifers; evaporation) exert on carbonate-clay-silica precipitation providing with a refined framework to understand the basin-scale chemical sedimentation in alkaline lakes. Furthermore, this model represents a robust geochemical template upon which critically test the superimposed kinetic factors likely attached to the genesis of specific mineral factories such as those encountered in the South Atlantic Presalt alkaline lakes.

Dissolved oxygen, biocontrolled calcification and marine microbial carbonate decline

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Bacteria, calcification, invertebrates, oxygenation, Phanerozoic

Shallow marine benthic microbial carbonate sediments episodically declined during the Phanerozoic. They were relatively abundant during the Cambrian to early Ordovician, latest Devonian to early Carboniferous, mid-Permian to mid-late Triassic, and to some extent in the late Jurassic to early Cretaceous. They were less abundant when invertebrate, especially reef, diversity was relatively high from the mid-Ordovician to mid-Devonian, and in the early Permian, late Triassic to mid-Jurassic, and mid-Cretaceous to present-day. These intervals of microbial carbonate abundance and invertebrate diversity generally transition from one to the other; but 'lows' and periods of 'overlap' also occur. 'Lows', when benthic microbial carbonate abundance and invertebrate diversity both declined, are apparent during the upper Carboniferous and early-mid Jurassic. 'Overlap', when microbial carbonates and invertebrates were both relatively common, occurs in the early Cambrian and late Jurassic.

Broadly, these patterns support the view that microbial carbonate abundance declined as calcified invertebrates increased. To further elucidate this relationship, we compared assessments of Phanerozoic microbial carbonate abundance and invertebrate diversity with estimates of changes in sea-surface temperature and marine dissolved oxygen. This analysis suggests that Phanerozoic invertebrate diversity varied directly with oxygen availability. Invertebrate diversity was low when dissolved oxygen was low in the early Ordovician, late Devonian to early Carboniferous, late Permian to early Triassic, and early to mid-Jurassic. We infer that, by reducing invertebrate diversity, low oxygen levels favored microbial carbonate formation. At the same time, low oxygen levels likely stimulated anaerobic metabolisms that favor carbonate precipitation. Based on these results, it appears that - directly or indirectly - the level of dissolved oxygen was a major influence on marine microbial carbonate abundance during the Phanerozoic and can largely account for the trajectory of its decline.

16th Bathurst Meeting

Abstracts Volume

Posters

Theme 1: Carbonate Platforms

Carbonate Factories, Depositional Environments and Processes, Growth, Architecture and Modeling

P-1 to P-58

Carbonate factories through the Earth history

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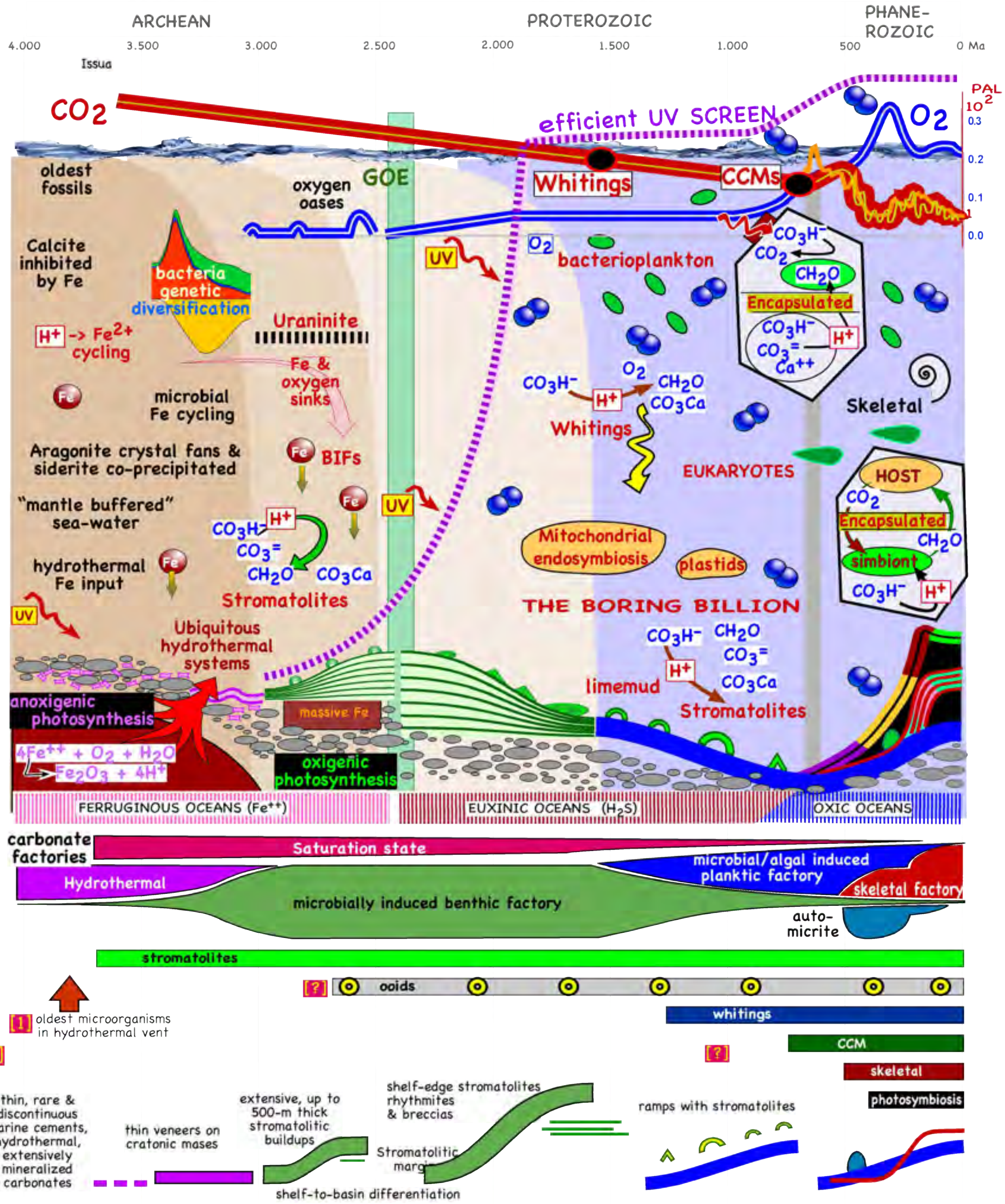
KEY WORDS: Carbonate, Factory, Precambrian, Phanerozoic.



Acknowledged project: CGL2014-52096-P

The mid-Neoproterozoic carbonate factory and the long-term evolution of the Precambrian $CaCO_3$ cycle

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Keywords: Akademikerbreen; biomineralization; CO_2; Neoproterozoic; Precambrian;

The Neoproterozoic Era marks a critical turning point along Earth's evolutionary trajectory. Sedimentary rocks from this time period record the breakup of a supercontinent, the advent of eukaryotic biomineralisation, the origin of complex multicellularity, and the most significant and enigmatic perturbations to climate and the carbon cycle in Earth's history. Nevertheless, nearly all models for the Neoproterozoic carbon cycle suffer from an absence of constraints on ocean-atmosphere carbon chemistry, leaving inorganic C burial as a critical but unknown factor in regulating Earth's surface carbon reservoir [1,2]. This has, in turn, precluded mechanistic links between biology, climate, and the lithosphere.

Here, by targeting successions hosting authigenic Mg-silicates, which independently constrain the marine carbonate system, we show that early Neoproterozoic seawater featured elevated alkalinity in the presence of high atmospheric pCO_2, which sustained excessive marine $CaCO_3$ supersaturation ($\Omega_{Calcite}$). Our data also show that between ~800-750 Ma, this inorganic carbon reservoir was halved. Because pelagic calcification was absent in the Proterozoic, alkalinity, DIC, and pCO_2 would have been strongly linked to the shallow marine CaCO3 sink [1]. Our documentation of the long-term (>10^6 yr) maintenance of high $CaCO_3$ supersaturation in turn requires the presence of kinetic inhibitors in seawater in order to have increased the $\Omega_{Calcite}$ threshold for $CaCO_3$ nucleation.

^{31}P solid state NMR and synchrotron-based µ-XRF and P-XANES collected from Tonian carbonates from the Akademikerbreen Group (Svalbard) show that elevated marine concentrations of PO_4, expressed as carbonate fluoroapatite inclusions within $CaCO_3$ and as early diagenetic cements, were associated with carbonate sedimentation across a variety of lithofacies. Our experimental observations [3] further confirm that because it is a strong inhibitor of $CaCO_3$ precipitation, enhanced marine concentrations of PO_4 (at the µmol/kg level) fundamentally altered the dynamics of inorganic $CaCO_3$ precipitation and fabric development of Akademikerbreen carbonates.

If representative of other Tonian carbonate depositional systems, our data suggest that kinetically-controlled shifts in $\Omega_{Calcite}$ (and therefore $CaCO_3$ precipitation fluxes) may have: (1) influenced the partitioning of carbon burial between organic and inorganic forms (i.e., $\delta^{13}C$); (2) impacted atmospheric pCO_2 and climatic stability; (3) imposed environmental pressure on eukaryotes to control unwanted calcification, thus establishing a key impetus for eukaryotic biomineralization (consistent with the observation that anti-calcifying molecules were already present in the last common ancestor to cnidarians and bilaterian animals and were later recruited by emergent organisms of the Ediacaran-Cambrian [4]). Thus, unraveling marine carbonate chemistry through this interval has begun to expose the mechanistic underpinning of a dynamic inorganic carbon cycle unknown from any other period in Earth's history.

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Eocene marine carbonate system through space and time: a pivotal paleoclimate transition period for carbonate factories.

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Carbonate prediction, global distribution, paleoclimate, carbonate architectures

The architecture of marine carbonate platforms result from the stratigraphic response of carbonate factories to local and global changes through geological times. We investigate the response of shallow-water carbonate systems to Eocene paleoclimate evolution at a global scale by compiling: 1) biotic assemblages, 2) sedimentary depositional profiles and 3) gross architectures (size and geometry) of carbonate platforms. About 180 Eocene formations were classified.

Eocene is a very interesting time interval that records the last greenhouse to icehouse climate transition from warm ice-free conditions (Early Eocene Climatic Optimum – EECO) to permanent Antarctic ice-sheet conditions. This Early Eocene period is characterized by the absence of coral buildups in the stratigraphic record and the development of LBF-dominated ramps in tropical paleolatitudes. Consistent with the highest atmospheric CO_2 concentrations, low Mg:Ca ratios in seawater and reduced hydrodynamic conditions during the Early Eocene (Ypresian), a prolific carbonate sedimentation dominated by calcitic larger foraminifera prevailed over aragonite production by corals (Pomar et al., 2017). High-latitude cooling began in the middle Eocene and showed an acceleration of deep-ocean circulation and a decrease of atmospheric CO_2 that implied a rapid biotic turnover. Despite these paleoclimate changes, ramps constantly dominated the shallow-water carbonates throughout the Eocene. This observation poses this critical question: more local controlling parameters should be involved in the building of shallow-water carbonate architectures such as initial topography (shelf physiography), transport (ocean dynamics), sea-level variations and local tectonics.

In this study, deciphering of the controlling parameters is based on 2D-3D stratigraphic forward modelling (Dionisos), sensitivity analyses of real and synthetic carbonate systems and published Eocene paleoceanographic models. Stratigraphic forward modeling allows testing different combination of carbonate production, sea-level curve and tectonic/topography/subsidence parameters. Early stage of analyses shows that grain transport is responsible for the homogeneous, flat architectures of the grainy Eocene carbonate platforms. In parallel, an Eocene stratigraphic chart including carbonate factories and platform morphometrics of shallow-water carbonate formations and four paleogeographic maps were produced to study Eocene carbonate systems through space and time. These living documents provide tools for the prediction of stratigraphic architectures in unexplored areas.

Rhodoliths might not rock and roll as much as previously believed: water energy and rhodolith morphology

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Key words: coralline algae, rhodoliths, temperate carbonates

Spencer Gulf is a semi-enclosed embayment along the southern Australian margin. The Gulf experiences inverse estuarine circulation and its seafloors are covered with heterozoan carbonates, including extensive rhodolith pavements (~3,000 km^2). These healthy rhodolith communities are found intermixed with carbonate sands and muds. Rhodoliths living in muddy substrates are rare and poorly understood, as coralline algae can easily be smothered by muds.

This study investigates the habitats, morphologies and taxonomies of Spencer Gulf's rhodoliths and relates these findings to oceanographic and environmental controls. Rhodolith pavements occur in high-energy channels and low-energy regions of Spencer Gulf at a variety of water depths (9-36 meters). Rhodolith growth forms and morphometrics from these diverse settings are compared and contrasted. All rhodoliths of the Gulf have protuberances; growth forms include fruticose, lumpy, warty, and intergrades between these forms. Most nodules are spherical with 0.5-5.0-cm diameters. Rhodolith growth forms, sizes, sphericities and branch densities do not vary consistently between rhodolith beds, despite dramatic environmental differences. The results of this study support the conclusion that rhodolith morphologies are not primarily controlled by seafloor water-energy conditions.

Additionally, rhodoliths of Spencer Gulf are made of at least five coralline algal genera (*Lithophyllum*, *Sporolithon*, *Phymatolithon*, *Hydrolithon*, and *Neogoniolithon*) and the taxonomic constraints on rhodolith growth are poorly understood. Environmental interpretations of rhodolith deposits should, therefore, never be based solely on rhodolith morphologies, but should integrate sedimentology, associated calcareous biota, and coralline algal taxa. These results will aid in paleoenvironmental interpretations in the rock record worldwide, including in the extensive rhodolith-dominated facies of Mediterranean Cenozoic deposits.

The seagrass skeletal assemblage from modern to fossil and from tropical to temperate

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Keywords: seagrass, foralgal, Mediterranean, Maldives, Eocene, Oligocene

Seagrasses are marine angiosperms that form extensive submarine meadows in the photic zone where carbonate producing biota dwell as epiphytic on the leaves or as infaunal forms, constituting prolific carbonate sediment factories. As seagrasses have a low preservation potential and records of exceptionally well preserved and plant material from marine settings are rare, these paleoenvironments are difficult to identify in the rock record. Consequently, sedimentological and paleontological proxies are the main indicators of the presence of seagrass-dominated ecosystems. In this work we investigate the skeletal assemblage of modern (Maldivian and Central Mediterranean) and fossil (Eocene, Apula and Oman Carbonate Platforms and Oligocene, Malta Platform) seagrass examples to characterize the skeletal assemblage of both scenarios. Two main types of grains, calcareous algae and foraminifers, constitute around 50% of the bioclastic sediment in both tropical Maldivian and temperate Mediterranean seagrasses. However, in the tropical setting calcareous algae are represented by green algae (*Halimeda*), while in the Mediterranean by corallinacean red algae. In contrast, in the Eocene examples, the foraminifers are the most conspicuous group, and the green algae are also abundant. The opposite occurs in the Maltese Chattian, which is dominated by coralline algae (mean 42%), although the foraminifers are still abundant. We suggest the use of the term foralgal to identify the seagrass skeletal assemblage. To discriminate between red algae and green algae dominance, we propose to introduce the prefix GA (green algae) and RA (red algae). The investigated examples provide evidence that the GA-foralgal is typical of tropical, not excessively dense seagrass meadows, characterized by a well-illuminated substrate to support the development and calcification of the *Halimeda* thallus. Contrarily, the RA-foragal is typical of high density tropical to subtropical seagrass meadows which create very dense oligophotic conditions on the seafloor or in temperate settings where *Halimeda* cannot calcify.

Relevance of Carbonate Factory Models for Prospect Assessment in the Oil Industry

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carbonate factories, conceptual models, risking, volumetrics

The fundamental differences of tropical and temperate carbonate factories (cfs) have been discussed among carbonate sedimentologists for many years, see for reference Lees & Buller (1972) and Schlager (2005). Question is, to what extend and in which format should and can industry implement concepts of carbonate factories and related reservoir characteristics into their risking and volume calculation workflows?
The Norwegian Barents Sea shelf provides an excellent example of Late Carboniferous-Late Permian sediment accumulation changing from tropical (Bashkirian-Sakmarian) to temperate carbonates (Kungurian-Wuchiapingian) and finally to chert-dominated spiculites (Wuchiapingian-Changhsingian, Figure 1). Key control factors of these fundamental changes in sediment production and preservation are the northward drift of the Barents Shelf platform, the closure of the Eastern European seaway and paleo-oceanographic constraints (e.g. fluctuation of the CCD), see Blomeier et al. (2013) and Ahlborn et al. (2014) for details.

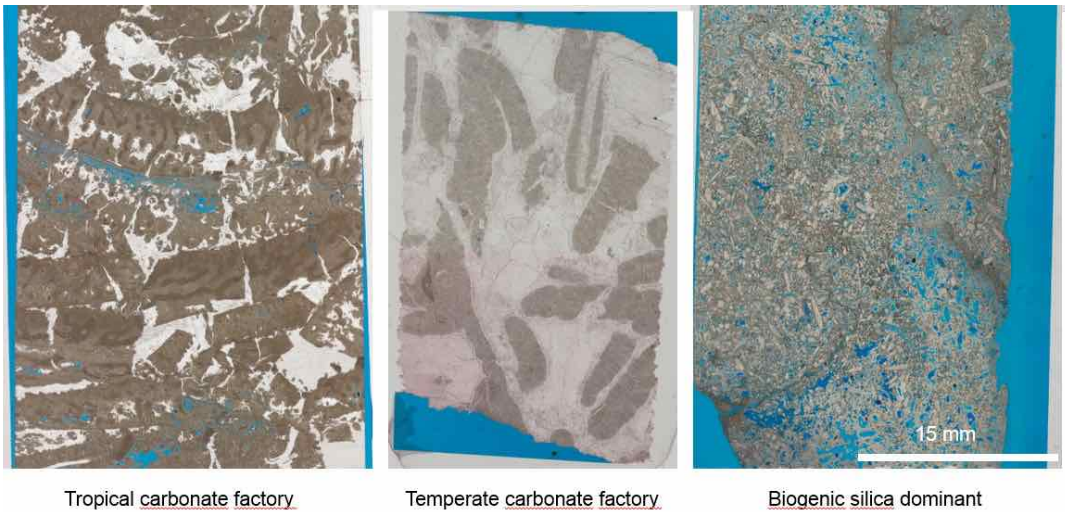


Figure 1: Thin section scans (PPL) showing reservoir quality of representative organic buildup samples (from left to right): tropical cf, *Palaeoaplysina* floatstone; temperate cf, fenestellid bryozoan 'cementstone' and cold-water cf, sponge spicule packstone.

Many oil companies developed over the years a two-fold approach for the estimation of recoverable hydrocarbon resources of a given prospect. On one hand, the uncertainty of possible hydrocarbon volumes is captured through ranges for specific parameters (e.g. volume of structure, thickness, net-to-gross, porosity, fluid parameters). On the other hand, up to six risk factors are defined to address the possibility of failure. Among these, trap presence (in the case of stratigraphic traps), reservoir presence, reservoir effectiveness, top seal presence and effectiveness are significantly controlled by sedimentologic processes and by paleo-oceanographic factors (Figure 2).

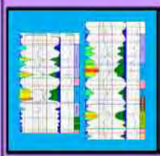
Main Relevance of Sedimentological Concepts for Risking and Volumes	Sedimentology		Net Pore Volume		
	facies orientation (i.e. coastline)	shape, extent, orientation of coarser streaks	Net/Gross	Porosity	Diagenesis
					
Uncertainty	H	H	L	L	M
Impact on HCIIP	H	M	M	M	M
Impact on Recoverable Volume	H	H	M	M	M

Figure 2: Matrix for integration and impact of sedimentological concepts into reservoir risking and volume calculation processes in E&P. H= high, M= medium, L= low

Based on petrography data from cores and cuttings (Wintershall proprietary data), well panels and public domain seismic data, we assess the reservoir potential of representative tropical, temperate and cool-water reservoirs prospects drilled in the Norwegian Barents Sea.

Our contribution for this Bathurst meeting is to discuss, based on Wintershall's results and experience, the relevance and applicability of state-of-the-art models of carbonate factories for the daily work in the oil industry.

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A possible case of seagrass/algal meadows environment in the Upper Triassic: insights from the skeletal assemblages of the Yukon, Canada

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Keywords : Calcareous algae, carbonate platform, foraminifera, meadows , Upper Triassic

Seagrasses are marine angiosperms which may form extensive submarine environments of great ecological importance: these highly productive communities (Duarte 1989) are able to provide habitat for a wide variety of carbonate producing organisms. Due to a low fossilization potential, well-preserved rest of these marine plants are rare, making the identification of seagrass meadows in the fossil records often challenging (Brandano et al. 2019). Therefore, a combination of indirect paleo-seagrass indicators (IPSIs) is often used to infer the presence of paleo-environments dominated by seagrasses (Reich et al. 2015).

This work investigates the facies association of an Upper Triassic, organic-rich, lagoonal environment from the Yukon, Canada. These peculiar facies, devoid of any siliciclastic input, were formed in restricted lagoonal environments: preservation of organic carbon in such a shallow marine environment can only be achieved when high levels of primary productivity induce reducing conditions at very shallow sediments depths.

Skeletal assemblages, mostly unsorted, are dominated by molluscs, gastropods, dasycladacean green algae and epiphytic foraminifers (Fig 1).

The higher abundance of epiphytic organism, never found in life position, is observed in the more organic-rich facies: these samples are also characterized by numerous fragments of coalified organic matter (Fig 1- C). At the same time, an inverse trend is observed if looking at the distribution of the green algae: the areas where organic-rich sediments forms are then probably unsuitable for green algae calcification.

A biomarker study is currently being undertaken: characterizing the type of organic matter would possibly give us new insights regarding the type of substrate (e.g., seagrasses, brown algae, red algae) which may have acted as site of attachment for the epiphytic organisms.

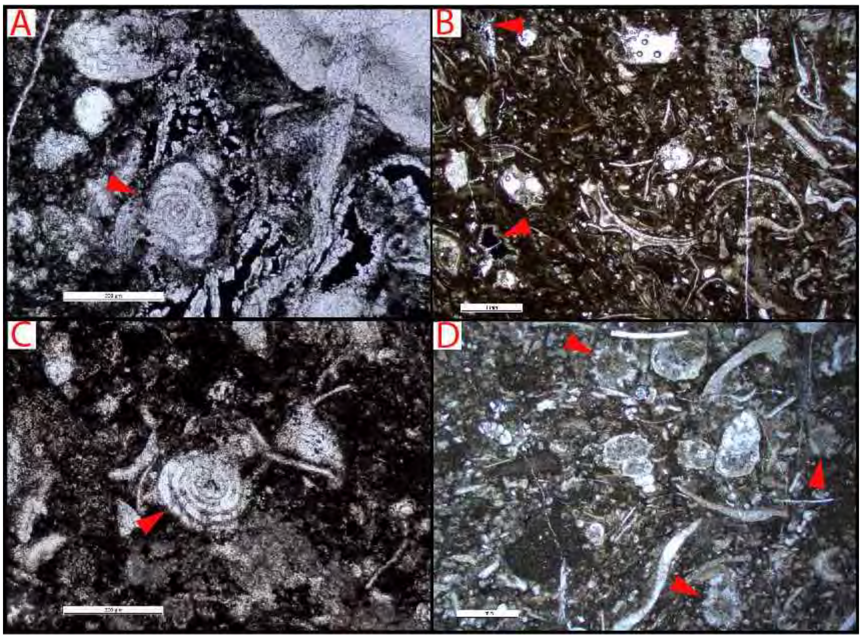

Fig. 1 – A, C) Norian epiphytic involutinid foraminifers (red arrows); B) general overview of this peculiar microfacies with coalified organic matter (red arrows); D) packstones rich in the dasycladacean green algae *Clypeina Besici* Pantić (red arrows).

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Controls on tropical carbonate production on a broad carbonate platform: insight from the Miocene southern North West Shelf (Australia)

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Key words: ramp to rim transition, tropical factory, foraminifera dominated carbonates, coral proliferation

Carbonate sedimentation has dominated across Australia's extensive North West Shelf (2400 km NE-SW length by 500 km width) since the Paleocene. Distally steepened ramps characterise much of the Cenozoic history of the NW Shelf, with significant additional barrier reef development during the Miocene. Here, we study transitions between platform-types on extensive, tropical shelves where carbonate systems may not easily fit into end-member platform types, and evaluate controlling influences. Miocene deposits are well imaged in the subsurface of the modern NW Shelf via high-resolution, publically-available 3D seismic datasets, although well data through the offshore carbonate sections are mainly limited to cuttings. These offshore successions from the southern NW Shelf are, here, correlated for the first time with outcrops from the adjacent onshore Cape Range area to better understand carbonate system evolution across broad shelfal areas.

In this new, integrated study we synthesise field, well-cuttings and seismic datasets to reconstruct the Miocene evolution of the carbonate systems of the southernly part of North West Australia. We infer a radical change in the style of carbonate sedimentation between the Early and Middle Miocene. During the Early Miocene, shallow water carbonate production is dominated by larger benthic foraminifera, and other carbonate producers are scarce. Carbonate accumulation on the shelf is limited, and there is a lack of evidence for coeval down-slope transport. Shallow water carbonate producers become much more diverse during the Middle Miocene. Shallow-marine micritic floatstones, rich in corals, algae and foraminifera, accumulated along with grainstone sand shoal deposits in the Cape Range Area. The deposition of these varied shallow marine facies is synchronous with the appearance of linear barriers and slope channels seen on the offshore seismic data.

Both Lower and Middle Miocene carbonate systems accumulated under warm conditions, and changes in temperature alone cannot explain this abrupt shift in carbonate producers. Moreover, the shift occurs just after a regional sea level fall potentially associated with extensive dolomitization, local karstification and early cementation. Resultant creation of uneven topography may have favoured the development of barriers, and associated protection of lagoonal-systems. A strong control of antecedent platform topography is an inferred major influence on the shift in carbonate producers and associated platform morphology. We invite discussion on factors influencing phase shifts in tropical carbonate producers, and associated changes in platform development over broad shelfal areas.

Early Sea-grasses fossil record and their geochemical fingerprint: new data from the lower Eocene deposits of the Jafnayn Formation (Oman)

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Keywords: Sea grasses, Oman, Paleogene

The recognition and understanding of vegetated habitats in the fossil record are of crucial importance in order to investigate paleoecological responses and indirectly infer climate and sea-level changes. However, the low preservation potential of plants and macroalgae hampers a direct identification of these environments in the geological past. A wide range of indirect indicators has been applied to infer vegetated settings in ancient deposits combining sedimentological, paleontological, taphonomic and geochemical approaches. The latter rely upon the assumption that ancient vegetated areas were comparable to modern ones in terms of habitat functions and type of associated organisms.

Here we present new geochemical data using C isotopes (in carbonates and organic matter) and elemental concentrations from the shallow marine carbonates of the late Paleocene-lower Eocene Jafnayn Formation of Oman cropping out in the Wadi Bani Khalid. The studied lower Eocene deposits consist of well bedded, nodular packstones dominated by encrusting acervulinid and alveolinid foraminifera passing upward to an alternance of packstones with echinoids and quartz grains and grainstones rich in *Orbitolites*, smaller miliolid foraminifera and quartz grains.

A preliminary study using sedimentological and paleontological evidences suggested a change from different seagrass-vegetated environments between the lower and the upper part of the section possibly caused by a major reorganization of the carbonate system. The oligo-mesotrophic assemblage of the lower part of the section was replaced upward by more heterotroph organisms such as large, discoidal Orbitolites and smaller miliolids. This change was, most likely, due to enhanced nutrient levels stimulated by the increased terrigenous sedimentation. which would have led to a change of phytal substrate, from cylindrical-leaf dominated grasses into flat-leafed ones.

However the assumption regarding variation of the trophic regime as well as the described changes on flora assemblages were yet speculative. The aim of this work is to show how geochemical proxies can help to understand the changes in carbonates production (carbonate factory) and differentiate the type of organic material and test the hyphotesis of a sea grasses dominated environment. We show a detailed sedimentary $\delta^{13}C_{\text{organic and carb}}$ and elemental record and discuss it in term of different input of the degraded organic material of the marine plants and organisms inhabiting the shallow waters of the “Jafnayn” platform during the Early Paleogene. This work assumes a particular importance because the Paleogene is the period when seagrasses environment started to develop.

Trends in Benthic Foraminiferal Relative Abundance and Diversity as a Bio-Indicator of Coastally Influenced Seagrass Habitats in a Mixed Carbonate-Siliciclastic Setting: Almirante Bay, Bocas del Toro, Panama

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Keywords: Benthic Foraminifera, Caribbean, Coastal Influences, Panama, Seagrass

Modern seagrass habitats are known for playing an important role in marine biodiversity and for their ability to protect coastlines by baffling wave energy while concurrently trapping nutrients and sediments, thus also serving as a reservoir for carbonate. However, identifying seagrass habitats in the fossil record is limited as a result of the low preservation potential of seagrass blades; therefore, previous studies have used seagrass-associated taxa such as mollusks, *Strombus,* and benthic foraminifera, *Archiais,* along with grain-size analyses to aide in their identification. The archipelago of Bocas del Toro (BDT), located on the northwestern coast of Caribbean Panama, is a unique yet fairly representative area for shallow-water, tropical study because of its mixed carbonate-siliciclastic sedimentological regime and because coastal habitats still remain mostly intact. Almirante Bay, the focus site of this project, is fringed with mangrove islands, seagrass beds (primarily *Thalassia testudinum*), and patch coral reefs. In an attempt to use *T. testudinum* as a bio-indicator of nutrient status in the lagoons of BDT, Carruthers *et al*. (2005) classified five types of seagrass habitats based on their influence from coastal processes: wetland, mangrove, ocean-swell, coral and river. The aim of this study is to determine trends in the relative abundance and diversity of benthic foraminifera according to the aforementioned classified seagrass habitats for the purpose of developing benthic foraminifera as a proxy to identify and further understand how seagrass habitats have responded to environmental change over geologic time.

This study compiles data from two separate sampling events. In August 2005, Richardson collected samples from 9 localities in BDT according to the habitats outlined in Carruthers *et al*. (2005). Forams from 12 blades per site were censused while living and still attached to the seagrass blade. As part of a separate study by Sider in December 2014, ten modern (<15 m) sediment samples were collected using a ponar-type grab sampler from seagrass habitats along the coasts of Almirante Bay. Sediments were washed through a 63-µm sieve, dried, and ~300 benthic foraminifera (live + dead) were picked, taxonomically sorted and identified to species level when possible. Preliminary results from both sampling events indicate a trend of greater foraminiferal diversity in mangrove and coral-influenced habitats, with diversity increasing with distance from freshwater input sources from the mainland. Though living epiphytic foram diversity is low, 24 total species with *Planorbulina acervalis* dominanting, an average of 49 species were collected from sediment samples, with no clear species dominance and test wall types indicative of normal marine conditions. Diversity is lowest along the Almirante peninsula connected to the mainland, near the city of Almirante, which is wetland and mangrove-influenced and where anthropogenic influence is a factor.

The identification and development of indicator species from these higher-diversity habitats will be useful for identifying seagrass habitats in the fossil record.

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Hydraulics of carbonate grains: Insights from settling tube and flume experiments

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Keywords: carbonate grain, flume experiment, hydraulics, settling velocity, turbidity current

The study of hydraulics is strongly biased towards terrigenous sediments, despite the global importance of the transport of carbonates as loose particles. This includes, but is not exclusive to, skeletal debris on beaches, shelves and platform slopes in tropical and non-tropical environments. The hydraulic behaviour reported here is specified to grains from the carbonate realm, whose characteristics are typically more complex than those of their siliciclastic counterparts due to an often biogenic origin. We present an extensive database of published grain-specific settling velocities, including that of corals, coralline algae, bivalves, brachiopods, gastropods, *Halimeda*, bryozoans, crinoids, echinoderms, *Alcyonarian* spicules, numerous benthic and planktonic foraminifers, and faecal pellets. Two types of experiments were conducted: (1) settling experiments with single carbonate sand grains falling unhindered through a column of still water at terminal velocity, and (2) flume experiments with density flows with various concentrations of up to very coarse carbonate sand.

The settling velocity of nearly 700 skeletal grains from tropical and non-tropical environments was investigated. Terminal settling velocity is primarily a function of grain size, but a significant control is exerted by particle form, which was approximated by the particle ellipsoid using the particle's axial ratios: spheroid, rod, disc, or blade. The highest average velocities were reached by spheroids, then rods, then discs, and finally blades. Graphical comparisons of calculated Reynolds numbers *versus* drag coefficients demonstrate that the transitional regime, between fully laminar and fully turbulent hydraulic behaviour, spans a wider range of Reynolds numbers for carbonate grains than for siliciclastic particles. This is a result of lower settling velocities of carbonate grains due to their enhanced irregularity. Because the drag coefficient varies reciprocally with terminal settling velocity, the drag coefficient is form-controlled with lowest values for spheroids and highest values for blades. This also controls the dominant settling motion (straight, spin, spiral or unstable), which is ultimately a function of particle Reynolds number.

Flume experiments with density currents were conducted to test whether a sorting mechanism governed by the form-dependent settling velocity of individual carbonate grains operates in calci-turbidity currents. Sand-size carbonate grains were added to water in a large reservoir to generate three mixtures of 4.5%, 9% and 18% sediment concentration. Mixtures were pumped at a rate of 8 L/sec into a 4 m long, 0.5 m deep, 0.07 m wide rectangular channel filled with fresh water and draining into a large expansion tank. Flume experiments lasted ca. 30-60 sec, depending on the concentration of the mixture, during which part of the carbonate grains settled to the bottom of the flume to form a deposit. Particle settling, however, was hindered by turbulent eddies that resuspended sediment and grain-to-grain interactions in a dense basal layer (traction carpet). Particle sorting in the experimental calciturbidites is primarily controlled by grain size, but is to some extent also affected by particle form, the effect of which is a function of the concentration of the sediment mixture. Future work will address the application of this concept to calciturbidites in the field.

V-shaped, carbonate and mixed coastal ridges (i.e. chevrons): origin and relevance for the reconstruction of past wind regimes

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Chevron, dune, eolianite, wind

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The worldwide distribution of V-shaped coastal ridges, or chevrons, makes them key deposits to understand coastal dynamics and to reconstruct past wind regimes at a global scale during the Quaternary period.

Chevrons have first been described in SW Egypt as km-scale, V-shaped bedforms transverse to the dominant wind direction (Maxwell and Haynes, 1989). Subsequently, three different genetic processes have been proposed to explain their occurrence along numerous recent and fossil coastlines around the world. Dated to the Last Interglacial (≈120 ka BP), the pure carbonate chevrons from the Bahamas have been associated with giant-storm wave action. The carbonate-siliciclastic V-shaped ridges of Holocene age observed in Southern Madagascar and in Eastern Australia are pluri-kilometric in size, and have supposedly been deposited by large tsunamis following a meteoric impact. Due to the similarities between chevrons and parabolic dunes, the wind has also been inferred as the main depositional process responsible for these bedforms at all three locations.

After a thorough review of the existing literature, we performed an analysis of the present-day wind regimes following the Fryberger method (Fryberger and Dean, 1979) and measured the morphological parameters of chevrons based on DEMs at all three aforementioned areas. Chevrons in the Bahamas, Madagascar and Australia display azimuths that show a narrow distributivity and a strong correlation with the resultant wind drift direction (RDD). In all three mentioned regions, strong present-day winds blow with mean speeds above the transport threshold of grains most of the year and are unimodal systems. Furthermore, the morphological parameters measured on chevrons (e.g. length, width) are several orders of magnitude larger than those of subaquatic bedforms, but coincide with those of subaerial dunes.

Although they formed in various climatic zones and at different times in the Quaternary, and despite their disparities in petrographic composition, chevrons thus appear to mainly result from aeolian processes. This interpretation is further consistent with the numerous features typical of an aeolian environment (e.g. wind-ripple lamination, rhizoliths) that frequently occur in these bedforms. Consequently, as these ridges likely correspond to coastal parabolic dunes, the necessity of using the term “chevron” in the sedimentological literature must be questioned.

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Carbonate deep-sea fans:
Advances based on outcrops, subsurface, and modern environment studies

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Key words: Carbonate, slope, deep-sea, fan

Deep-sea fans have been extensively studied in siliciclastic environments including both outcrops and modern analogues. Siliciclastic deep-sea fans can be defined as point-sourced systems deposited at the outlet of submarine canyons mostly fed by rivers and their continental drainage basin. Like their siliciclastic counterparts, carbonate deep-sea fans (CDSF) are point-sourced, but compared to them, the involved sediment is mostly the product of "in-situ" submarine carbonate production accumulating at the termini of gullies or canyons. Previous studies based on ancient examples have pointed out that CDFS mostly occur at the toe of gently dipping slopes, especially the ones flanking distally steepened ramps, while they cannot form adjacent to rimmed platforms characterised by steep slopes (Payros & Pujalte, 2008). The common coeval progradational pattern of the ramps has led to consider CDSF as typical lowstand deposits, emplaced classically during regressive phases. Comparatively, studies of modern environments have shown CDSF at the toe of high-relief, flat-topped platforms, implying different responses to sea-level changes and opening new ways for CDSF exploration. This work focuses on the prevailing conditions that influence the deposition of CDSF, based on an extensive literature review encompassing outcrops, subsurface examples, and modern analogues. We investigate the depositional context of CDSF (i.e., slope profile and composition, nature of the source, carbonate platform type), and the scales involved in quantifying: (1) the slope dimension, (2) the size of CDSF, (3) their potential drainage area, (4) the distance from the source, and (5) the timing of deposition. Finally, we aim at evaluating the development of CDSF in a sequence stratigraphic framework with respect to different carbonate platform morphologies.

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Is "wave base" in carbonate systems physically baseless?

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Keywords: oceanography, sediment, isolated platform, ramp, facies

The concept of "wave base" has been a lasting sedimentologic paradigm. Individual facies, facies associations, and entire carbonate successions have been interpreted in the context of fair-weather and storm-wave base, with changes reflecting variable sea level, wave climate, and paleoceanography. Several sets of observations from modern carbonate systems and numerical models suggest the absence of an objective, reproducible physical basis for defining sedimentological "fair-weather wave base" and "storm-wave base" that impart meaningful signatures on the carbonate stratigraphic record.

To use it as a quantitative tool (e.g., estimating water depth), several linked concepts – physical oceanographical, sedimentological, and bathymetrical – must be assumed. Each can be invalid, or is demonstrably incorrect, applied to carbonates. These assumptions include:

1. *Waves are bimodal*. Many studies invoke "fair weather" and "storm" conditions. Data from the Bahamas, Mexico, and Kiribati illustrate that oceanic waves have a continuous frequency spectrum, rather than exhibiting a bimodal distribution (cf., Peters and Loss, 2012). The waves include variable amplitudes, wavelengths, and directions, reflecting different origins, and the data show how distal swell, unrelated to local winds, impacts equatorial carbonate settings 1000s of km and 30-40° of latitude distant.
2. *Waves of a given energy and wavelength transport sediment at a consistent depth*. To be useful for stratigraphers, there must be a sedimentological record of waves - their impact must be imparted on the seafloor (entrainment, transport, deposition) and recorded. These sedimentological signals are a function of both wave attributes and sediment attributes. Yet, examples from the modern document how carbonate production is highly variable; in the same location, grains from mud to boulders form, resulting in inconstant sediment grade at the exact same depth. These carbonates - of distinct size, shape, and density - have variable transportability, and limited possibility to faithfully and unambiguously record identical wave energy comparably.
3. *Depth of sediment movement due to waves is consistent regionally and temporally*. Even assuming bimodal waves and constant sediment grade across a shelf, the bathymetric irregularities (e.g., reefs, shoals, islands) ubiquitous in carbonate systems create protected environments, and the wave directional distribution will create along- and across-strike variability, such that "wave base" becomes a relative depth, and thus of limited quantitative value. An example from the Bahamas illustrates such changes across distances of but a few km.

In light of these considerations, such a question as "what is wave base in the Bahamas?" cannot be answered with one number; instead, "It depends." With sufficient information, however, on historical winds, distal swell, *in situ* sediment production and attributes, local forces inducing sediment transport (other than waves), and contextual bathymetry, the depth to which sediment is disturbed by a given wave could be modeled. The question “what was wave base in the Mississippian of Derbyshire?,” however, remains unknown, and an intractable challenge. Thus, although the stratigraphic record makes it evident that waves disrupt and transport and deposit sediment, physics mandates that the interpretation of these processes remain restrained and qualitative, rather than a focal point for interpretation.

Mixed siliciclastic-carbonate deposits: a world yet to be discovered

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Mixed siliciclastic-carbonate deposits consist of a suite of different types of mixing between the two components, from bed (core-plug) to stratigraphic (seismic) scales, producing a high vertical and lateral lithological variability. Mixed deposits results from the interaction of siliciclastic input and coeval carbonate production controlled by temporal and/or spatial factors. Although mixed deposits are very diffuse in the geological record, studies about these deposits are scrappy and not well encoded. Accordingly, mixed deposits represent a labyrinth for researchers who want to investigate them for the first time. Different types of mixing (compositional versus strata) controlled by different allocyclic (e.g. sea-level, climate) and/or autocyclic (e.g. depositional processes) factors that operate at different scale can be described.

Chiarella et al. (2017) proposed a first order classification of mixed deposits recognized and described at three main scales of observation: bed/coreplug scale; lithofacies/well-log scale; and stratigraphic/seismic scale. This observation led to split analized deposits in two main mixing type:

(i) Compositional mixing type, that reflects the contemporaneous accumulation of the two heterolithic fraction in space and time. This type of mixing is observable at lamina to bed scale, locally producing depositional structures diagnostic for particular depositional environments.

(ii) Strata mixingtype, that results from the alternation of the two heterolithic fraction in time. This type of mixing is observable at lithofacies to stratigraphic scale and can be related to depositional processes, climatic variations and/or relative sea-level changes.

A correct identification of these different types of mixing and the scale of their occurrence is crucial in revealing (i) physical processes that control the sedimentation, (ii) environmental factors that influence the carbonate factory related to the siliciclastic dispersal mechanisms, and (iii) internal heterogeneity of the resulting sedimentary deposit. Furthermore, the petroleum industry is interested to unravel new insights about internal properties of mixed siliciclastic-carbonate systems (e.g., porosity, permeability) and to reconstruct predictive 3D models for the related reservoirs.

The correct prediction of internal heterogeneity and the recognition of lateral and vertical compartmentalization have an important impact on hydrocarbon exploration and exploitation.

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An iron-rich carbonate tidal sequence, Cryogenian Angepena Formation, South Australia

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Keywords: oxygenation, marine cements, Neoproterozoic, peritidal

The Neoproterozoic Era is characterized by the most dramatic environmental changes in Earth's evolutionary history, encompassing the radiation of complex life and the buildup of significant atmospheric/oceanic oxygen. Neoproterozoic sediments can provide a window into the environments and conditions that existed during this critical interval in Earth history. The Cryogenian Angepena Formation of South Australia records deposition in an iron-rich peritidal environment landward of the Balcanoona Formation reef complex. These Neoproterozoic tidal sediments are unusual compared to Phanerozoic tidal sequences, and illustrate depositional processes at the interface of an oxidizing atmosphere with anoxic marine systems.

The most carbonate-rich beds of the Angepena Formation are most proximal to and laterally interfinger the Balcanoona reef complex, while dolomitic red mudstone facies are the most landward facies. Subtidal–intertidal oolitic shoal/tidal channel facies are crossbedded, ooid-intraclastic grainstones with intragranualar dolomite cements and fenestrae. This peritidal facies of the Angepena Formation laterally interfingers with and is interbedded with the Balcanoona Formation backreef facies, represented by ooidal–peloidal grainstones with abundant tepees and sheet cavities filled with marine cements. More shoreward, the intertidal teepee belt facies are pink laminated teepeed dolomite with fenestrae and pendant dolomite cements. The intertidal and supratidal tidal mudflat facies are red dolomitic iron-rich mudstone with mudcracks. In the Angepena Formation, cyclic interbedding is common, and is often represented by erosively based oolitic grainstones, overlain by laminated dolostone with teepees, and then iron-rich dolomitic mudcracked mud. These cyclic successions are progradational shoaling upwards packages: from subtidal–intertidal grainstones to intertidal teepee belts to intertidal and supratidal coastal mudflats. The cyclic deposition of the Angepena Formation highlights the progradational nature of this peritidal system.

The intertidal Angepena Formation appears to have been a more oxidizing environment than the equivalent subtidal Balcanoona reef facies. The Angepena Formation contains distinct hematite-rich beds and abundant iron oxides: the dolomititc mudstones contain ~3–6% iron oxides, teepees and intraclasts often contain early-formed iron oxides, ooids often nucleate on iron oxides, and ooids and intraclasts are often coated with iron-rich laminations and precipitated hematite rims. This indicates syn-sedimentary iron precipitation in a peritidal oxidized environment. The Angepena Formation likely represents the oldest iron-rich formation in the Proterozoic sedimentary succession of the Adelaide Rift Complex. Broadly, this may indicate that peritidal environments were the first oceanic environments to be oxidized during Earth's evolution, and this places importance on understanding the distribution and sedimentology of these environments.

Did transgressive, landward-migrating carbonate barrier islands exist in the Chazyan (Ordovician) of eastern North America?

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Keywords: Barrier Islands, Dune Fields, Ordovician, Shoals, Transgressive

The response of neritic carbonates to sea-level fluctuations can differ significantly from siliciclastic equivalents. In many cases, this leads to the need to modify siliciclastic sequence-stratigraphic concepts for carbonate systems. Despite this, under certain conditions carbonate sediment can behave indistinguishably from siliciclastics. Siliciclastic sequence stratigraphic concepts should be directly applicable to these systems. One such concept is mobile transgressive barrier islands, which are common in modern and ancient siliciclastic deposits, but which have been rarely interpreted in carbonate sediments of any age.

The mixed carbonate-siliciclastic Chazyan succession (Ordovician) of the northern Appalachian Basin contains several conspicuously cross-bedded skeletal grainstones, which have been previously interpreted as subaqueous shoals. Analogy has been drawn to modern shoals and islands that nucleate on antecedent topography, bioconstructions, or meteorically cemented deposits. However, critical re-evaluation suggests an alternative depositional model.

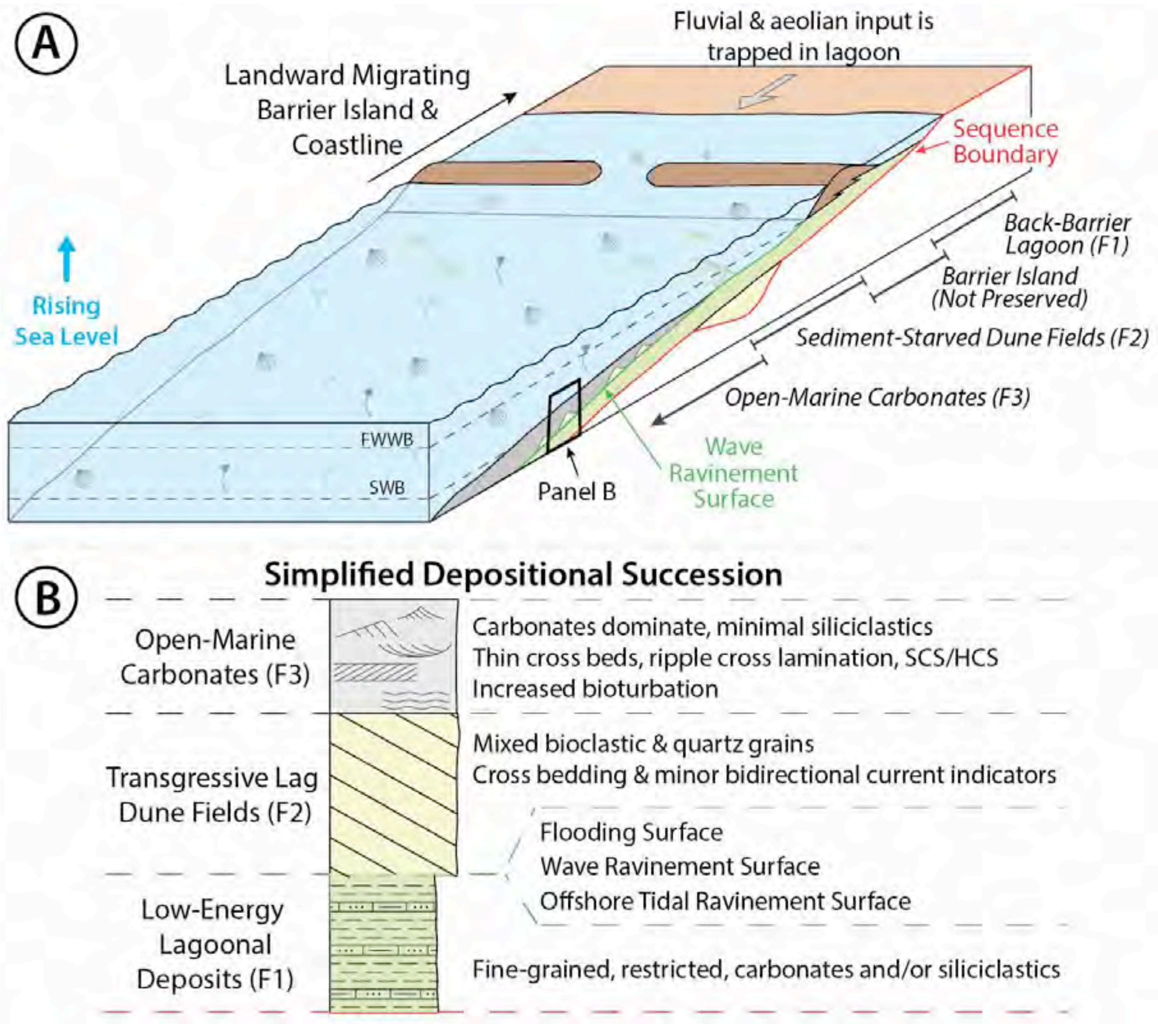
Detailed study reveals a depositional motif of three facies stacked in a recurring succession: 1) fine-grained, restricted, mixed siliciclastic-carbonate lagoonal deposits, 2) erosionally based, cross-bedded, quartz-rich grainstones produced by sediment-starved subaqueous tidal dune fields, and 3) near pure grainstones with wave-generated sedimentary structures that accumulated in open-marine conditions.

This motif is strikingly similar to that of well-studied, transgressive, wave-dominated, siliciclastic coasts with landward-migrating barrier-island systems. The Chayzan deposits are thus interpreted as recording the formation of a mobile barrier island and back-barrier lagoon system that migrated landward during transgression. Lagoonal deposits are separated from overlying carbonates by a wave ravinement surface created by landward translation of the barrier-island shoreface. Detrital quartz from siliciclastic lowstand deposits was reworked into the barrier islands and then stranded on the platform during ravinement. Seaward of the barrier island, residual tidal currents produced erosionally based dune fields (i.e., transgressive lags) on the ravinement surface, with mixed quartz and bioclastic grains. *In situ* open-marine carbonate production subsequently buried these deposits, causing an upward decrease in detrital quartz.

The presence of carbonate barrier islands was likely caused in part by local oceanographic conditions. Skeletal grains are predominantly calcitic, ooids have radial cortices, and marine and early meteoric cementation is minimal. As a result, the studied Chazyan carbonates would have behaved as calciclastic sediment, with no significant differences from siliciclastic equivalents apart from grain mineralogy.

While subaqueous shoals, which are also present in the Ordovician of the Appalachians, can produce similar cross-bedded units, the studied successions clearly record a disparate depositional setting. The proposed landward-migrating barrier-island model is thus an alternative to the subaqueous shoal model, and might be an under attributed interpretation for some ancient calcarenites. Similar examples are likely to be more common during times (calcite seas) or locations where early cementation is lacking and carbonate systems behave similar to siliciclastics.

Although carbonate sequence stratigraphy is often plagued with complexity caused by biological and chemical controls, this study demonstrates that understanding the degree to which carbonates "behave" like siliciclastic sediments is essential to determining whether siliciclastic sequence stratigraphic concepts can be applied to improve the interpretation of ancient carbonates.



Depositional model (A) and simplified depositional succession (B) for the Chazyan barrier-island systems.

Did aragonite whitings lead to the accumulation of thick and widespread pelagic carbonate successions during the mid Carboniferous?

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Keywords: aragonite mud, pelagic limestone, Serpukhovian-Bashkirian, Variscan foreland basin, whiting.

Pelagic and hemipelagic carbonates were limited in thickness and lateral extension and mostly corresponded to condensed successions and/or periplatform deposits adjacent to shallow-water carbonate systems, before the Mesozoic appearance and diversification of calcareous plankton. This study focuses on a potential example of upper Mississippian–lower Pennsylvanian (Serpukhovian–lower Bashkirian), nearly 300 m thick pelagic–hemipelagic limestone accumulated due to carbonate precipitation over very broad areas of the southern Variscan marine foreland basin (the remnant of the Rheic Ocean) located in the western Palaeo-Tethys embayment at 10º–20º S latitude.

These limestones are exposed in the N of Spain and S France, forming two laterally extensive stratigraphic units over a large area, >300 km wide and >700 km long, along the basin axis. These figures, calculated after restoration of Variscan deformation, could be greater if other potentially equivalent successions of SW Spain were accounted for. They were deposited on a 20–40 m thick Visean pelagic red-nodular and goniatite-rich condensed limestone unit, and towards the foredeep interfingered with orogen-sourced turbidites, which finally replaced them during Bashkirian times. Lithofacies are remarkably homogeneous and consist of dark-coloured and slightly burrowed or laminated calci-mudstones (recrystallized to microsparites), representing generally >95% of the sediment volume. These calci-mudstones are almost devoid of benthic biota and contain scarce radiolaria. Trace element analyses reveal high Sr concentrations (Q1=980 ppm, median=1750, Q3=2427.86 ppm) and high U concentrations (Q1=2.78 ppm, median=3.58, Q3=4.05 ppm), which together with the common presence of diagenetic celestite suggest that the original sediment contained a significant proportion of aragonite.

Considering the rather uniform thickness distribution of these deposits and the absence of broad shallow-water benthic factories in the basin, we interpret that most of the aragonite-rich mud was generated in the water column by biologically induced/influenced and/or abiotic precipitation in open off-platform areas. Maximum reported linear sedimentation rates of ~ 70–90 m/My for the latest Serpukhovian–earliest Bashkirian time interval imply a net carbonate sedimentary flux of ~ 190–250 g/m^2/yr, comparable to the mean whitings production rates of 300–500 g/m^2/yr estimated for the Great Bahama Bank by several authors.

The inferred direct precipitation of aragonite-rich carbonate muds would have resulted from a particular regional geotectonic scenario and from global changes in atmosphere composition and ocean chemistry shortly following the transition from calcite to aragonite sea. It also coincided with the two glacial episodes recorded during the onset of the main phase of the Late Palaeozoic Ice Age and with the mid-Carboniferous eustatic lowstand. These specific environmental and oceanographic conditions would also have favoured the nucleation of the earliest Bashkirian microbialite-cementstone factories in the basin that gave birth to the prolific Bashkirian–Moscovian microbial carbonate platforms of the Cantabrian Zone, under a scenario that could be in part comparable to that witnessing the deposition of lime-mudstones in the Southern Alps after the end-Permian extinction followed by the growth of the Triassic microbial carbonate platforms in the western Tethys.

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Evaporitic sedimentation recording a sea-level fall in the remnant of the Rheic Ocean during the mid-Carboniferous (N Spain)

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Keywords: Basin restriction, gypsum evaporites, pelagic-hemipelagic limestones, Serpukhovian-Bashkirian, Variscan foreland basin

The Cantabrian Zone and western Pyrenees display excellent outcrops of the Variscan marine foreland basin succession that developed during the collision between Gondwana and Laurentia during the Carboniferous. During late Serpukhovian–early Bashkirian a homogeneous 450–70 m-thick succession composed of pelagic–hemipelagic, dark, laminated calci-mudstones (Barcaliente Fm in the Cantabrian Zone and Iraty Fm in the western Pyrenees) accumulated in the distal realms of the foreland basin over an area as wide as 300 km and covering more than 200,000 km^2. The upper part of the succession (upper Alportian, early Bashkirian) shows a gradual facies change, as the characteristic laminated calci-mudstones begin to contain calcite pseudomorphs after gypsum crystals, which increase gradually upwards, reaching 50% of the rock volume at the top. The pseudomorphs exhibit monoclinic equant prismatic habits and deform the surrounding matrix, suggesting a displacive growth of the gypsum crystals within the carbonate sediment at, or slightly underneath, the sediment–water interface. The upwards increase in pseudomorph abundance is accompanied by a decrease in crystal size and a change in crystal arrangement: crystals evolve from being up to 1 cm in size and randomly distributed in the lower part, to becoming smaller than 2 mm in size and forming continuous laminae in the upper part, which is indicative of a salinity increase. The presence of evaporites in these pelagic–hemipelagic deposits suggests that large areas of the marine foreland evolved into evaporitic conditions. This interpretation is also supported by organic geochemistry results, which show biomarker parameters (low pristane/phytane, high C35 homohopane) consistent with hypersaline conditions in the basin.

In the distal realm of the basin, in areas closer to both the foredeep and the foreland, in addition to the evaporitic facies, microbial features (crinkly laminae with filamentous microstructures, fenestral porosity, stromatolites) and other structures (desiccation cracks and flat-pebble breccias) suggestive of a shallow environment, are present in the upper part of the succession. Furthermore, in other sections close to the foredeep, the upper part of the evaporitic interval is absent and instead an edaphic nodular breccia occurs in the same stratigraphic position. The edaphic breccia is composed of calci-mudstone clasts (commonly containing calcite pseudomorphs after gypsum), showing sutured contacts and a clayey matrix and, locally, root-like structures. All these sedimentary features indicate that important changes occurred in the basin during the latest Alportian likely linked to an important sea-level fall that has been recorded in other basins. The distinctive evaporitic and shallow-water features of the upper part of the studied succession were probably caused by a significant sea-level fall, which led to the restriction of large areas of the distal realm of the basin with the development of evaporitic conditions, and eventually caused subaerial exposure. Marly limestones with diverse marine biota and coeval microbial bioconstructions were deposited atop of the evaporitic interval, suggesting that normal marine salinity conditions were restored in these areas of the basin during the subsequent sea-level rise.

Detailed facies analysis of a Zechstein 2 carbonate outcrop analogue in northern Germany

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Key words: Carbonate, Facies, Outcrop analogue, Permian

A high-resolution facies model was created based on outcrop data and the analysis of cored drill holes representing Zechstein 2 carbonates (Ca2) from a quarry in the southwestern Harz Mountains in northern Germany. The Zechstein 2 carbonates are an important research topic as they are among the most prolific reservoir rocks in northern Germany. Their reservoir quality is defined by facies and mineralogy. This study integrates outcrop and near-surface drill hole data as well as geoelectric transects into a subsurface model. The model and dataset can then be used for analogue comparisons to known subsurface Ca2 models and provide new insights into the spatial distribution and transition of the different facies types.

The studied cores comprise a succession ranging from the Zechstein 1 (Werra) copper shale to the Zechstein 2 (Stassfurt) basal anhydrite. This study focuses on the Lopingian Zechstein 2 carbonates, in specific on the "Main Dolomite" (Hauptdolomit), a sequence that formed at the southern platform margin of the North German Basin. In relation to the Werra Anhydrite palaeorelief, the interpreted depositional environment is in transition from platform to slope, either as part of a highstand systems tract or as a lowstand prograding wedge. Overall, the cores show a shallowing upwards sequence deposited in an intertidal to subtidal environment, which contains platform and upper slope subfacies types.

Above the basal anhydrite, bioclast-rich packstones are overlain by a clay-rich subtidal upper slope environment, which changes into intervals of grainy shoal and ooid shoal with high porosities, shallowing to intertidal tidal-flats and pelletal tidal flats with intercalated algal-laminated shoals. In transitional areas, the bounding surfaces are difficult to pinpoint. Further analyses presented include porosity and permeability measurements of selected core samples, supplemented by rock properties derived from spectral gamma ray measurements. Detailed thin section analyses help to distinguish the Ca2 facies and subfacies in detail.

Ichnodiversity of Middle Triassic ramp carbonates, *Wellenkalk* facies, Upper Silesia, Poland

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Key words: paleoecology, Poland, substrate consistency, trace fossil, Triassic.

The Middle Triassic (Muschelkalk) carbonates of the Germanic Basin provide an opportunity to better characterize the ecological recovery of shallow-marine benthic communities after the Permian/Triassic mass extinction. The Upper Silesia region (southern Poland) was situated in the Silesian-Moravian Gate, one of the three submeridional seaways connecting the semi-enclosed Germanic Basin with the Tethys Ocean in Middle Triassic times. The proximity to the ocean resulted in open-marine sedimentation and normal-marine faunas for most of the time. Here, the ecological recovery is expressed as an overall increase in diversity of skeletal faunas during the subsequent transgressive pulses from the Tethys (Hagdorn, 2007), climaxed by the growth of scleractinian-sponge reefs during the middle-late Anisian.

To verify if the recovery is also reflected in trace fossil assemblages, we studied ichnodiversity changes prior to the reef development, with focus on the transgressive phases of three consecutive third-order depositional sequences because these phases display the same depositional facies and sedimentary evolution. Each of the transgressive systems tracts begins with mid-ramp shoal sands, grading up into outer-ramp tempestites and intercalated inter-storm lime mudstones, overlain by pure lime mudstones marking maximum flooding. All these facies are termed as Wellenkalk (wavy limestone) because of the volumetric dominance of thin-layered micritic sediments.

At least 28 invertebrate ichnotaxa were identified in the Upper Silesian Wellenkalk. Most trace fossils occur in the outer-ramp micrite deposits and are dominated by structures formed in soft sediment: *Rhizocorallium*, *Thalassinoides*, *Planolites*, *Ptychoplasma*, *Protovirgularia*, and *Oravaichnium*. The bioturbation degree ranges from very low to complete, resulting in two end-member types of lime mudstone: platy and nodular, respectively. Sporadic periods of ceased sedimentation are recorded as firmgrounds with *Balanoglossites* and hardgrounds with *Trypanites* and *Placunopsis* encrustations. Tempestites contain isolated to locally more abundant *Rhizocorallium* and *Oravaichnium*, and this low ichnodiversity and low bioturbation degree likely reflect quick burial of storm layers under post-storm lime muds. Shoal sands are generally devoid of trace fossils, with only few levels comprising residential burrows of *Skolithos*, *Pholeus*, and/or *Arenicolites*.

Despite this repetitive pattern in the distribution of trace fossils within transgressive systems tracts, there is a clear change in the dominant traces between the three depositional sequences: *Rhizocorallium* prevails in the first sequence, bivalve traces predominate in the second sequence, and the third sequence abounds in *Thalassinoides*. Because the depositional facies and environments are the same for the three sequences and consequently substrates types, ecological niches, and environmental conditions seem to remain unchanged, the observed reorganization of trace-maker communities from worm-, through bivalve-, to crustacean-dominated, seems to record a revival after the P/Tr crisis.

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Tempestite- and beach-like grainstones in pelagic sequences (Jurassic, Subbetic, South of Spain)

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Keywords: Grainstone, Hummocky cross-stratification, Internal waves, Jurassic, Pelagic sediments

Fine-peloidal- to coarse oolitic-bioclastic grainstones with hummocky cross-stratification (HCS) occur interbedded in Jurassic pelagic lime-mudstone successions (Subbetic, Betic ranges, Southern Spain). These strata were deposited in pelagic troughs and swells, away from continental areas, in the Southern Iberian Paleomargin. Previously interpreted as tempestites based on the occurrence of HCS (Molina et al., 1997: Vera and Molina. 1998) are here reinterpreted as the product of breaking internal waves.

The selected examples include: a) A coarse oolitic grainstone unit encased in pelagic marls, with wedge-shaped crossbedded-sets with gently seawarddipping parallel lamination, and sets of low-angle up-slope dipping parallel lamination. These sedimentary structures are similar to the ridge-berm-swash zone of modern beaches; b) Peloid grainstones with HCS deposited on the flanks of volcanic guyots, interbedded with radiolarite marls. with “filaments”, sponge spicules and radiolarians; c) Peloid-bioclastic (radiolarians, “filaments”) grainstone beds with HCS, interbedded with pelagic limemuds; d) Crossbedded peloidal-skeletal (*Saccocoma*) grainstones with HCS and wave ripples on top, interbedded with pelagic mudstones and wackestones with abundant bioturbation and ammonites (Ammonitico Rosso facies).

All the examples here presented share: 1) Grainstone beds are interbedded with pelagic mudstones and marls; 2) Grainstone components were reworked by oscillatory–superimposed to unidirectional tractive flows (HCS and unidirectional ripple lamination); 3)

Components were either derived from shallow-water (e.g., ooids), or produced in pelagic conditions (e.g., radiolarians, *Saccocoma*, "filaments"); 4) Although surface-storm tempestite flows can be required to bring downslope components from shallow-water settings, the grainstone beds reflect sediment reworking at a depth dominated by fine pelagic background sedimentation.

Internal waves (IWs) propagating along a pycnocline and breaking against a sloping surface are the best candidate to induce the sedimentary structures and sediment organization that characterize these grainstone beds. Breaking IWs produce episodic high-turbulence events and remobilize sediments at the depth where the pycnocline intersects the sea floor. The swash run-up produces erosion and the backwash return flow can bypass the breaker, favoured by the dip angle of the slope, and travel downdip where the oscillatory-flow component of the IWs become dominant to form the characteristic HCS bedforms.

Coarser sediments “trapped” at the breaker zone form sediment accumulations similar to the sediments caught by the “littoral fence” in a surface beach. This scenario evidences the HCS not to be necessarily linked to the surface storms but to the pycnoclinebathymetry, solving the problem of having HCS in pelagic zones where the storm and hurricanes wave action can be considered “out-of-context”.

The alternative interpretation for the HCS here presented is of prime value. It makes easier to understand the occurrence of grainstone units in basinal settings with pelagic sediments. But most important, it provides models to explain and predict the occurrence of drain layers, particularly for unconventional oil and gas resources.

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Facies evolution of the Lower Jurassic (Sinemurian) carbonate platform of Mallorca (Spain): environmental and tectonic controlling factors

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Key words: Balearic Basin, carbonate platform, Lias, peritidal facies, Tethyan rift

The Early Jurassic was characterized by the development of wide shallow-water carbonate platforms in the Peri-Tethyan basins. This work analyse the character and distribution of the Lower Jurassic (Sinemurian) carbonate platform facies in Mallorca (western Tethys), along six detailed stratigraphic profiles, which conform a ca. 70 km wide NW-SE transect of the platform (Fig. 1A). The studied successions belongs to the Es Barraca Member (Álvaro et al. 1989) and include twenty-nine facies grouped into seven facies associations: tidal flat, restricted lagoon, bar/shoals, inner platform/open lagoon, muddy shallow open platform, muddy outer platform, and middle to outer platform environments (Sevillano et al. 2019). Spatial and temporal (2D) facies distribution reflects significant changes of the carbonate platform profile, subenvironments and facies with time (Fig. 1B). The platform evolved from a broad peritidal platform (Stage-1, early Sinemurian–earliest late Sinemurian) to a muddy open platform (Stage-2, late Sinemurian), and finally to a peritidal to outer carbonate platform (Stage-3, latest Sinemurian). Stage-1 corresponds to a nearly flat peritidal-shallow subtidal epicontinental platform, characterized by a typical Bahamian-type carbonate factory and by facies belts that shifted far and fast over the whole study area. Stage-2 represents a rapid flooding of the peritidal-shallow subtidal platform and the demise of the Bahamian-type carbonate factory, which is substituted by an open platform with the proliferation of muddy substrates and suspension-feeders. This change coincides with the onset of differential subsidence in the area. Stage-3 is characterized by the recovery of Bahamian-type carbonate factory. Differential subsidence controlled the development of peritidal and shallow platform environments to the east-southeast (Llevant Mountains domain) and middle-outer platform environments toward the northwest (Tramuntana Range domain). The described stages of platform evolution responded to the interplay between the initial extensional tectonic phases related to Early Jurassic Tethyan rifting, contemporaneous environmental perturbations, and progressive platform flooding related to the Late Triassic-Early Jurassic worldwide marine transgression and associated accommodation changes.

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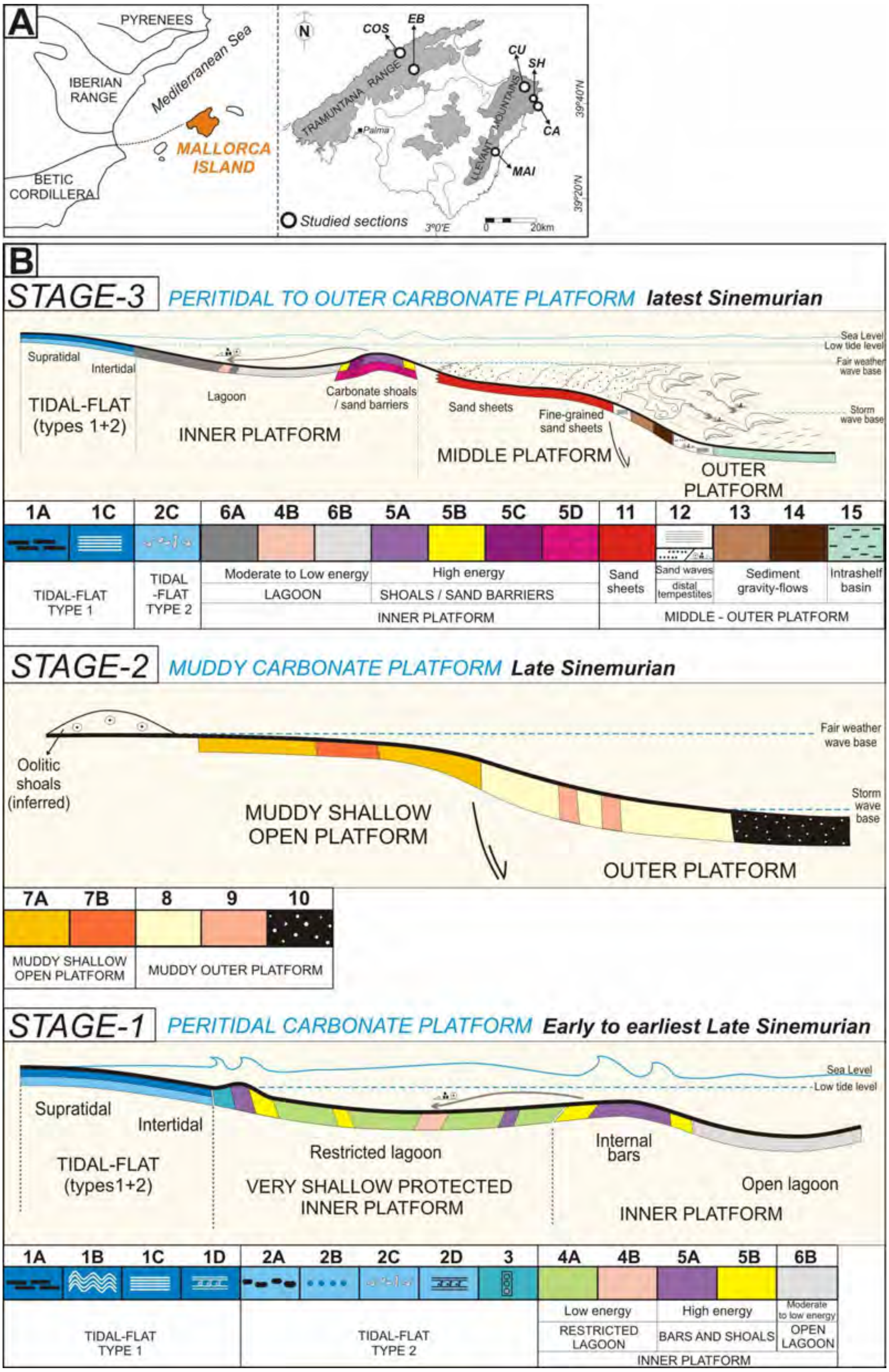

Figure 1: (A) Location of the study area and sections. (B) Idealized platform profiles (conceptual models) with the distribution of the facies associations, facies types and depositional environments that characterize the three platform stages 1, 2 and 3.

The Early Jurassic coastal environments with vegetation (Albanian Alps) in microfacies view

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Key words: Early Jurassic, mangrove, microfacies, *Lithiotis*

Late Triassic to Early Jurassic carbonate facies are outcropping along the mountains road between Rapsh and Grabom villages, north of Shkodra (Albanian Alps) near Montenegro border. The 300 m section begins with Late Triassic dolomites with Lofer-type sequences, then pass in to shallow-water limestones full of *Lithiotis*–type bivalves, with suggested Pliensbachian and/or Early Toarcian age. *Lithiotis*-type bivalves – *Lithiotis*, *Cochlearites*, *Lithioperna*, *Mytiloperna*, *Gervileioperna*, belong to the group of characteristic bivalves up to 50-70 cm in long, which occurred along southern margin of the Tethys. In the studied section five bivalves horizons occur between grey-dark bluish bioclastic and marly limestones. The microfacies assemblages recorded very dynamic environmental changes, which prevailed on the carbon platform. Microfacies were divided due to the environment of origin after Flugel (2004) using Wilson (1975) model: (FZ 9) arid platform interior - evaporitic: laminate mudstone, wackestone, laminate wackestone, bindstone with cyanobacteria; (FZ 8) restricted or partly restricted platform interior: peloidal waskestone to packstone, oncoidal packston with dolomite crystal; (FZ 7) open lagoon with episodically normal salinity: bivalves wackestone to packstone, bivalves bindstone; (FZ 6) oolitic shoals, tidal bars, beaches: bioclastic grainstone, oncoidal packstone, oncoidal grainstone, bivalves packstone, bioclastic packstone with erosional boundary.

Singular beds of dolomite and gypsum crystals indicate periodic evaporative conditions, episodic emersions were responsible for fenestral structures. The facies corresponds to restricted or partly restricted lagoon, periodically drying out or flooded. In the upper part of the section several coal-bearing intercalations occur. In a few layers, the rooted systems (including air roots) of plants have been preserved that bring to mind coastal bushes of mangrove-type. Leaves found in close proximity to the roots are of two types: – *Pachypteris* genus (seed fern) and *Brachyphyllum* sp. (conifer). Both of them are believed to be adopted to salty substrate and/or salty mist. Based on their gross morphology and cuticular structure as well as on depositional environments in which usually reminded, they were interpreted as growing in coastal habitats, which here is confirmed by root systems. Probably, the lagoon periodically overgrew vegetation which as a result of rising sea level or storm was destroyed.

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Upper Jurassic pelagic succession of the Krížna Basin Tatra Mts. (Poland) – microfacies and stratigraphy.

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Key words: Upper Jurassic, microfacies, Carpathians

The area of research is located in the Western Tatra Mts, which belong to the Central West Carpathians. The studied Lejowa section, 47 m thick, comprises: (1) the uppermost part of calcareous radiolartes (Czajakowa Radiolarite Formation, 2.5 m), (2) red platy and nodular limestones of *Ammonitico rosso* type (Czorsztyn Limestone Formation, 10.5 m) and (3) grey marly limestones of the Jasenina Formation (34 m). *Bositra*, radiolarian-*Bositra* and *Bositra*-radiolarian-spiculite wackestone microfacies dominate within the Czajakowa Formation. The abundant *Saccocoma* appears as the most important microfacies component in the Czorsztyn Formation. A variety of microfacies of wackestone/packstone type have been described here: *Saccocoma*-radiolarian, *Saccocoma-Globochaete,* radiolarian-*Saccocoma-Globochaete, Saccocoma,* subordinate*: Bositra,* bioclastic, spiculite-radiolarian. In the lower part of the Jasenina Formation, *Saccocoma* microfacies still dominate. Higher, the calpionellids start to occur and they stepwise replace the saccocomids and combinations of calpionellid – *Globochaete* – radiolarian wackestone/packstone microfacies become the most common. Crinoidal , spiculite –crinoidal and radiolarian-crinoidal grainstone microfacies are subordinate.

The described association of microfacies is typical for the Tethys ocean and was described from the Carpathian – Balkan area by numerous authors (e.g. Pszczółkowski, 1996; Lakova and Petrova, 2013; Reháková et al. 2011; Jach, 2014) with minor differences resulting from paleogeography.

Based on the calcareous dinocysts, calpionellids and magnetic stratigraphy, the age of sediments spreads from the Upper Kimmeridgian (Moluccana Zone) to Upper Tithonian (Crassicollaria Zone).

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Unraveling the transient nature of Paleocene-lower Eocene tropical carbonates: a critical analysis based on the Pyrenean platform record

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Keywords: Paleocene-Eocene, carbonate platform sediments, carbonate factories, aragonite to calcite sea

The Cenozoic began in the western Tethys with extensive carbonate platform development across south and central Europe, from the Pyrenees to the Carpathians, and along northern Africa, from Tunisia to the Gulf of Suez. These platforms fully attest to the transient nature of shallow tropical sedimentation during the Paleocene and early Eocene, with facies and skeletal associations resembling those of the Palaeogene and Neogene, but developed under climates, sea levels and oceanographic conditions akin to the Cretaceous greenhouse.

The Pyrenean basin stores one of the most complete and varied records of Paleocene-lower Eocene carbonate platforms found in Europe, unlike in many other Tethyan basins only affected by moderate tectonic deformation and digenetic overprint. These platform successions, ranging 300-500 m in thickness and extending some 30-40 km across dip, occur made up of shallow-water limestones deposited on beaches, tidal flats, lagoons, shoals and a variety of reef constructions, with minor proportions of siliciclastics and evaporites. Basinwards, they grade through narrow slopes, to rhythmic hemipelagic basinal deposits, and landwards interfinger with alluvial-lacustrine coastal plain sediments, classically known as the “Garumnian” red beds. This regional setting, aided by a robust stratigraphic framework, allows a complete and detailed appraisal of the spatial and temporal evolution of shallow carbonate factories through the early Paleogene.

Here, we review the characteristics and evolution of the Paleocene-lower Eocene platforms from the Pyrenees focusing on four closely related issues: 1) the impact of the Cretaceous-Paleogene biotic crisis on platform biotas and the rates of shallow carbonate production, 2) the temporal changes between coralgal and LBF skeletal associations, and its strong imprint on platform morphology and architecture, 3) the interchange between aragonite and calcite-rich skeletal and non-skeletal sediments, with its effects on diagenesis, and 4) the transition in littoral successions from peritidal to seagrass-related carbonate deposits. All these topics will be documented with representative facies and key outcrops across the extensive south Pyrenean domain.

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The role of oceanographic conditions on Cenozoic carbonate platform drowning: the examples of alpine and apennine foreland basins

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Keywords: foreland, carbonate ramp, environmental and oceanographic conditions, carbonate platform drowning, upwelling

Two Cenozoic carbonate ramps are analyzed to illustrate the main factors that influenced their drowning. A key setting to investigate carbonate platform drowning is the foreland basin, where shallow water sedimentation may develop. The Nummulitic Limestone ramp developed in the foreland of the western Alps (Alpes Maritimes) during the Bartonian, while the *Lithothamnion* and Bryozoan Limestone ramp deposited in the foreland of the central Apennines between the Burdigalian and the Serravallian. The Nummulitic Limestone succession evolves upward from the middle to the outer ramp up to the hemipelagic marls without significant breaks in the sedimentation, as shown by the lack of main unconformities. The progressive drowning of the larger benthic foraminifer carbonate factory is related only to the reduction of light for the photo-dependent biota according to the progressively increasing depth and the minor efficiency of the aphotic carbonate factory. In the *Lithothamnion* and Bryozoan Limestone the vertical evolution from shallow water to hemipelagic sedimentation is marked by a phosphatic hardground coinciding with a relative maxima in worldwide oceanic phosphorus burial rates, high sea-level, a positive $\delta^{13}C$ shift, periods of global warming, and upwelling activity. Therefore, the drowning of the *Lithothamnion* and Bryozoan Limestone ramp is attributed to the deterioration of the environmental conditions that predate tectonic subsidence related to the Apennine orogenesis. Eutrophication triggered by upwelling events induced a crisis in the shallow-water carbonate production, while during the following tectonic subsidence the shallow-water carbonate factory was definitively inactive.

The Central Mediterranean upper Miocene C-cycle dynamics and its influence on the evolution of two carbonate ramps

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Keywords: Carbonate ramps, C-isotopes, Mediterranean, Miocene, Tortonian

The late Miocene is an extremely dynamic period which might represent an example of the climate development of the near future. It was slightly warmer than the present, and marks an important step in the evolution of the modern climate, being sandwiched between the Mid Miocene Climatic Optimum (MMCO) and the onset of the Arctic glaciation at the Miocene-Pliocene boundary. Furthermore, an underrated global carbon cycle perturbation occurs in the Tortonian, known in literature as Carbon Maximum 7 (CM7). Our work aims to identify the Central Mediterranean shallow-water carbonate system's response to the CM7, as well as discriminating potential regional controlling factors related to the geodynamic evolution of the area that might have affected carbonate production changes and carbonate platforms evolution. The Tortonian $?^{13}C_{carb}$ record has been analysed on bulk samples belonging to outer ramp facies of the Latium-Abruzzi and the Apula platforms (Central Apennines, Italy). A detailed microfacies analyses and SEM observations have been carried out for the Apula platform succession in order to identify changes in the carbonate production as well as the diagenetic history of the limestones. A positive C-isotope excursion in the lower Tortonian testifies for the record of the CM7 carbon cycle perturbation in the Central Mediterranean area. However, the upper Miocene evolution of the two carbonate ramps is significantly different. A deepening upward trend characterises the Tortonian portion of the Latium-Abruzzi platform, while the Apula platform shows a shallowing upward trend. Furthermore, the Latium-Abruzzi ramp drowns in the lower Tortonian, immediately after the CM7, as testified by a hardground surface overlain by hemipelagic marls. Conversely, the lower Tortonian outer ramp deposits of the Apula platform are overlain by upper Tortonian inner ramp facies. These preliminary results imply that the carbon cycle perturbation of the early Tortonian contributed to the deterioration of the trophic conditions that favoured the drowning of the Latium-Abruzzi platform, but that eventually regional controlling factors, such as the tectonically-driven subsidence related to the migration of the Apennine accretionary wedge, were responsible for the end of the carbonate sedimentation in the Latium-Abruzzi domain.

Delineation of the Brac Unconformity on Grand Cayman, B.W.I.: implications for late Oligocene – early Miocene paleoclimate and glaciation

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Unconformities Karst $^{87}Sr/^{86}Sr$ Sea Level Paleoclimate

Due to their isolated position in the Caribbean Sea, the carbonate sedimentary succession on the Cayman Islands is ideally suited for assessing eustatic changes in sea level. The Bluff Group, which forms the core of each island, consists of the unconformity-bound Brac Formation (Lower Oligocene), Cayman Formation (Middle Miocene), and Pedro Castle Formation (Pliocene). The unconformities developed as karstic surfaces when the islands were emergent during periods of sea-level lowstand. The Brac Unconformity, which defines the upper boundary of the Brac Formation, developed over a 6 – 11 million-year period during the late Oligocene and early Miocene. In the subsurface of Grand Cayman, the Brac Unconformity is a paraconformity that denotes the boundary between the fabric retentive, finely crystalline dolostones of the Brac Formation and the fabric retentive, microcrystalline dolostones of the overlying Cayman Formation. Although the Brac Unconformity is readily apparent in the cliff faces (up to 20 m above sea level) on the east end of Cayman Brac, it is difficult to recognize in the subsurface based on well cuttings and/or core. Accordingly, biostratigraphic information and the $^{87}Sr/^{86}Sr$ isotope ratios have been used to establish the location of this unconformity.

Variations in the position of the Brac Unconformity reflect the effects of eustacy and tectonism that contributed to karst development. Cayman Brac was uplifted and tilted westward during Pliocene-Pleistocene times, whereas there is no evidence that Grand Cayman experienced tectonic uplift or tilting. In well RTR-1 on Grand Cayman the Brac Unconformity is 129 m below sea level – 149 m below where it is found on the east end of Cayman Brac. This value represents the absolute maximum lowstand position, if it is assumed that Grand Cayman has experienced no tectonic uplift/subsidence. In contrast, the erosional relief on the Brac Unconformity reflects the absolute minimum lowstand position, if it is assumed that the present-day depth to the unconformity is entirely due to post-Oligocene subsidence. Available evidence indicates that the erosional topography on the Brac Unconformity developed as a karst surface rather than constructional processes. In well GET-1 on Grand Cayman the Brac Unconformity is at 73 m below sea level, 56 m above where it is found in well RTR-1. There is, therefore, at least 56 m of erosional relief on the Brac Unconformity.

Although the general framework of eustatic changes in sea level is well known, the absolute magnitudes of such fluctuations are open to debate. Estimates of the magnitude of eustatic fall during the late Oligocene-early Miocene transition, for example, range from ~160 m to ~60 m. Information from the Brac Unconformity on Grand Cayman indicates that the late Oligocene-early Miocene lowstand was between 56 m and 129 m below present-day sea level.

Too salty? Too deep? This is also Sarmatian! (Some new data from the wide range of sedimentary environments in the Central Paratethys, Hungary)

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Key words: brackish, Central Paratethys, Hungary, hypersaline, Sarmatian

In the past years some new data have come to light concerning the Sarmatian (late Serravallian) sedimentary environments in Hungary, which were located in the western part of the Central Paratethys.

Sediments of deep sublittoral facies were revealed by a hydrocarbon exploration well in SW Hungary. The lower Sarmatian succession comprises pieces of lower Badenian deposits due to gravitational redeposition promoted by intense tectonism. It is characterised by the *Anomalinoides dividens–Polycope orbicularis–Cytherois sarmatica*-dominated assemblage, which dwelt in an approximately 200 m-deep marine poorly-oxygenated environment of normal or quasi-normal salinity. Planktonic taxa indicate open-sea connection. Microfossils show great similarity to that of the assemblage of A. dividens Zone of the Transylvanian Basin (FILIPESCU 2004).

In well *Szirák-2* (Zagyva Trough, N Hungary), the marine Badenian (late Langhian–early Serravallian) succession is overlain by lower Sarmatian evaporite-bearing sediments, covered with fine-siliciclastic beds of brackish-water facies. Evaporites were formerly considered as deposits of a restricted, shallow lagoon; nevertheless, based on *Anomalinoides dividens* -dominated foraminiferal assemblage they represent off-shore environment and may have been deposited even in the deep sublittoral zone. The predominant part of the microfauna was strikingly small-sized, which can be explained by high salinity due to a local antiestuarine circulation caused by the existence of a tectonic threshold between the Zagyva Trough and the open sea in the early Sarmatian. During the Sarmatian the depth of the sedimentary basin became increasingly shallower.

Shallow, hypersaline lagoonal environment has long been known from the Zsámbék Basin (20-25 km far to the W of Budapest), where, based on the foraminifer *Spirolina austriaca* and the mollusc assemblage, sedimentation took place in the late Sarmatian (Görög 1992, Cornée et al. 2009). The Late Sarmatian succession is made up of compact, limestone, oolithic limestone of grainstone-packstone texture, and coarse porous limestone. The lower section shows symmetrical cross lamination within the bedding. Beds incline south-southeastwards at about 25°, following the former basement dipping increasingly steeply towards the basin centre. Sedimentological features, the dominance of Miliolids and the occurrence of *Spirolina austriaca* indicate a shallow (max. depth: 20-30 m), occasionally hypersaline back-reef lagoon environment characterised by warm, agitated water. Encrusting forams, ostracods and molluscs, as well as bryozoans and red algae fragments can also be observed.

Biogenic reefs developed in the vicinity of Vanyarc (N Hungary): oncoidic limestones represent the rim of the Sarmatian sedimentary basin (the outcrop is found about 9 km to the WNW of the Szirák well). The diameter of oncoids reaches even 15 cm.

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Tsunamis in the Central Paratethys?

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Key words: backwash, boulders, Central Paratethys, carbonate platform, tsunami

Distinct horizons of a few cm-metre sized limestone boulders can be observed within the lime sand successions of the Sarmatian carbonate platform around Budapest. The shape of the boulders are often elongated with the long axis being parallel to the stratification. The boulders are more or less rounded and can be encrusted by microbial coating. They are often accompanied by 1–8 cm large quartz pebbles. The thickness of the boulder layers can reach several 10s of centimetres. The most boulder horizons, seven in number, can be seen in the limestone quarry near Sóskút, SW of Budapest.

The phenomenon can be noticed in the horizontal, very shallow water near land strata, as well as in the steeper, basinward part of clinoforms.

Within the horizontal layers, the boulders are well rounded and mostly encrusted (e.g. Biatorbágy, SW of Budapest). According to Cornée et al. (2009) the crust consists mostly of red algae, subordinately serpulids, nubeculariids és microbialites.

The boulder layers generally settle on a low-angle truncation surface within the clinoforms. The boulders are less rounded and encrusted to a less degree than the ones within the horizontal strata. Imbrication indicating a basinward transport direction can also be observed. The clasts are badly sorted and are mixed with coeval lime sand. The limestone boulders can be grouped in certain parts of the clinoforms.

As for their formation, the boulder horizons have probably developed in several steps. Coastal limestone cliff pieces were ripped up by storm wave action, then rolled and rounded by wave action. Meanwhile, the boulders became microbially encrusted. The rounded and encrusted boulders together with freshly ripped-up clasts and terrestrial quartz pebbles were picked up by a sudden high energy wave and removed basinward. The moving sediment truncated the upper part of the clinoforms and part of the boulders were deposited on this erosional surface. Another part of the unsorted material reached the deeper, low-angle part of the clinoforms and settled there embedded in the normal sequence.

The question is, what force could pick up the often 50–100 cm large rock bodies and transport them even as far as a few hundred metres: a huge storm or a tsunami?

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Erosion of Tortonian phosphatic intervals in upwelling zones: the role of internal waves

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Keywords: Internal wave, coastal upwelling, phosphorites, Tortonian, carbonate ramps

Accumulation of authigenic phosphate in phosphorites and phosphate-rich sediments has been widely used for paleoclimatic and paleoenvironmental reconstructions. During Miocene, the upwelling was assumed to be important in the formation of many Mediterranean phosphate occurrences in carbonate platform successions.

There are different types of upwelling mechanisms such as equatorial upwellings, ice-edge upwellings, and coastal upwellings. The carbonate platforms are interested mainly by wind-driven coastal upwelling system. During upwelling season the seawater of coastal area is strongly density stratified, and the permanent pycnocline rises inshore forming an inclined frontal layer. The liaison between upwellings and internal waves is widely documented in the literature (Walter et al. 2014, 2016 and references therein). Internal waves result from perturbations of the hydrostatic equilibrium, where balance is sustained between the force of gravity and the buoyant restoring force (Pomar et al. 2012 and references therein). Any perturbation of the pycnocline will propagate as an internal wave. In a coastal upwelling, a key role for wave propagation is played by the permanent pycnocline. The run-up swash currents develop during the break of internal waves and produce erosional processes. In particular, the backwash return flow may produce erosion of seafloor sediments and downslope transport of these sediments as bedload (Pomar et al. 2012).

Erosion of phosphate-rich intervals has been extensively documented (Föllmi et al. 2008, 2015; Vescogni et al. 2018). The deposition of gravity-flow sediments is followed by intervals of non-deposition, incipient lithification, phosphogenesis, and erosion. In this work, we evaluate the role of the internal waves to produce the resedimented phosphatic rich intervals characterizing the basal portion of the hemipelagic *Orbulina* marls. These marls deposited on the low angle Latium-Abruzzi carbonate ramp representing deposition in a foreland basin during the early stage of evolution of the Central Apennine Belt during the early Tortonian.

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A Circum-Arabian Holocene Sea Level Highstand

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Keywords: Arabian Peninsula, Holocene sea-level, deglaciation

During the last 20 ka, the waning of ice sheets has been the first order influence on the world-wide rising sea levels, accompanied by local relative sea level changes influenced by glacio-hydro isostacy and tectonism. A compilation of new and reported age data from around the Arabian plate (Arabian Gulf, Arabian Sea and Red Sea), provides a circum-plate record of the initial transgression which started flooding the present day coastline about 8000 Calendar yr BP (cal. yr BP). The transgression peaked with a Holocene sea level highstand 5000 to 3500 cal. yr BP and regressed until recently, followed by an ongoing sea level rise. The Arabian Peninsula's response to recent sea-level fluctuations is possibly important for understanding the human history in Arabia and predicting the effect a future sea-level rise may have along a coastline with densely populated urban centres (Dhahran, Jeddah, Bahrain, Abu Dhabi, Dubai, Muscat, Doha, etc).

New data are reported from four localities and integrated with six data sets previously reported, to provide a circum-Arabian data set. The new data are from the Red Sea (Al-Wahj and KAUST, Saudi Arabia), the Arabian Sea (Bar Al Hickman – Oman) and the Arabian Gulf (Al-Kheeran, Abu Dhabi, UAE). At Al-Wahj and KAUST, the exposed reef terraces at modern coastline were mapped, sampled, and radiocarbon dated (coral samples dated 6-3 cal. yr BP). At Barr Al Hikman, corals, sea-shells, and rhodoliths were mapped, sampled, and dated by uranium-thorium ("U-series"), radiocarbon, and strontium methods (dated - 5039- 665 cal. yr. BP). At Al-Kheeran, Abu Dhabi a 11.2 ft core was collected and radiocarbon dated (coral and shell samples dated - 7220 – 680 cal. yr BP). Published data on the Holocene highstand along shores of the Arabian Peninsula also have been included in this study (Gulf of Aqaba, Shu'ayaba, Al-Birk, and Farsaan Island - Red Sea; Mussfah Channel - Abu Dhabi (2); Dukhan Sabkha – Qatar (3); and Subiya – Kuwait (4) - Figure 1).

Notably, the approximate initial flooding occurred by ~8000 cal. yr in Kuwait, ~7500 cal. yr BP in Qatar, ~7100 cal. yr BP in Abu Dhabi in Arabian gulf, older than ~6000 cal. yr BP at Barr Al-Hikman, Oman, and ~4000-7000 cal. yr BP along eastern Red Sea coastline. The lag in the initial flooding along Arabian coastline may have been caused by glacio-hydro isostacy causing variable relative sea-level changes but may also be related to tectonics.

The circum-plate data set may provide an explanation for coastal and climate impact on past human history in Arabia but may also allow prediction of sea level variability along the Arabian coastline in the future.

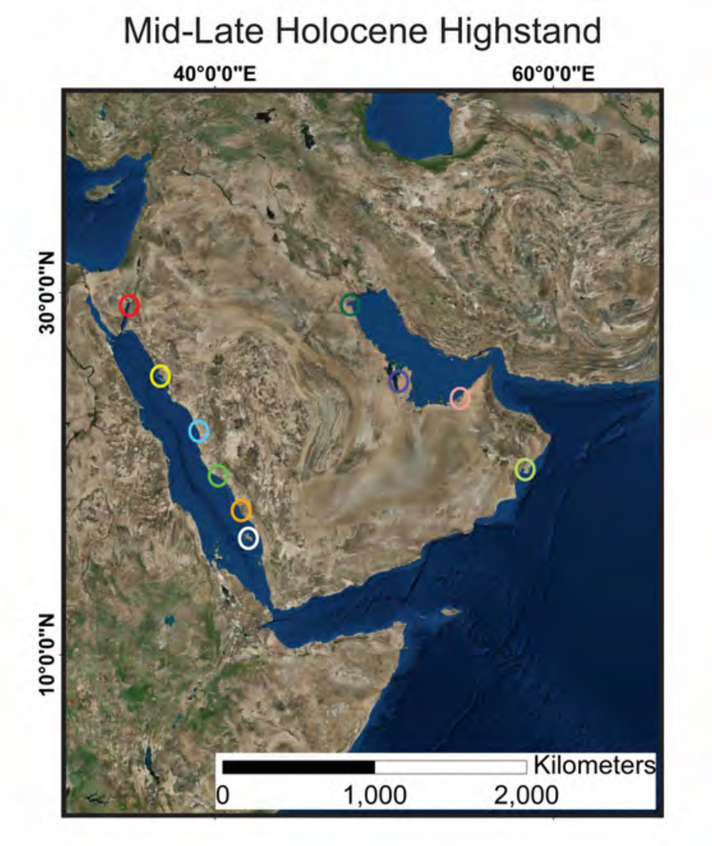

Figure 1: Location of the Holocene Highstand dated sediments. The locations are marked by circles which represent (Red – Gulf of Aqaba, Yellow – Al-Wahj, Sky Blue – KAUST, Green – Al-Birk, Orange – Shu'ayaba, White – Farsaan Island, Light Green – Barr Al-Hikman, Light Pink – Abu Dhabi, Purple – Qatar, Dark Green – Kuwait).

A present-day snapshot of a carbonate depositional system and its record of multiple sequence stratigraphic systems tracts (Tun Sakaran Marine Park, Celebes Sea, Sabah, Malaysia)

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Key words: Carbonate Platforms, Malaysia, Holocene, Sea level, Sequence Stratigraphy

The carbonate platforms of the Tun Sakaran Marine Park in the Celebes Sea, east of Sabah, Malaysia, are renowned for their beauty and spectacular diving sites. They display a wide variety of depositional patterns ranging from multiple reef margins, margin back-stepping, platform fragmentation and deep lagoons occupied by mesh reefs to elevated beach rocks, shallow sediment filled lagoons and reef margins that become emergent at low tide. A previous explanation put forward to support these contradicting observations were structurally controlled, relative sea-level fluctuations, i.e. syn-depositional tectonics were invoked to allow these present-day patterns to co-exist. In this paper, we collate observations made during various visits and in various parts of the Marine Park and position the depositional and architectural elements in different sequence stratigraphic systems tracts that responded to Holocene sea level fluctuations.

Sibuan is one of the smaller islands in the Marine Park. It shows the highest topography, comprises elevated beach rocks, and is eroded in the NE whereas an active prograding carbonate sandspit is developing in the SW. Present-day wind and current patterns can explain the beach erosion and progradational patterns. The beach rocks contain high concentrations of large shells. The accumulation of the shells is interpreted as an anthropogenic accumulation, meaning the collection was formed by humans who were consuming them, possibly during annual harvest events. Published age dates of the beach rocks average around 3500 year before present.

On all platforms, double, and in some cases triple reef margins are observed in map view with the outermost reef fringe sitting at a depth of 10 m below mean sea level, whereas the innermost and shallowest reef margin is exposed during low tide. The backreef and forereef environments surrounding the innermost reef flat display a diverse and healthy reef. In the deeper parts of several lagoons reticulate ridges of reefs occur. These mesh reefs are partly covered and smothered by prograding back reef sand apron sediments. These sand aprons in their turn are fringed by reefs. In some cases, lagoons have been completely filled with sediments and in one case, on Maiga Island, the lagoon becomes emergent at low tide. A

Mickey Mouse mathematical model is able to explain the relationship between the carbonate sand factory and observed lagoonal infill patterns.

Several more observations will be presented that document the wide variety of depositional patterns and architectural elements of the carbonate platforms in the Tun Sakaran Marine Park. In summary, the present-day snapshot illustrates the reef responses display back-step, keep-up, prograde, and emergent patterns. In other words, transgressive, highstand, and falling stage systems tracts are all recorded. A single eustatic sea-level curve covering the post-glacial Early Holocene sea level rise, a mid-Holocene sea-level highstand and subsequent drop during the late part of the Holocene is able to explain the responses of the carbonate depositional system. A compilation will be presented of similar observations that have been made in the region and across plate boundaries and thus support eustatic sea level as a key controlling factor.

Ground truth of carbonate reef facies identified from remote sensing data with underwater photography: towards a global, shared data base(?)

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Key words: Reef facies, modern-day analogues, ground-truthing, satellite images

Present-day and ancient carbonate depositional systems can be highly heterogeneous. In the recent years large amounts of remotely-sensed satellite images, including time-lapse data, wind, current and temperature data, have become available in online databases and they can be used to map, understand and better predict these heterogeneities (e.g., Rankey, 2006; Teoh & Warrlich, 2017). However, ground truthing these remote sensing data is critical to ensure accurate classification of the images and therefore accurate mapping, but availability of in-situ observations for ground-truthing is often problematic due to difficulty of access, and hence done less frequently (e.g., Purkis et al., 2015) resulting in lack of a comprehensive database.

This project aims to use a use a data set of georeferenced underwater images, acquired during snorkeling and diving in coral reefs of Kubbar (Kuwait) and East Sabah (Malaysia), to ground–truth satellite imagery and produce robust maps of carbonate facies heterogeneity. The two reef systems chosen are also both stressed by significant terrestrial run off, and in the case of the Kuwait, also annual water temperature variations between 15 and 30+ degree Celsius. The project objective is to identify and quantify key drivers on reef systems developing in areas where coral reefs are under environmental pressure. Studying modern reefs in stressful environments allows bracketing of the ranges of stress factors they can tolerate, and potentially allows a link to be made between controls and various parameters related to reef morphology, composition and growth potential, in turn allowing better understanding and prediction of conditions in the geological past.

For the two locations, semi-quantitative facies distribution maps are being constructed using high-resolution Google Earth satellite imagery combined with nautical charts and available structural data. Ground-truthed sediment-type data, compiled from 100 GPS-located underwater images and 10 sediment samples, are used to construct a multi-data-type database. This will form the basis for maps using supervised and unsupervised image classification methods. Using online data sources (e.g. http://earth.nullschool.net/) maps of summer versus winter wave conditions from vintage imagery, along with wind, temperature and salinity maps are constructed. Classified maps enable investigation of facies distribution at multiples scales, critical in reservoir modelling and production forecasting. Conceptual comparison between maps and heterogeneity inferred from seismic images of carbonate platform interior strata uses inferred controls to predict from modern system the likely spatial distribution of facies in ancient platforms.

It is hoped that this project can be extended to a wider data base with examples from other geographical settings, through participation of researchers on an open sharing platform to better understand driver for carbonate platform facies and heterogeneities development.

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Microplastic accumulation in different carbonate depositional environment of the Kepulauan Seribu complex, Indonesia

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Abstract

Presently the most abundant marine litter is plastic. Marine litter is accumulating at the beach, floating on the oceans, and a large proportion is projected to sinks and remain on the seafloor. Microplastic accumulates in benthic sediments and shorelines with harmful effects to the environment due to its small size. Ingestion of microplastic by reef corals with potentially detrimental effects on coral growth was observed in laboratory experiments. Microplastic is reported to have the ability to adsorb toxic chemicals from surrounding sea water, which can be pathologic if consumed by marine animal. Plastic waste also carries pathogens that are held responsible for the outbreaks of disease on coral reefs. Microplastic therefore poses a threat to reef corals and their ability to act as framework builders in coral reef systems. Despite this, microplastic accumulation in reef systems remains largely unquantified. We aim to analyze the control of sedimentary processes on the distribution of microplastic in different carbonate environments. A Sediment Microplastic Isolation unit is used to extract microplastic from sediment with NaCl as floatation media. Other commonly used floatation media such as $ZnCl_2$ are acidic and would react strongly with the carbonate matrix, producing CO_2 bubbles which hamper effective density separation. Microplastic in the size range from 125 µm to 1 mm is investigated in the surface marine sediments of the subtidal lagoon, the reef margin, the sand apron with variable sea grass cover and the intertidal beach. Potential sources for microplastic are mismanaged waste from densely populated islands, marine fishing, aquaculture and tourism. The result will contribute to a better understanding of the sedimentary processes that govern microplastic accumulation and distribution within different environmental and sedimentologic settings.

Keyword: carbonate, environment, marine litter, microplastic, sediment.

Development patterns of an oligo-mesophotic isolated carbonate buildup (Upper Burman Limestone, Lower Miocene, Yadana field, offshore Myanmar)

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Keywords: facies analysis, depositional model, oligo-mesophotic environments.

The development history of a strictly oligo-mesophotic, Lower Miocene, isolated carbonate platform in the northern Andaman Sea (Yadana platform) has been evidenced from the integration of sedimentological core studies, well-correlations, seismic geomorphology and analysis of the ecological requirements of the main skeletal components.

Three types of carbonate factory operated on the top of the platform, depending on water-depth, turbidity and nutrient level: 1) a scleractinian carbonate factory developing under mesophotic conditions in shallow turbid, nutrient-rich waters, 2) an echinodermal carbonate factory occupying aphotic to oligophotic area of the shelf coevally with the scleractinian carbonate factory, 3) a large benthic foraminiferal (LBF)-coralline algal carbonate factories prevailing under oligo-mesophotic and oligo-mesotrophic conditions. The low lateral changes in facies and the layer-cake depositional architecture inferred from well-correlations and the seismic expression of the Yadana buildup suggest a deposition on a flat shelf. Carbonate production and accumulation on the Yadana platform has been shown to be mainly controlled by light intensity, nutrient content and water energy. Scleractinian-rich facies have been shown to result from transport of coral pieces developing on mesophotic environments (mounds?) and deposition in deeper, low light and mud-rich environments characterized by abundant communities of suspension-feeders such as ophiuroids.

Changes in monsoonal intensity and terrestrial runoff from the Irrawaddy River during the Early Miocene, are likely responsible for the repeated development of turbid (high-nutrient?) conditions that promoted the development of an oligo-mesophotic, incipiently drowned platform.

Climate control over carbonate platform growth in tectonically active basins

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Key words: seismic forward modelling, stratigraphic forward modelling, syn-rift carbonates.

Characterization and understanding of carbonate strata developed in tectonically active extensional settings is challenging. Architecture and facies distribution of syn-rift carbonate platform result from simultaneous interplay of climatic conditions, tectonic processes, the sedimentological properties of the produced sediments and a likely biological influence. Qualitative investigations of these controlling factors do exist, mainly based on interpretation and analysis of subsurface and outcrop data, but extensive, quantitative characterization and ranking of the processes influencing carbonate growth over extensional faults would be useful.

A 3D numerical stratigraphic forward model, Carbo-CAT, has been developed to explore and analyse growth and evolution of carbonate platforms under different climatic, tectonic and sedimentological scenarios. Carbo-CAT has been improved to include more realistic representations of processes critical to produce facies heterogeneity in carbonate environments. New subroutine to better represents the principal mechanisms controlling carbonate sediment removal, transport and deposition and a novel, ray-tracing approach for modelling wave energy distribution have been developed and included in Carbo-CAT.

Carbo-CAT has been used to perform a detailed sensitivity analysis on platform growth in three tectonic scenarios: nucleation and development of a half-graben system, a fault-bounded isolated horst, and interaction of two overstepping faults. For each configuration, different associations of climatic, structural and sedimentological parameters have been tested and the resulting strata evaluated for facies distribution, stacking patterns and various other related quantitative metrics. In addition, in order to evaluate differences between syn-rift and post-rift strata, carbonate sedimentation continue for a certain amount of time after fault displacement ceases.

Preliminary analysis of the modelled carbonate strata suggests a strong control by climate conditions (i.e. wind direction and icehouse versus greenhouse eustasy) over the platform facies heterogeneity despite the active tectonic setting (Figure 1). Transition to a post-rift setting, dominated by constant regional subsidence alone, leads to more stable conditions where platform margin reef systems become better established in an aggradational mode.

Populating the resulting 3D facies models with elastic properties and using a depth-domain convolution model, integrating both illumination and resolution effects, allows to calculate synthetic seismic images. Comparison of synthetic seismic with known examples of subsurface syn-rift carbonates allows testing and application of these model results to help assess the likely climatic and tectonic control on ancient carbonate platform.

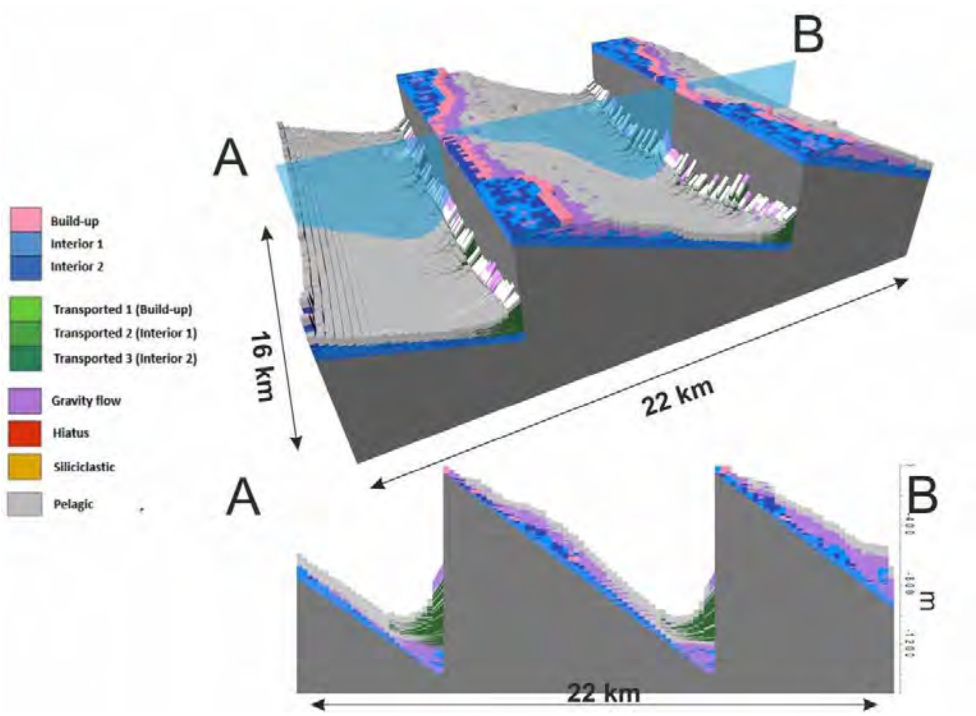

Figure 1. 3D stratigraphic forward model of carbonate strata developed over a half-graben system.

Controls on carbonate platform growth within the Lower Carboniferous of the Pennine Basin

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Platform architecture, biostratigraphy, forward modelling, Palaeozoic carbonates

This project assesses the interplay of depositional, diagenetic, and structural processes on carbonate platform evolution within an extensional basin. Syn-rift carbonate platforms often evolve from ramp to rimmed shelves, but the interplay of fault propagation, bioconstruction, volcanism and clastic interaction on platform architecture remain poorly understood. In order to assess this, two late Viséan (333 to 326.4 Ma) carbonate platforms are compared: the Derbyshire Platform (DP), situated in the Pennine Basin of northern England, and the North Wales Platform (NWP), located 130 km westwards. Both platforms formed during the transition from a greenhouse to an icehouse climate, on the footwalls of normal and oblique-slip faults. The DP was remotely land-attached and experienced syn-depositional volcanism, whereas the NWP was land-attached with significant siliciclastic input and was not influenced by volcanism. This aim was to assess the influence of multivariate controls on the evolution of these two contemporaneous carbonate platforms, formed within the same basin, using field-based sedimentology, petrography, and biostratigraphy combined with forward modelling.

In the Asbian the windward margins of both platforms were dominated by bryozoan and coral carbonate mud-mounds with well-defined core and flank facies. Skeletal grainstone shoals infilled intra-mound topography and also formed decimetre scale sheet-like sandbars. On the platform top, a mosaic of upward-shallowing crinoidal packstone-grainstones, and brachiopod and coral floatstone-rudstones are capped by exposure surfaces. These surfaces comprise thick, clay rich, and nodular cemented palaeosols on the NWP, and pot-holed limestone overlain by volcanic-ash rich clays on the DP. Statistical 1D modelling demonstrates that the periodicity of emergence cannot be confidently predicted on the basis of stacking patterns, implying that they are likely to have been influenced by local tectonism and self-organisation, rather than eustatically controlled sea level fluctuations.

A platform-wide emergent surface marks the top of the Asbian on the DP. Contemporaneous marine siliciclastic deposition inundated the NWP, whilst the DP was protected from this influx by an intervening basin. Inundation of fluvio-deltaic siliciclastics in the

Brigantian increased water column turbidity. Consequently, facies became thinner and darker with abundant chert and a faunal assemblage dominated by *Gigantoproductus* brachiopods. On the Derbyshire Platform, mounds became common on the platform top, rather than the platform margin, growing preferentially along faults and on the margin of intra-shelf basins. Cessation of carbonate platform growth occurred as the result of a decrease in carbonate productivity due to siliciclastic poisoning and/or relative sea level rise.

Overall, this project shows that two age-equivalent platforms in the same basin developed different architectures as a result of variable proximity to landmass and volcanic activity. The role of faults in controlling platform architecture and facies distribution is unclear; equally there is apparently less influence by relative sea level fluctuation on facies distribution than previously thought. Consequently, platform and basin-wide correlation using sequence stratigraphic principles appears challenging.

Probability Constrained Geological Modeling of Carbonate Reef and Shoal Reservoir in Permian Changxing Formation, Yuanba Gasfield, Sichuan Basin, China

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Abstract： The reef and shoal reservoir of the Changxing Formation in Yuanba Gasfield has various lithofacies types, special reservoir configurations and complex physical properties distribution. The existing modeling methods are difficult to accurately characterize the heterogeneity characteristics within the reef and shoal reservoir and can’t achieve the accuracy requirements of geological modeling and reservoir simulation. Based on the analysis and summary, a phase modeling method is proposed, which is guided by reservoir architecture of reef and shoal facies, using dual constraints of geological and seismic probability volume, and hierarchical facies modeling method. With seismic inversion data as constraints, the attribute parameter model of reef and shoal reservoir is established by using facies-controlled sequential gauss simulation method. The model characterize the reservoir and fluid heterogeneity of carbonate reef and shoal facies accurately and objectively, so as to meet the needs of accurate calculation of gas reservoir simulation.

Keywords：probability constrained，geological modeling, reef and shoal reservoir, Changxing Formation, Yuanba Gasfield

Lateral facies variations in the Triassic Dachstein Platform: A challenge for cyclostratigraphy

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The Triassic Dachstein platform limestone at Steinernes Meer, Saalfelden, Austria, includes 611 m of limestone with 222 peritidal cycles overlain by 273 m of subtidal, non-cyclic and weakly cyclic limestone. Beds are laterally discontinuous, and cycle bounding surfaces are laterally variable in the studied strata. Of 558 subtidal and intertidal beds measured, 121 (21.7%) disappear laterally. An additional 73 beds (13.1%) show significant (>10%) lateral variations in thickness. Mean thickness variation is 50%. Both lateral variations and terminations appear to lack a spatial vector. Disappearances toward the inferred platform interior (west) total 10% of the beds. East toward the inferred platform margin 11.6% of the beds disappear. Thickness changes occur in 6.5% of beds in each direction.

The lack of lateral continuity of beds precludes a simple allocyclic forcing model and is consistent with a non-eustatic component to stratification. Erosion of intertidal intervals is the process that can be most readily documented. Erosion, transport, and non-uniform distribution of sediments, superposed on stratigraphic sequences driven by eustasy, as proposed by Ginsburg (1971), among others, probably contributed to the complex, randomly recorded cycle patterns.

Cycle duration may not be exclusively determined by Milankovitch processes, as suggested by the discrepancies in cycle duration and in interpretations among stratigraphers of the Dachstein, as well as of other Phanerozoic carbonate platforms. Signals deduced from linearly measured sections likely represent a composite of inherent and extrabasinal factors; they should not be uncritically interpreted as exclusive records of orbital forcing.

Lateral discontinuities and thickness variations could also produce inaccuracies in spectral analysis of thickness patterns, typically conducted in search of “Milankovich frequencies.”, as well as in construction of “Fischer plots,” to analyse long-period oscillations in relative sea level. Any section subjected to cycle analysis should be examined for lateral changes, to the extent permitted by the exposures, in order to produce the most complete (composite) section possible.

Keywords: Austria; Carbonate-platform cycles; Cyclic processes; Milankovitch theory; Triassic.

Architectural and compositional evolution of the Jurassic carbonate succession of Eastern Sardinia (Italy)

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Key words: carbonate platform, coral-microbial reefs, facies architecture, Jurassic

The Jurassic was a time of tectonic, climatic and sea level changes in the context of the break-up of Pangea. In the Late Jurassic favourable conditions led to widespread reef growths, with the Oxfordian-Kimmeridgian stages representing the Phanerozoic peak of coral-sponge-microbial reef development. The study of facies character, biota and architecture of Jurassic carbonate depositional systems contributes to the understanding of the influence of global and regional tectonics, paleogeography and climate on carbonate systems.

The Eastern Sardinia (Italy) Callovian-Berriasian carbonate succession consists of three superimposed carbonate platforms evolving through time from a homoclinal ramp to a low-relief shelf.

Platform 1 (Dorgali Fm., Callovian) records the transgression over the Hercynian basement and the onset of carbonate sedimentation. It is a homoclinal ramp with dolomitized middle ramp peloidal packstone (Facies 1), inner ramp grainstone with micritized ooids and scarce skeletal components (Facies 2). The dolomitization front corresponds, in part of the study area, to the platform 1 upper boundary, locally represented by a subaerial exposure surface.

Platform 2 (Tului Fm.; Oxfordian-lower Tithonian) was a ramp characterized by cross-bedded ooidal grainstone adjacent to boundstone with microbialites, skeletal framework of corals, chaetetids, stromatoporoids and siliceous sponges passing to basinal cherty wackestone/packstone. Outer ramp facies consisted of peloidal packstone (Facies 3), whereas middle ramp facies were skeletal-coated grain-intraclastic packstone-grainstone (Facies 4-5). The middle ramp hosted distal siliceous sponge bioconstructions and proximal metre-scale coral-microbial-chaetetid reefs (Facies 6). The inner ramp was dominated by ooidal shoals (Facies 7) and stromatoporoid-dasyclad packstone-grainstone (Facies 8-9-10). Platform 2 was subaerially exposed during the early Tithonian. This event contrasts with the contemporaneous global sea-level rise and could be related to local tectonic uplift. The following transgression established basinal deposition with marly calci-mudstone and debris flow pebbles of resedimented carbonate lithoclasts (Pedralonga Fm.).

Platform 3 (Mt. Bardia Fm., lower Tithonian-Berriasian) was a low-relief shelf in which a coral-stromatoporoid margin divided a sheltered platform interior with foraminifers and green algae packstone, from prograding low-angle clinoforms consisting of skeletal grainstone/rudstone with coral, stromatoporoid and microbialite debris.

The Eastern Sardinia Middle Jurassic-Lower Cretaceous succession represents a well-exposed case study providing a better understanding of the controlling factors on facies character and platform architecture of an evolving carbonate succession. The evolution from ooid dominated platform 1 to platform 2 with coral-sponge-microbial boundstone record the regional spreading of coral-microbial reefs in the northern Tethys during the Oxfordian-Kimmeridgian. The change in platform geometry from homoclinal ramp (platform 1 and 2) to shelf with progradational clinoforms (platform 3) seems to reflect changes in the dominant carbonate factory changing through time from coated grain grainstone to coral-sponge-microbial boundstone, suggesting a major control by the interplay of global and regional tectonic, paleogeography and climate.

Tectonic and environmental controls on passive margin carbonate platform development. Jurassic of the Essaouira-Agadir Basin, Morocco.

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Controls, Jurassic, Morocco, Passive margin, Platform

Carbonate depositional systems record potentially complex interplays between relative sea level, tectonics and local to global environmental conditions. Identifying the relative importance of each factor can be challenging. Extensive Jurassic post-rift carbonate platforms in the Essaouira-Agadir Basin (EAB) of Morocco allow a study of this interplay. The Essaouira-Agadir Basin is situated at the junction between the Atlantic and Tethyan rifts, via the Atlasic trough. Therefore, a complex tectonic history associated to eustatic and environmental variations likely influenced the evolution of the EAB platforms throughout the Jurassic. Three main stages of carbonate platform development have been identified between the Sinemurian and the Kimmeridgian.

The late Sinemurian to early Pliensbachian record an initial open marine platform dominated by oolitic and bioclastic units. These were subsequently tilted tectonically and eroded by Toarcian continental siliciclastics. Later in the Toarcian, a 300 m thick peritidal succession is composed of oolitic and peloidal grainstones to wackstones alternating with stromatolites and thick evaporites. Three different units displaying distinctive variations of the facies association were identified in this formation. This second platform expansion might be linked to the middle Toarcian global sea-level rise. It is followed by marine and continental siliciclastics during most of the Middle Jurassic. These siliciclastic deposits are restricted to the south and center of the basin and are here tentatively linked to movements of the hinterland (Anti-Atlas principally), as well as a change to wetter climatic conditions.

A third, extensive platform initiated in the Callovian. This carbonate ramp can be divided into three units separated by major hardgrounds and recording important shifts of depositional environments. The first unit is mainly composed of oolitic grainstones, the second is dominated by brachiopod-rich floatstones and rudstones, and the third one consists of marls with minor rudstones intervals and is followed by Oxfordian coral build-ups. This succession has been re-dated as lower Callovian to middle Oxfordian by ammonite biostratigraphy. The appearance of coral build-ups during the middle Oxfordian has been documented along the Northern Tethys and has been linked to environmental changes. Similar controls are assumed in the EAB, where the global middle Oxfordian warming and increase of CO_2 levels likely triggered the general development of coral build-ups by creating more favourable living conditions for these organisms.

The Oxfordian build-ups ecological succession is based on a first colonisation by flat microsolenid corals in a muddy matrix. This initial phase is locally followed by more diversified coral species, including branching and massive forms which are characteristic of shallower environments. The sizes and the geometries of the coral colonies is variable, from 2 m wide dome-shaped colonies to 800 m wide colonies forming prograding clinoforms. The coral build-ups disappeared in the upper Oxfordian, when localized siliciclastic influx and a drop of sea-level induced a decisive change of environmental conditions and lead to the establishment of peritidal conditions across the platform.

Seismic geometries and controlling factors of an Upper Jurassic carbonate platform margin to basin transition (offshore Morocco, eastern Central Atlantic)

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Keywords: offshore Morocco, eastern Central Atlantic, Late Jurassic, carbonate platform, steep margin to basin transition.

This study presents 3-dimensional seismic data from the Upper Jurassic Flamant Carbonate Platform located in the eastern Central Atlantic margin offshore Morocco. Our motivation is (1) to describe the seismic geometries and facies of the platform margin to basin transition, and (2) to predict the sediment factories and interpret the growth patterns and the main controlling parameters. The importance of the study is that these systems provide insights into (1) the processes that control the sediment transfer from the platform-top into the basin, (2) the impact of platform-top *vs.* upper-slope sediment factories on the growth patterns of the system, and (3) the occurrence of platform margin and slope hydrocarbon reservoirs.

In the Central Atlantic, Tethys, and areas of the Pacific, Upper Jurassic carbonates have often been described to include gently-dipping ramps in sectors of tectonic quiescence and steep platform margin to basin transition in tectonically active sites. The Flamant Platform sits above a footwall high, which was tectonically active during sedimentation and reveals a flat platform-top, a NE-SW-striking margin, and an aggradational margin to basin transition with inclination up to ~40° and ~450 m relief. In plan view, a scalloped margin is observed due partial collapses and/or partial or complete erosion. Near the margin, the maximum thickness reaches ~900 m and most of it exhibits chaotic seismic facies with only a few and discontinuous, low-amplitude reflectors. These reflectors are parallel to the top of the platform but they occur inclined near the slope. In the basin, the system reduces its thickness to a maximum of ~350 m and it mostly presents transparent seismic responses. Also, blocks ~100 m across are interpreted in areas of the basin near major collapses. The Flamant Platform is undrilled and no direct lithological information is available, but a comparison with the Upper Jurassic (drilled) Abenaki Formation from the Nova Scotia conjugate margin is used here to make coarse predictions of the sediment factories. We interpret that large parts of the chaotic seismic facies at the Flamant Platform margin could include poorly-stratified to massive boundstones and associated high-energy facies rich in coral, sponge, calcareous algae, and stromatoporoid debris. Other than fallout of calcareous plankton, the slope would include sediments transported from updip as well as intervals with *in situ* carbonate production (microbial- and/or coral/sponge-rich lithologies), the latter more abundant near the margin top and probably key to promote its accretion in the sectors of a steeper slope. Finally, the relatively thin section in the basin suggests it was sediment-starved and could include grains from marine rainfall, materials transported from the margin and slope, and possible siliciclastics.

Although conditioned by the absence of direct data, a working hypothesis is that the architectural evolution of the Flamant Platform margin to basin transition could be controlled, in general, by fault-block rotation during rifting and an overall rising sea level and, in particular, by higher carbonate production near the margin top as opposed to lower carbonate production at and lower sediment transfer to the slope and basin.

Carbonate shelves of Guyana and Suriname:

Late Jurassic to Early Cretaceous Evolution and Demise

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Keywords: Guyana, Suriname, Demerara, Carbonate shelf, Jurassic-Early Cretaceous

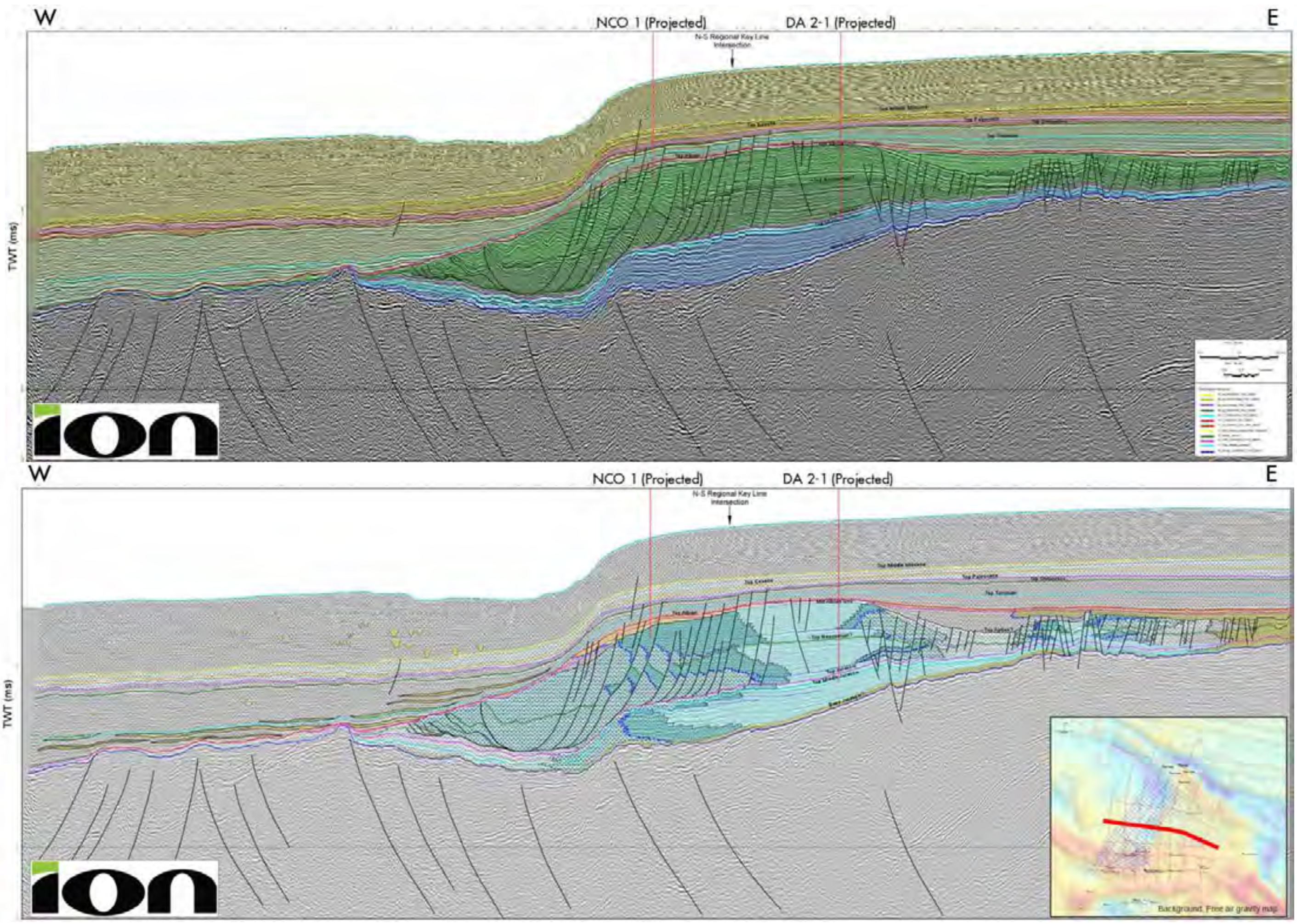
A recent discovery off Guyana in an isolated carbonate platform of assumed Early Cretaceous age sparked a renewed interest in unlocking other potential carbonate plays within this continental margin. A thick section of carbonate sediments, ranging from Late Jurassic (?) to Albian, were deposited on a more than 1000 km continuous carbonate shelf that extended along the Guyana-Suriname margin reaching a maximum width of up to 100 km in some sectors. Carbonate platform models with steepened margin predicts the existence of high energy facies (oids shoals) or even reef builders (corals, rudists) on the platform margin. Although none of the wells drilled in this margin has been drilled in the best location to test this model, the fact that only mudstones with variables amounts of forams and small skeletal fragments have been encountered raises reasonable doubts about the validity of a rimmed platform model and other scenarios should therefore be considered.

A recent Joint Industry Project led by CoreLab, funded by a limited number of companies including Shell, performed an extensive review of most of the existing well data along this margin. New insights concerning lithological and textural aspects of the Late Jurassic (?) to Early Cretaceous carbonates were integrated in the regional studies conducted in the region.

The acquisition of deep seismic 2D data providing a much better imaging of the stratal architectures of the older stratigraphic intervals and a review of the biostratigraphy in the available wells, have been used to propose a new sequence stratigraphic framework. The Late Jurassic (?) to Early Cretaceous section can be sub-divided into five major tectono-sedimentary sequences bounded by drowning surfaces. In the Guyana margin and western sector of Suriname these sequences show an overall back-stepping architecture. On the western margin of the Demerara Plateau, the stacking patterns evolved from back-stepping to prograding (see interpreted seismic section below). The earliest drowning event is not calibrated by well data but it occurred during a period of tectonic quiescence and has been assumed as being eustatic in origin. Subsequent drowning events in the Early Cretaceous occurred during a period of regional tectonism related to the continental breakup that lead to the opening of the Equatorial Atlantic.

Strike-slip deformation uplifted the northern and northwestern edges of the Demerara Plateau causing a major collapse of the shelf margin. The deformation progressed through time from north to south affecting the architecture of the carbonate shelf that became progressively disconnected from the southern segments until its final demise at the end of Albian time. Deposition of carbonate mud continued on the western sector of Guyana until the Turonian time.

For a period that could span over 50 M.y., and spite of the tectonism, the carbonate factories that lived in this continental margin produced essentially mud. There are no clear evidences on seismic of reef builder organisms, or high energy facies, but somehow, these flat top shelves were protected from wave action. A conspicuous, maybe microbial rim provided the shelter to these large, wide platforms, while producing more mud.



Revisiting peritidal carbonate-evaporite facies models: a new look from the Lower Cretaceous stromatolite-bearing cycles of the Oncala Group (N Spain)

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KEY WORDS: anhydrite nodules, Cameros Basin, laminites, microbialites, tidal flat.

Most widely-used peritidal carbonate and carbonate-evaporite facies models are based on present-day tidal flats. However, despite their usefulness, the present-day sedimentary settings are much more complex than reflected in the models, because facies distribution is not only and directly related with depositional depth, but it is also influenced by several other factors, such as, topographic gradients, agitation, sediment supply, turbidity, and inhabitant organisms. Consequently, the application of these facies models to the study of many fossil peritidal cycles is not easy. A classic example of the difficulties in interpreting ancient peritidal cycles are the Lofer cycles of the Northern Calcareous Alps, which have been interpreted as deepening upwards, as shallowing upwards or as rhythms with no clear deepening or shallowing trend.

This challenge has been addressed on the extraordinarily well-exposed, Lower Cretaceous peritidal deposits of the Oncala Group (Cameros Basin, N Spain). The studied succession is characterized by the vertical stacking of tidal facies mainly composed of stromatolitic, laminated and intraclastic carbonates, similar to those of Shark Bay, disrupted by evaporite nodules, similar to those of the Arabian Gulf, which formed in settings characterized by hypersaline subtidal environments and evaporative supratidal flats. In general, the Oncala peritidal cycles consist of: 1) domal to flat-laminated stromatolites developed in subtidal-intertidal zones, 2) thinly-bedded to laminated carbonates formed in flat microbial mats in subtidal-supratidal zones, 3) intraclast breccias caused by desiccation and reworking of stromatolites and thinly-bedded to laminated carbonates in intertidal-supratidal zones, 4) pseudomorphs after anhydrite nodules precipitated in the supratidal zone. These cycles may be capped by erosive deflation surfaces. However, common lateral and vertical changes are observed in the studied peritidal deposits depending on if they developed in agitated steep areas, where stromatolites and breccias dominated, or in less agitated flatter areas, where thinly-bedded to laminated carbonates predominated and stromatolites developed scatteredly.

Sedimentary features of the Oncala peritidal deposits could be interpreted as indicative of arid climatic conditions, similar to those in present-day Arabian Gulf sabkhas. However, fluvial-tidal flats inhabited by dinosaurs and with large freshwater input developed adjacently to the Oncala peritidal cycles, suggesting seasonal semi-arid conditions and implying that arid climates should not be interpreted directly from the presence of sabkha evaporites.

Furthermore, the Oncala peritidal deposits show abundant similarities with other fossil peritidal deposits in the geological record, especially from the Proterozoic, when microbial communities dominated peritidal systems. This highlights the difficulties in assigning specific features to certain geological ages, and makes the Oncala peritidal cycles useful for analysing other ancient successions that are not fully explained by their comparison with present-day models.

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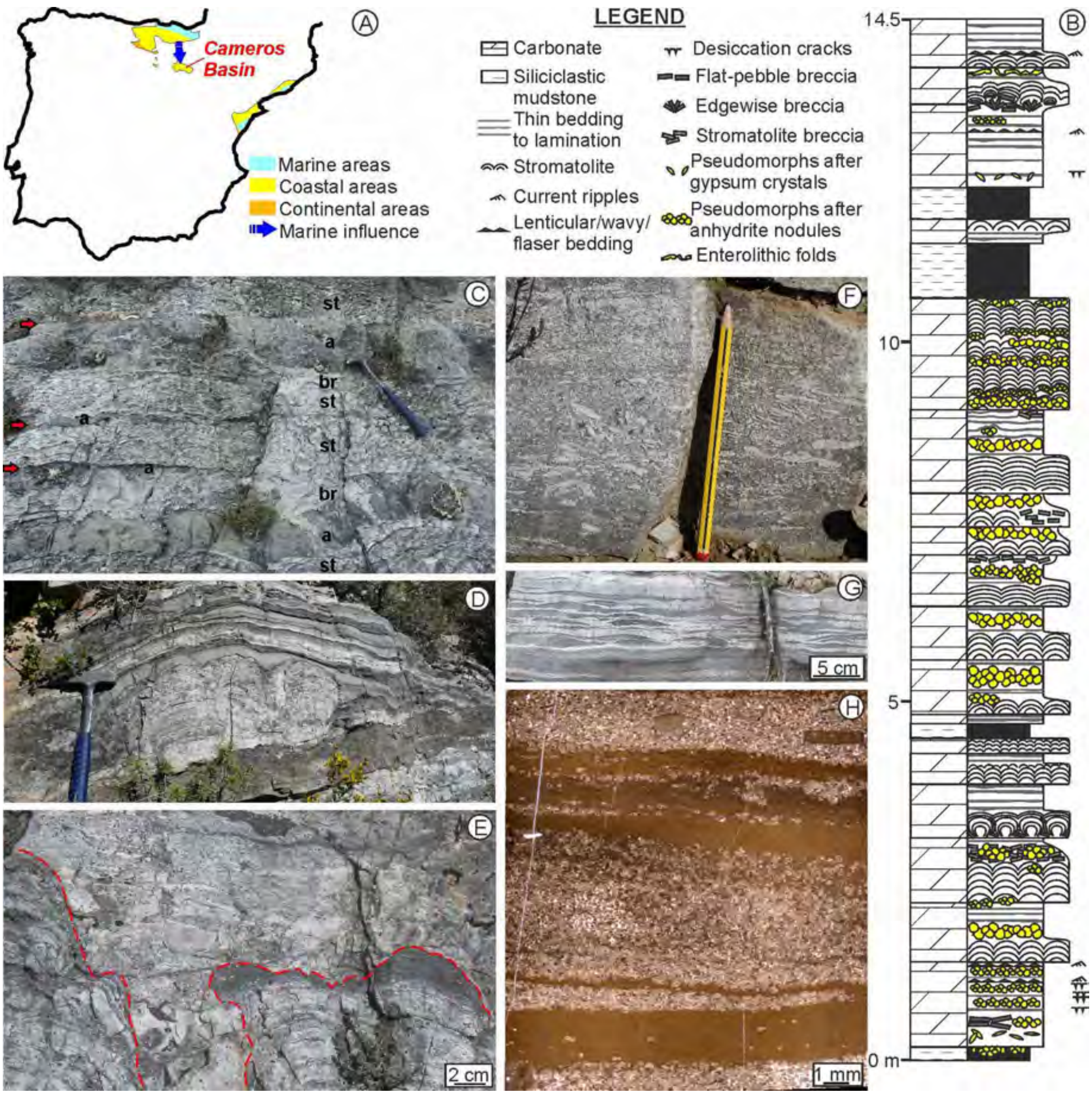

Fig. 1. A) Paleogeographic map of Iberia during the Berriasian. B) Stratigraphic section of the peritidal deposits of the Oncala Group. C) Peritidal cycles composed of stromatolites (st), intraclast breccias (br) and anhydrite nodules (a), separated by deflation surfaces (arrows). D) Domal stromatolite overlain by, and laterally passing to, thinly-bedded to laminated carbonates. E) Eroded stromatolites overlain by breccia. F) Intraclast breccia. G-H) Thinly-bedded to laminated carbonates.

The Barremian–Aptian Urgonian platforms from southeast France: towards a regional chronostratigraphic model?

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Since the 19th century, southeast France is recognized as a key area for the study of Early Cretaceous geological systems, particularly those of the Barremian–Aptian period. Reference unit-stratotypical sections of this time interval has been defined in the Vocontian Basin and surrounding carbonate platforms, the so-called “Urgonian limestones”. In addition, standard eustatic curves and biostratigraphic charts of both shallow-water and basinal index species for the Barremian–Aptian transition mostly derive from the Vocontian domain and its margins.

Urgonian platforms are considered as valid outcrop analogues of Middle East oil-producing carbonate reservoirs. Uncertainties in predicting subsurface sedimentary and petrophysical heterogeneities can, therefore, be reduced from their analyses. However, geologists from different “schools of thought” developed contrasting models regarding the chronostratigraphy, the sedimentary model and the overall architecture of the peri-Vocontian Urgonian platforms. As a result, the geological characterisation of Urgonian carbonate bodies remains a matter for debate that hampers the harmonisation of a regional platform model.

Based on a thorough historical review, our study explores some of the major debates by providing a complete synthesis of the literature and a re-examination of current concepts. Integration of available data together with the acquisition of new material bring extra evidences and constraints for addressing past controversies. First results document a comparable regional stratigraphic evolution despite a significant syndepositional tectonic activity. Global changes in sedimentary system and possible links to oceanographic changing conditions across the Barremian–Aptian boundary are also examined.

Keywords: Barremian–Aptian, Chronostratigraphy, Outcrop analogue, Synthesis, Urgonian platforms.

Acknowledgements
The authors thank TOTAL for funding this R&D project and giving permission to present this work.

Fossil contourites in chalk (Coniacian – Santonian, Normandy, Paris Basin, France): hydrodynamism and fauna control on architecture and facies heterogeneity distribution

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Keywords: chalk, contourite, contour bottom current, bryozoan mound.

Chalk was often considered as a tabular and homogeneous formation. However, large geometries were observed in North Sea through seismic imaging (e.g. Esmerode *et al*., 2007), and interpreted as contourites and turbidites. Anderskouv *et al.* (2007) observed this type of geometry in Denmark outcrops, where effects of biogenic growth (bryozoan mounds) and slope parallel bottom currents are combined. The observations mainly report some scale outcrops and no seismic scale ones.

Normandy cliffs (northern France) are famous chalk outcrops, up to 100 m high and 100 km length that display exceptional conditions for multiscale observations from detailed thin-section facies to hectometre scale up to kilometre scale panoramas. Geometries, with small wavelengths (60 m) to very large (1 km), were identified. This approach aims to recompose the construction dynamics of these geometries, and the respective influences of hydrodynamism and carbonate production on their evolution. The 3D geometry of these structures is accessed through observations of the basement and cliffs. 3D geometries are mostly asymmetric mound-like features, all elongated along the same directions and separated from each other by more or less deeply incised channels. Channels are all orientated parallel to palaeogeographic lines, demonstrating the predominance of contour currents and asymmetry reveal lateral variations in current velocities.

All geometries (small and large) display recurrent organisation and facies distributions that allow the proposition of a facies/geometry elementary model of these deposits (Figure). 6 steps and associated facies were identified for the building of these geometries: (1) initial aggrading facies, (2) convex-up aggrading facies, (3) condensed interval, (4) high energy and gravitational deposits, (5) prograding infilling facies, and (6) final infilling facies. Steps 1 to 3 correspond to a progressive build-up phase followed by a progressive infilling phase for steps 4 to 6. Bryozoan dominate during the beginning of build-up stage, whereas echinoid dominate in the higher energy environment during the beginning of infilling stage. The lateral variation of velocities supposed by the asymmetry of the geometry is confirmed by the variation is size and abundance of undetermined fragments.

Our results demonstrate a combined influence of biogenic and hydrodynamism. Geometries build-up is starting as small symmetric bryozoan rich mounds, which allows the biogenic stabilisation of sediments. They progressively evolve to asymmetric mounds, with a by-pass flank and a gentler flank where accumulation occurs. Bryozoans are still abundant but more reworked, revealing stronger influence of bottom currents. The transition between the build-up and infilling phases are the coarsest (grainstone), most sorted deposits, associated with hardgrounds, and echinoids, revealing high current velocities with winnowing and by-pass. Within the infilling phase, progressive waning of current is revealed by finer grained (mudstone) and less sorted deposits upward. This study illustrates strong interaction between benthic activity and contour current, and predictive facies model for contourite in chalk.

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Esmerode, E.V., Lykke-Andersen, H., and **Surlyk, F.** (2007) Ridge and valley systems in the Upper Cretaceous chalk of the Danish Basin: contourites in an epeiric sea. *Geological Society, London*, *Special* Publications, **276**, 265-282.

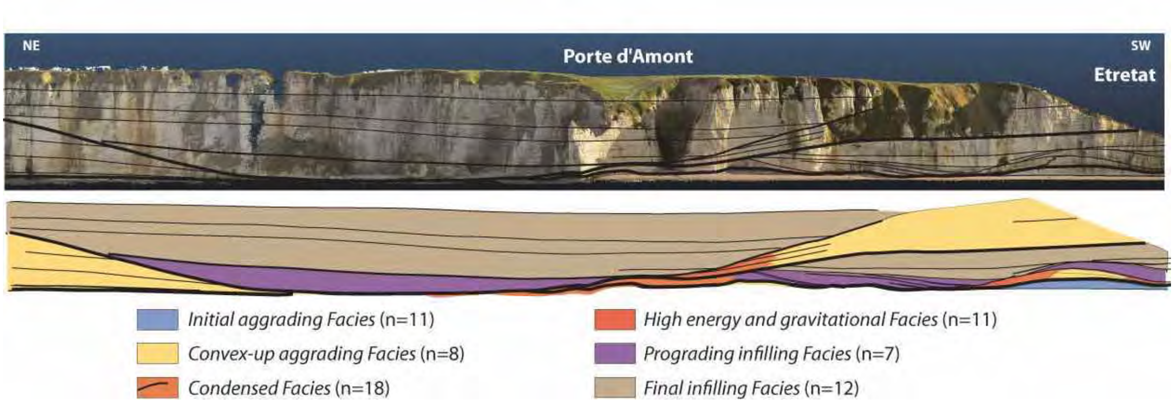

Figure: Line drawing and facies distribution on Etretat outcrop (length: 1 km, height: 70m). See stacking of hectometric and kilometric geometries.

Architecture of the Lutetian marine succession in the Empordà area and distribution of their petrophysical properties: Key points for a geothermal reservoir

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Key words: Empordà, geothermal reservoir, Lutetian, marine carbonates

A well-developed marine interval was sedimented in the south-Pyrenean foreland Ebro basin during the Middle-Upper Eocene, from the Lutetian to the Priabonian (Serra-Kiel et al, 2003a, b). In the Empordà area, this sedimentary record is represented by limestones and marls of the Girona Fm., marls of the Banyoles Fm. and limestones of the Bracons Fm. The Lutetian marine deposits are divided into four sedimentary cycles constituted by several transgressive and regressive systems represented by different depositional environments and containing abundant larger foraminifera, mainly *Alveolina* and *Nummulites* (Serra-Kiel et al, 2003a, b). These Lutetian marine deposits are underlain by the clays, sandstones and conglomerates of the fluvio-alluvial facies of the Pontils Formation, and overlain by Bartonian sandstones (Folgueroles Fm.).

In this contribution we describe the geometries and distribution of the different facies constituting the Lutetian sedimentary cycles, and their boundary units, together with the petrophysical properties of the key lithotypes. These include measurements of porosity and permeability and thermal properties (thermal conductivity and diffusivity). This information is used to evaluate the plausibility of the Girona Fm. rocks as a potential geothermal reservoir in the area.

The results reveal that the sediments of the Girona Fm. are distributed heterogeneously in the study area, with strong lateral facies changes occurring in distances of a few tens of meters. This was probably the result of rapid changes in space and time of environments of deposition, carbonate factory and the input of clastic sediments. Furthermore, the Lutetian marine rocks are highly affected by faulting, mostly normal faults with metric displacements related to the Neogene extension. These structures produce a potential compartmentalization of the carbonate units from a reservoir point of view.

Preliminary petrophysics results show that most of the packstones and grainstones of the Girona Fm. can be attributed to the same lithotype, which is characterized by the higher densities and the lower porosities of the analyzed samples (between 2.60 and 2.68 g/cm^3, and between 1.1 and 3.5%, respectively). The second lithotype is constituted by the marls, sandstones and conglomerates, and show intermediate values of density and porosity (between 2.51 and 2.59 g/cm^3, and between 2.2 and 6.8%, respectively). Finally, the third lithotype, constituted by marly limestones, karstic fillings and Folgueroles formation sandstones, presents the lower densities and higher porosities of the studied rocks (between 2.30 and 2.31 g/cm^3, and between 2.4 and 12.4%, respectively). Furthermore, the third lithotype samples have the lowest thermal conductivity (<1,85 W/mK) of the Girona Fm rocks.

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Miocene to Pliocene reef demise or survival in the Browse Basin, NW Australia

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Keywords: 3D-seismic; Browse Basin; carbonate platforms; Cenozoic; reef demise

The upper Miocene to Pliocene interval of the Browse Basin on the Australian North West Shelf (NWS) comprises a significant paleo-environmental change in its sedimentary record concerning the decay of middle to late Miocene tropical reef build-ups. The triggering factors for this decay (e.g. changes in subsidence, eustasy, current regimes, tectonics, climate change) are still discussed and have not been studied in detail. The foundation of the analyses presented is the investigation of a giant 2D and 3D seismic-reflection data set covering a study area extending over 130.000 km² supported by industry borehole data (logs, cores, and cuttings). SR-Isotope dating, X-Ray diffractometry (XRD) and microfacies analysis of late Miocene to Pliocene sediments were conducted for 19 boreholes and integrated with the seismic data, providing rock evidence on stratigraphic change. RBG-blending horizon slices were generated by spectral decomposition of the 3D seismic volumes. This method allowed the basin-wide mapping of the extent of three large middle Miocene carbonate platforms. Seismic observations towards the Pliocene show a clear landward migration of carbonate build-ups in the eastern part of the basin, while very high subsidence rates seem to have outpaced most reef growth in distal shelf-edge positions. Nevertheless, the Scott Reef and the Seringapatam Reef were able to withstand shelf-edge drowning, which indicates a significant contribution of inversion-related uplift for reef survival. The XRD data document a general decrease in carbonate content and an increase in siliciclastics during the Pliocene. However, rock samples of borehole *Heywood-1* do not follow this trend, documenting as exception the localized continuation of reef growth until recent on a shallow shelfal inversion ridge.

Al Wajh – A modern land-attached carbonate platform in an active rift basin (Red Sea, Saudi Arabia)

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Keywords: Carbonate platform, facies heterogeneities, reservoir analogue

In the previous decades, isolated carbonate platforms such as Great Bahama Bank and Maldives were the target of numerous research projects and investigations. Nowadays, especially Great Bahama Bank is considered to be a well-studied carbonate platform, whose architecture, facies distribution and paragenesis is also widely used in the industry to improve the understanding of similar reservoirs in the subsurface. However, modern land-attached carbonate platforms are only limited studied. With a length of around 75 km and a width of 35 km, Al Wajh carbonate platform in the northern Red Sea represents the largest modern, land-attached and rimmed carbonate platform on our planet. Rim of the platform is shaped by an almost closed coral reef belt with intersecting channels and islands, sitting on the edge of a rotated rift block. Platform interior is characterized by a 40 m deep lagoon with numerous islands and shoals varying in size. Shapes and geometries of both are significantly influenced by wind induced SW currents. The distribution and arrangement of the modern islands and shoals implies a prominent preexisting morphology.

The presented results will give an overview of an ongoing large-scale research project targeting the rift basin carbonate platform, so called Al Wajh platform. Based on an outstanding data base of around 800 km sub-bottom profiler lines, 250 van Veen grab samples and more than 90 cores with length ranging from 15 to 40 m, this investigation focuses on the lateral facies distribution and architecture of the platform. First results indicate an expected prominent Pleistocene surface that is covered by irregular distributed Holocene sediments. In addition prominent morphology of the platform interior is most likely controlled by Pre-Holocene continental sediment discharge during times of sea-level low stand.

Based on the similar dimensions of the Al Wajh platform compared to some of the huge reservoirs of the Middle East, and the wide array of different carbonate depositional settings (e.g. reef rim, lagoon, sand shoals, patch reefs, etc.), outcome of this study will improve the understanding of expectable reservoir heterogeneities in reservoir layers deposited in similar settings.

The origin of remotely sensed circular structures on seafloor of the Weymouth Bay (UK); large-scale, Early Cretaceous brackish-water lacustrine build-ups.

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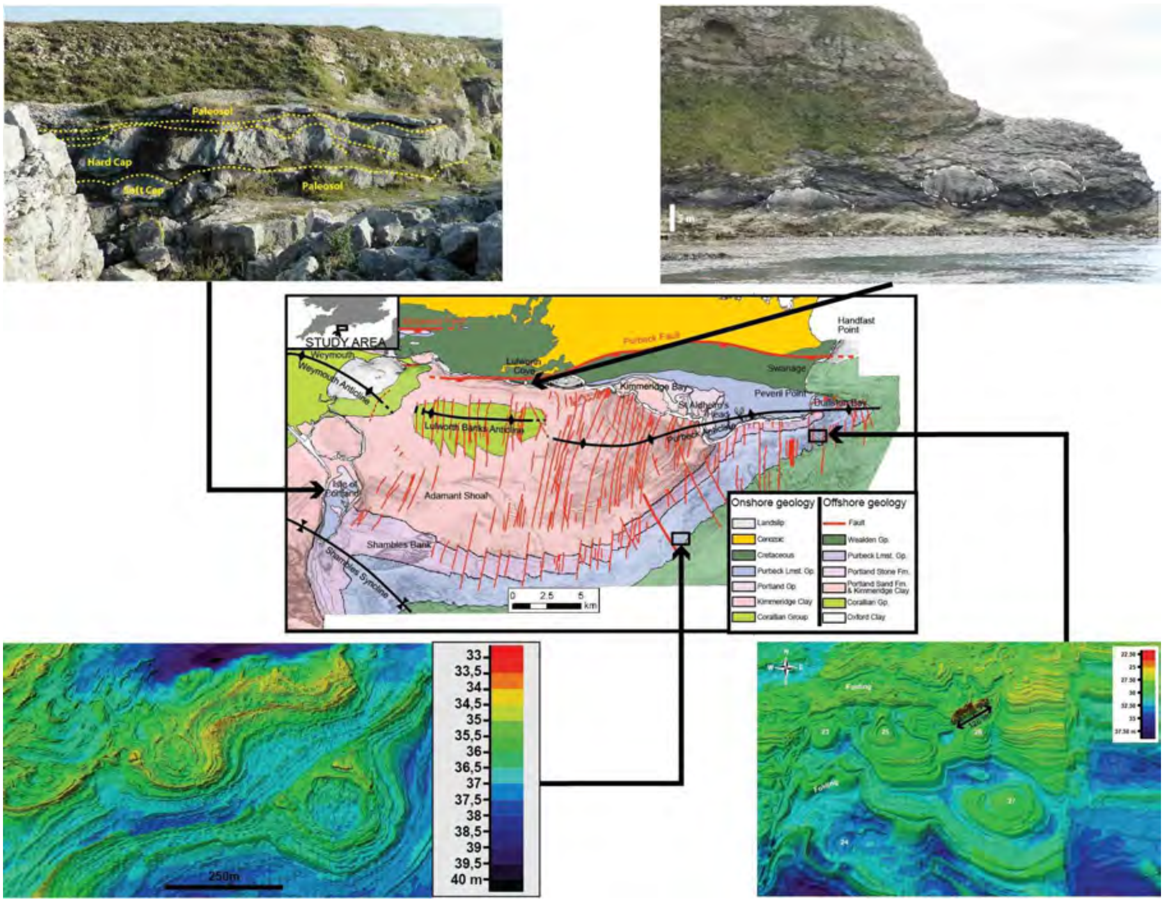
Keywords: Microbialites, Purbeck, MBES, Dorset, Wessex Basin.

Microbialites are classified based on their internal structures and their external shapes. However little is known on the impact of the environment (climate, hydrology and water depth) on mound morphologies and microbial processes on the preserved internal structures, limiting their use as palaeoenvironmental indicators and in sedimentological analyses. This study compares documented microbialite mounds of the lower Purbeck Limestone Group (Late Jurassic) exposed along the south Dorset coast with enigmatic circular structures imaged on Weymouth Bay seafloor by multi-beam echo-sounder (MBES) data. These structures have not been previously identified in this otherwise well-studied region.

Observations from outcrop and remote sensing imaging (lidar), coupled with petrography, are used to differentiate microbialite mounds and bedded inter-mound packstone-grainstone areas. MBES imaging of Weymouth Bay seafloor bathymetry reveals circular structures, formed from truncated, concave-down domes developed in the upper Purbeck Limestone Group (Early Cretaceous). Their stratigraphic level is determined by tracing prominent bedrock units exposed in the shoreline into the offshore areas where they occur in water depths of 30-40 metres. They have not yet been sampled but their morphology and context indicate they are most likely to be large carbonate mounds up to 150m across.

The onshore exposed microbialite mounds occur within bedded, inter-mound peloidal packstones-grainstones located in three metre-scale lacustrine cycles separated by palaeosols. The microbialite mounds reveal complex and irregular shapes due to their association with tree remains and to inferred lake level fluctuations. Interpretation of high-resolution, ground-based lidar data enables a quantitative description of the morphology of the mounds and their relationship with tree remains and inter-mound facies. In cross-section, microbialite mounds commonly show tabular-shaped small mounds (up to 50cm high and 1m across) that constitute large, more complex-shaped mounds (up to 4m high and 18m across). In plan-view these microbialite mounds have a circular shape up to 20m in diameter. The mounds are principally constructed by well-preserved filamentous microbes forming thrombolite framestones. Within the framework, accumulations of peloids, intraclasts, spherulites, molluscans and ostracods, together with thrombolites, are lithified by early fringing fibrous cements. The inter-mound facies shows horizontal stratification that onlap and interfinger with the mounds suggesting that the deposition occurred contemporaneously with the thrombolite framework.

The circular structures imaged on Weymouth Bay seafloor show many morphological similarities with lacustrine carbonate mounds. Although the lithologies are still unknown, the circular structures represent angled slices through concave-down domes that are onlapped by surrounding strata. Seafloor mapping correlates the mounds with the type locality of the Durlston Formation but no mounded geometries are visible in the extensive onshore outcrops. Alternatively, possible origins as salt diapirs and periclinal folds are discounted on the basis of morphological and geological context. Like the mounds of the lower Purbeck limestones, the seafloor mounds occur as a depth restricted palaeoshoreline-parallel band. Similarly, the lower Purbeck mounds are interpreted to have formed in brackish-water environments (prior to overlying evaporites) which have also been interpreted for the Durlston Formation of Dorset on the basis of its preserved molluscs.



Microbialite mounds as seen in the field and circular structures as seen on MBES survey.

Numerical forward modelling of a peritidal carbonate system: autocyclic behaviour, sensitivity dependence and complexity

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Key words: numerical modelling, autocycles, spatial self-organization

Abstract

It is well established that cyclical shallow-marine carbonate strata can form due to both allogenic and autogenic processes, yet most outcrop interpretations still tend to focus on external forcing by relative sea-level oscillation as the predominant control on high-frequency sequence formation. Given this, it is worth revisiting the Ginsberg's model of carbonate autocycle development. CarboCAT is a latest-generation 3D numerical stratigraphic forward model that can explore the dynamics of how high-frequency sequences form in carbonate platform interiors by shoreline progradation and island migration that can generate complex, heterogeneous, lateral-discontinous sequence and facies distributions. CarboCAT is an entirely deterministic 3D forward model of carbonate platform depositional processes. Carbonate production rate is water-depth and wave-energy dependent and produced facies distribution is also controlled by cellular-automata that represents spatial competition between different carbonate factories. Sediment transport occurs due to regional onshore flux, with local variation caused by wave refraction, and small-scale offshore downslope diffusional transport.

Two separate sensitivity analysis has been run. The first less complex set focus on how initial conditions and basic parameters determine how sediment flux, rate of sediment production and rate of accommodation interact to control high-frequency sequence thickness. For example, increasing sediment transport rate reduces the duration and thickness of each parasequence, as less accommodation is created over the time required for shoreline or island to prograde. This has been demonstrated previously, yet is rarely if ever considered in interpretations of platform interior strata. The second more complex set of models explores how various non-linear behaviour and stratal heterogeneity arises from more complex process interactions. For example, cellular automata produces patchy strata distribution, which can be smoothed by local downslope diffusion depending on surface reliefs. Wave refraction causes flexure of sediment transport pathway towards those bathymetric highs or the shoreline where flows decelerate and lose transport capacities. In summary, these results demonstrate how autogenic processes can control stacking patterns in platform interior strata, and suggest more realistic understanding, interpretation and prediction of heterogeneity should include consideration of these autogenic processes.

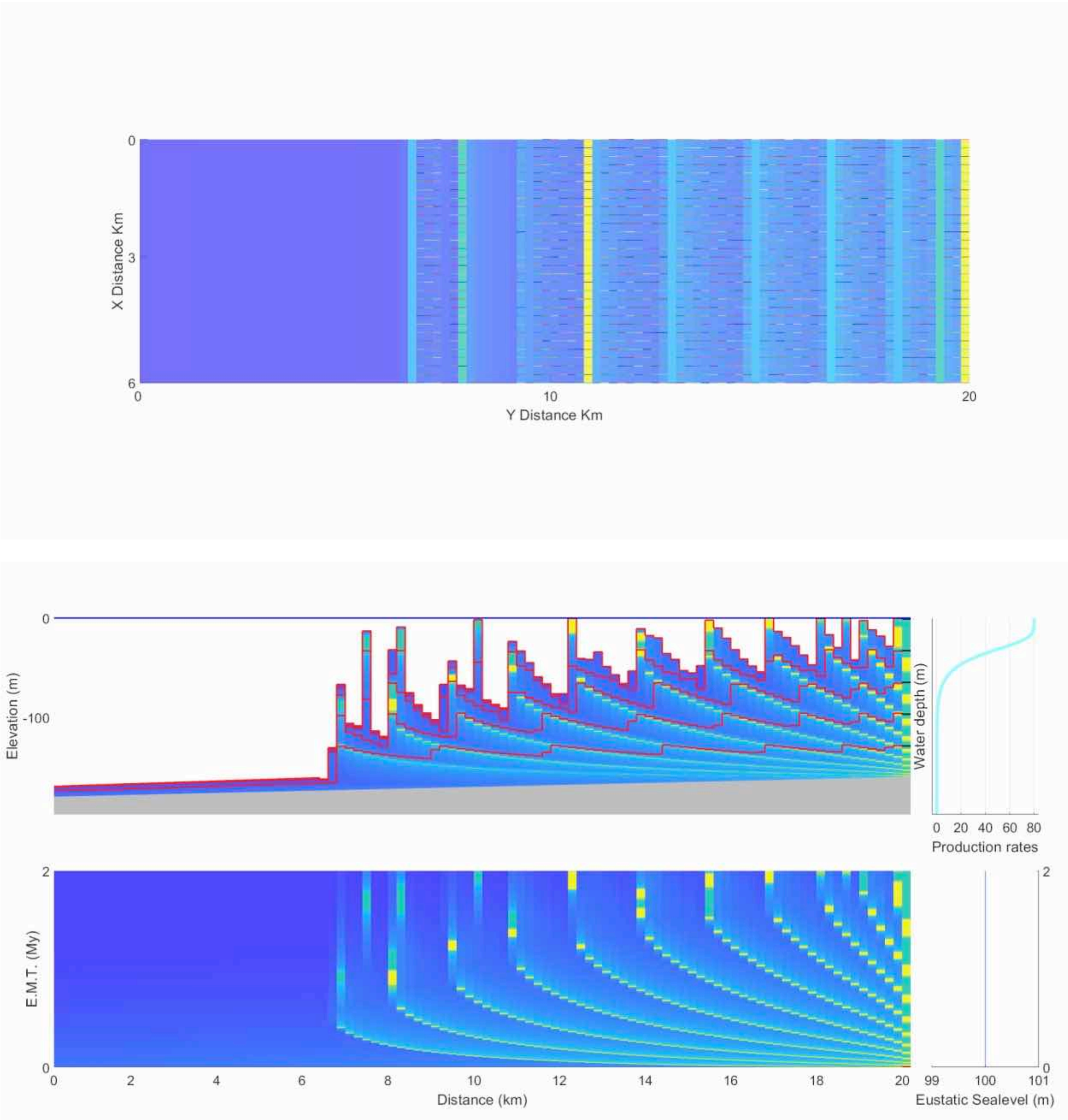

Figure: Map view and cross section of autocycles generated in a simple straight transport model run. Strata are coded in terms of depositional water depth.

Stratigraphic inverse modeling of carbonate platform based on global optimization

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Abstract: There are two major categories of methods that are used to build 3D facies models, geostatistical simulation and geological process-based modeling such as stratigraphic forward modeling (SFM). Geostatistical simulation is a dominant modeling method in oil and gas reservoir characterization and its main advantage is conditional simulation, that is, the simulated model honors observed dataset such as drilled well and/or seismic data. The process-based modeling, though better in describing realistic geology such as 3D facies models, has been lack of a method which can condition the modeling result with observed dataset. To overcome this difficulty, one of key techniques needed is how to compare quantitatively the modeling results with the observed dataset. For instance, how do we quantify the difference of sedimentary facies successions between two measured outcrop sections or drilled wells. It is stratigraphic inverse modeling (SIM) that can integrate two advantages that the model can describe more realistic geology, whereas the modelled results can honor the observed data.

A stratigraphic inverse modeling system consists of three major techniques: 1) a stratigraphic forward modeling that simulates strata of a carbonate platform based on geological processes such as tectonic subsidence, sea level change, crust flexture, potential and kinetic energy in a carbonate platform, carbonate production, erosion and transport, sedimentation, and so on. 2) a comparative technique that quantifies the difference of sedimentary facies successions between modelled results and measured outcrop sections or drilled wells. 3) an inverse technique that reduces the difference between modelled result and observed data during iterative simulations until the difference becomes zero or is minimized to an acceptable predefined criteria. When a good enough match between modelled result and observed data has been reached, it is said that stratigraphic inverse modeling has converged, and the modelled result can be used as a prediction for un-observed values, or related properties, and its uncertainty can be further analysed statistically based on multiple modelled results. For instance, an inversed 3D facies model that honors drilled well data can be used to predict porosity and permeability in oil and gas reservoirs.

In our current study, SIM has been successfully applied to synthetic datasets, and has also achieved good results as applied to a real example in modeling the western margin of Great Bahama Bank from 5.3 Ma to present. In the first synthetic example, 5 pseudo wells of facies successions (1 in interior platform, 2 in platform margin, 1 in slope, and 1 in basin areas) were taken as observed dataset from a modeling result of a steep-sloped carbonate platform by our stratigraphic forward modeling. After inversion, 12 parameters of SFM, related to subsidence, carbonate production, sealevel change, and potential and kinetic energy have been recovered correctly while the inverted model matches 5 pseudo well data at their locations. A similar workflow was applied to a synthetic dataset of a carbonate ramp, and similar reasonable result was achieved. In Bahama example, 4 well data, Unda, Clino, ODP-1005 and ODP-1007 along with a 2D seismic profile have been used as dataset, subsidence rates, a sea level curve of 3 cosine functions, carbonate production, potential and kinetic energy parameters are used in inversion, with an initial topography interpreted and modified from seismic data. A very reasonable inversion result, the best matched with data so far as we know, has been achieved as shown in Fig. 1, though a further improvement is needed to make the SIM technique more practical. The synthetic and real inversion examples show it is possible that partial data can be used to recover more complete info of a carbonate platform system.

Key words: carbonate facies model, geostatistical modeling, process-based modeling, model predictability, stratigraphic inverse modeling

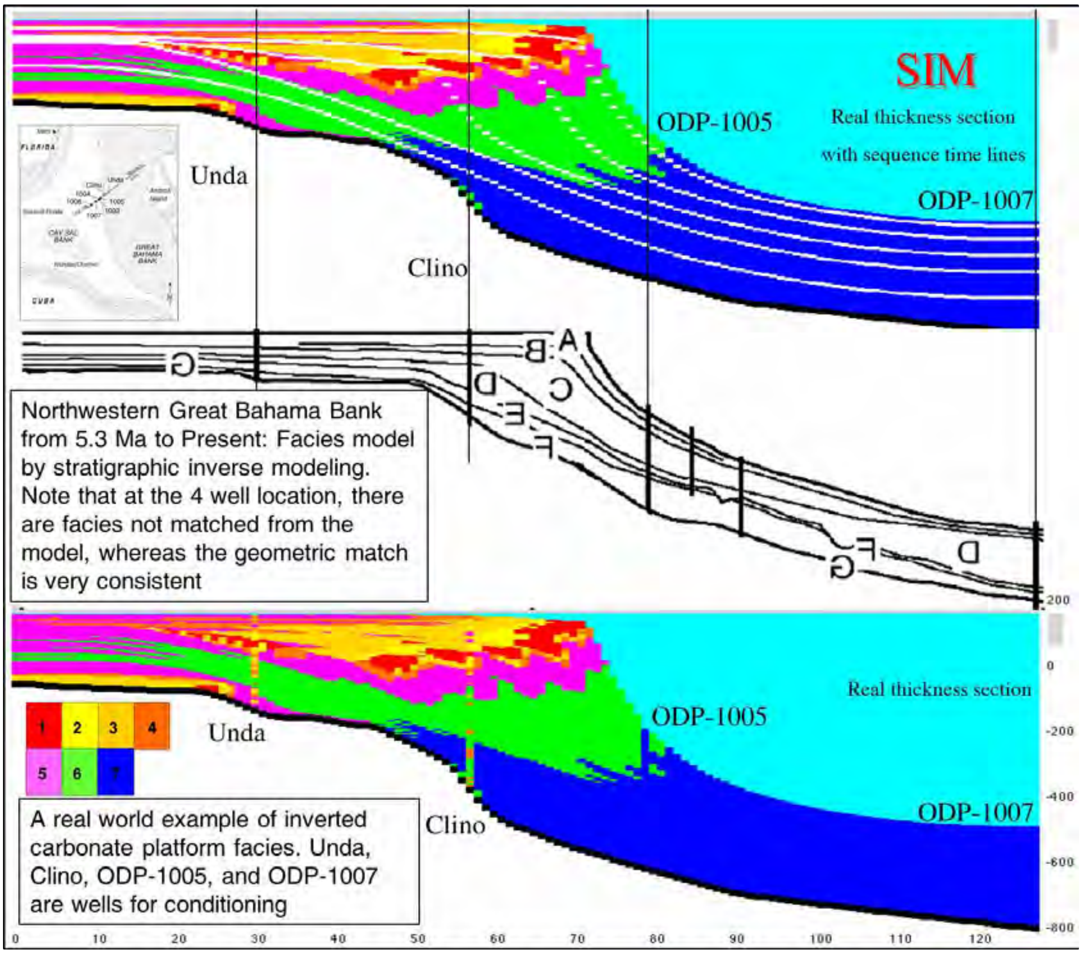

Figure 1 Stratigraphic inverse modeling result of western margin of Great Bahama Bank (in meters) compared to seismic data (in twt time) noting 6 sequences division

3D scale Geo-sedimentary models of coral reefs: Santa Pola Messinian atoll (western Mediterranean)

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Key words: 3D Geomodel, Carbonate sedimentology, Geoheritage, outreach, Messinian Salinity Crisis

The Messinian coral reef (atoll type) of Santa Pola cape (SE Spain) is one of the most relevant Geosites from the Neogene record of southeastern Spain (Esteban et al., 1996; Corbí et al., 2018). It is located in the northern Bajo Segura basin, a western Mediterranean Neogene basin of the eastern Betic Cordillera, where is exceptionally recorded the Messinian Salinity Crisis. The current exhumed relief exhibits the original morphology of the atoll providing excellent outcrops where the three-dimensional geometry of the different sedimentary environments can be recognized (lagoon, backreef, reef flat, reef front dominated by *Porites* showing morphological zoning, and with regularly spaced channels and buttresses; *Halimeda* fans and reef slope). In this contribution, we present different 3D scale Geomodels of this relevant Messinian site, which can be an essential key not only to teach geoscience at different educational levels, but also to promote and disseminate to general public the geoscientific and didactic value of a Messinian coral reef and its distinctive sedimentary environments and sub-environments.

The 3D scale Geomodels (20 x 20 cm each one) has been developed at two different scales: the entire atoll structure (Fig. 1A) and the best representative outcrop, which has been identified combining the analysis of the digital elevation model (hydrography network) and directly observational field data (Fig. 1B). In this outcrop a high-resolution 3D model has been developed with the Structure from Motion photogrammetric technique processing about 1000 high-resolution images carried out with Remotely Piloted Aircraft Systems (Drone Phantom DJI 3 Advanced).

Two different 3d models have been implemented for each selected scale (4 models in total, 20 x 20 cm): the first, reproducing the current relief (small mountain above the sea level); and the second, an artistically and geoscientific recreation attempting to simulate the sedimentary environments during the Messinian formation process (Fig. 1C-F). The process of geomodelization includes the following steps: 1) obtain the digital elevation model (DEM) dataset for the study area; 2) print the 3d models with a 3D printer Vulcanus Max 40, FDM, PLA material; 3) generation of plaster molds and silicone counter molds; 4) remove and polish the Pliocene and Quaternary fillings and covers adding plaster in the canyons and gullies; 5) generation (remodeling manually with plaster textures and reliefs) of the geomorphic features, actually eroded or buried under more recent sediments (principally patch reefs, and back-reef zone; see Fig. 1D-

F); 6) coloring the scale models emulating similar sedimentary environments represented (original geomorphic structures); 7) covering (without pasted) the 3D model with blue epoxy resin in order to simulate the marine environment; and 8) elaboration of an infographic transparent sheet signaling the different sedimentary parts of the coral reef (front view) and the geological cross section (lateral view).

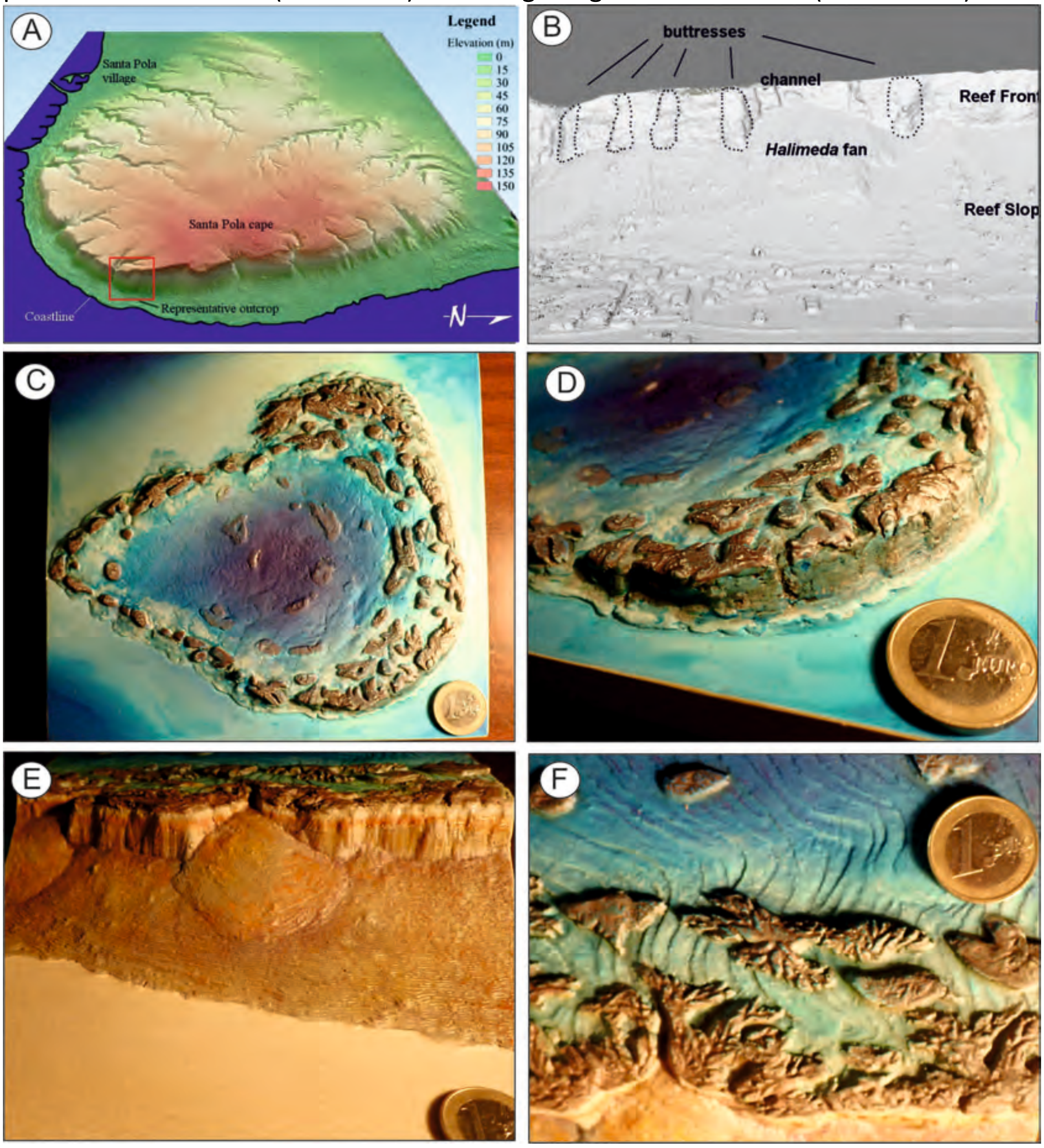

Fig. 1. A: Digital Elevation Model of the Santa Pola coral reef. B: High resolution 3D model of the representative outcrop (Structure From Motion technique). C-: 3D scale geosedimentary models of the entire structure (C-D) and the best representative outcrop (E-F). In all images coin for scale.

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UAV-based photogrammetric acquisition along large-scale cliffs: novel workflow for seismic-scale 3D outcrop studies

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Key words: Large scale cliffs, Virtual outcrops, 3D models, photogrammetry, UAV

Exponential development in the domain of commercial UAV in the past few years has led to the popularization of techniques such as photogrammetry. In field geology, relatively light drone-based photogrammetry has progressively substituted heavy LIDAR acquisition techniques to generate 3D outcrops models. Rather than replacing field geology, such technique provides an excellent complementary platform to plan field campaigns, integrate field data and observations as well as share results. Drone-based photogrammetry also brings many advantages in terms geometrical observation thanks to its easy access in otherwise inaccessible areas, broader range of viewing angles, and reduced cost. Following this trend, software solutions are being rapidly developed providing fit-for-purpose quantitative and qualitative tools improving structural, stratigraphic and sedimentological interpretations of photogrammetric geological outcrop models. In recent years, a number of UAV flight planning software and mobile applications have been developed to help pilots to automatically acquire photogrammetric data using drones. However, acquisition along large-scale steep cliffs still requires time consuming preparation and hand-driven acquisition, resulting in un-optimized data collection largely influenced by the drone pilot and the complexity of the outcrop. For this reason, high resolution 3D outcrop models are therefore often limited to small and medium size objects (ten's of meter height to kilometer long). Having a key interest in large, seismic-scale outcropping carbonate systems, we developed a novel workflow integrating self-developed and commercial software solutions leading to automatized, more efficient and accurate UAV-based photogrammetric data collection along large scale cliffs. The method has successfully been used to model world-class carbonate systems on outcrops in various locations in North Africa, Europe and Middle East. Main challenges are now pushing towards computer and software capabilities to process, interpret and valorize the large amount of collected data. Key milestones, work flows and challenges will be discussed using examples of ongoing large-scale carbonate outcrop studies.

3D Carbonate and Mixed Outcrop Analogues: novel acquisition methodologies and application to petroleum and water reservoirs

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Key words: DOM, data integration, reservoir parametrization

3D high-resolution geological models integrating exposed and subsurface stratigraphy are of paramount importance for water, oil and gas analogue reservoir studies. This is especially true in carbonate sequences where the controls on rock proprieties distribution are highly dependent on post-depositional processes. Digital outcrop models (DOM) allow the extraction and integration of structural and stratigraphic information as well as karst features at mm scale resolution. The integration of stratigraphic information derived from DOM with subsurface geological and geophysical data fills a gap in the flux for reservoir models construction. This work presents a method for acquisition, processing an interpretation of 3D high-resolution DOMs applied to three different case studies with distinct age, facies and topographic settings. Studied sections include quaternary tufas and collapsed caves in Potiguar Basin, exposed in Brazilian NE semi-arid region; and Middle to Upper Jurassic carbonate and mixed successions from Brenha Group and Amaral Formation in Lusitanian Basin, at Portuguese west coast.

DOM construction

Structure from Motion – Multi-View Stereo (SfM-MVS) algorithms allows the construction of 3D dense point clouds based on overlapping photographs taken from different positions on the same target. Typical geological features for 3D analogue reservoir modelling, such as external geometry, lateral continuity, and complex fracture network are exposed on vertical escarpments. Photograph acquisition in such setting is favoured by the use of Unmanned Aerial Vehicles (UAV). The proposed method includes the production of a high-resolution Digital Elevation Model (2 cm/pixel) and a DOM (0.5 cm/pixel). The use of the SfM algorithms aligns photographs, and 3D dense point clouds are calculated using the MVS algorithms. A decimated mesh surface is created based on the 3D point cloud resulting in a textured mesh with few mm spatial resolution. Internal geometry is obtained by 2D and 3D GPR, ERT and Seismic data which are integrated into 3D to construct reservoir models from cm to km scale.

Interpretation and sharing

DOMs has been the integrating platform to support the interpretation of data acquired from these methods with the support of facies analysis and thin sections from vertical section description, spectral gamma-ray log, biostratigraphic analysis, calcimetry, and X-ray diffraction data. Reservoir zonation and parametrisation are made through high-resolution sequence stratigraphic analysis together with mapping of karst, structural, and depositional features, for example (Figs. 1 and 2). Outcrops and DOMs can be used within the scope of scientific research projects and field-trip training program for academia or industry.

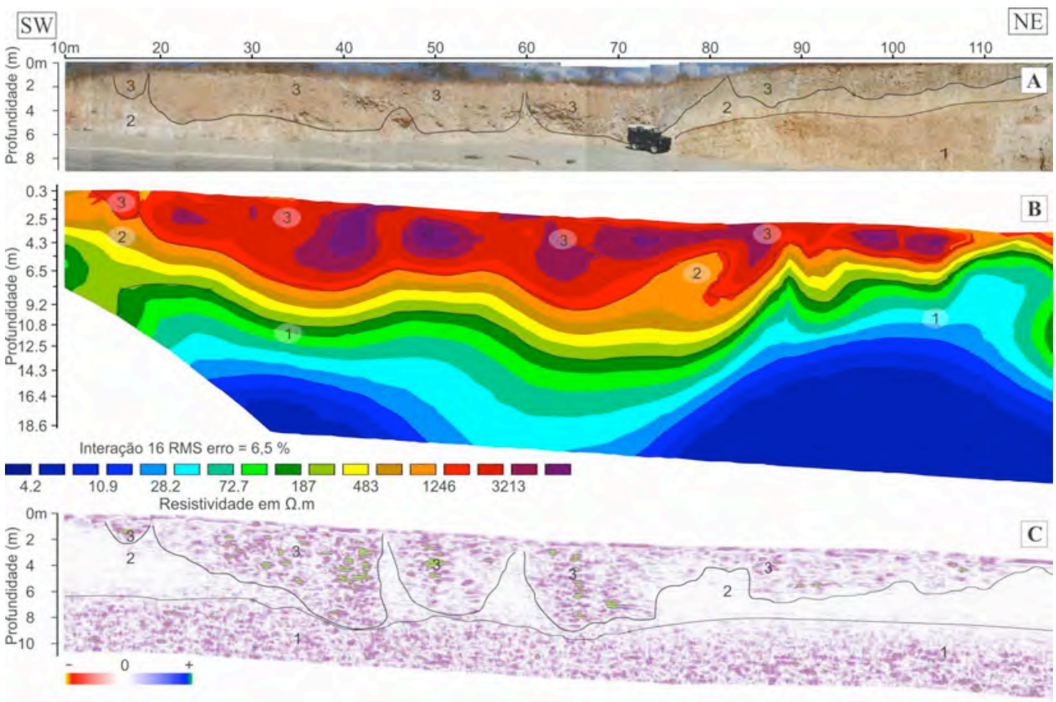

Fig. 1: Example of integration between outcrop and subsurface geology using ETR and GPR data.

Fig. 2: 3D Mapping of reservoir bodies for geocellular model construction.

16th Bathurst Meeting

Abstracts Volume

Posters

Theme 2: Diagenesis and Geochemical Markers

Carbonate Precipitation/Dissolution, Diagenetic Processes and Products
Dolomitization
Soils and Karst
Geochemical Markers and Dating

P-59 to P-130

Pseudospar

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Lithification of carbonate mud involves a complete reorganization of the original material and pore space. According to Folk's seminal paper (1965) the fine-grained matrix in limestones is arbitrarily classified according to its grain size, with grains between less than 1 and 4 µm called "micrite", from 5 to 30 µm named "microspar", and crystals larger than 30 up to a few hundred µm called "pseudospar". In this paper only pseudospar that is formed by neomorphism of carbonate mud is considered, not the one that results from inversion of organic skeletons. Whereas micrite and microspar can easily be recognised both in thin section and SEM pseudospar is often difficult to distinguish from pore-filling spar because with increasing crystal size it becomes more and more translucent, and on the other hand true void-filling spar can exhibit grain sizes down to microspar size. According to Folk both microspar and eventually pseudospar are the result of progressive aggrading (coalescive) neomorphism of a former micrite, a process where smaller grains are cannibalized by larger ones. In the 90s of the last century it has been documented that most microspar crystals in fact represent small low-Mg calcite cements which precipitated in porous aragonite-dominated mud in very shallow burial conditions rather than being the result of aggrading neomorphism as supposed by Folk. Pseudospar, however, has received very little attention. In this paper results from thin sections and SEM samples from Ordovician pseudosparitic bryozoan limestones are presented. According to the data the grain sizes of the pseudospar crystals depend mostly on the primary interparticle porosity. Some pseudospar crystals cross the boundary between originally empty pore space and sediment indicating that at least in this example, they represent cement crystals that precipitated very early in an extremely porous sediment, and are not the result of any sort of recrystallisation.

Magnesium Zonation in Calcite Microcrystals: Influencing Water-Wet Conditions in a Microporous Depositional Chalk (Tor Formation, Norwegian North Sea)

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Keywords: Diagenesis, Mg/Ca, Microporosity, Scanning Electron Microscopy, Wettability

Microporosity is common in conventional and unconventional carbonate reservoirs and can host significant hydrocarbon reserves. Microporosity can complicate reservoir recovery efficiency, cause inaccurate hydrocarbon reserves estimates, and produce high-water saturation measurements on wireline logs. Microcrystal growth reduces pore throat size, and therefore permeability, by physically obstructing pores and altering their geometries. Microcrystal growth also increases the chemical interaction between mineral and fluid, altering key reservoir properties (e.g., wettability).

To study this microcrystal growth, core samples were taken from the Tor Formation (Late Campanian to Maastrichtian deep-water depositional chalk), Norwegian North Sea. A chalk was chosen because it is more thermodynamically stable than aragonite or high-Mg calcite, and was deposited in a deep marine setting and therefore likely to have a diagenetic history lacking meteoric diagenesis or subaerial erosion. Bulk geochemical analyses show a 2‰ decrease in microcrystal $\delta^{18}O$ with increasing depth as well as a six-percentage-point decrease in porosity. These trends imply progressive calcite cementation with burial. Scanning electron microscopy and energy dispersive x-ray spectroscopy were used to explore for chemical zonation in calcite microcrystals that might document this burial cementation model. Microcrystals ranged in size from 1 to 10 microns and magnesium-zonation in many microcrystals was evident. Some samples exhibited large core-to-rim variation (22.2 to 5.7 mmol/mol Mg/Ca), while others less (9.7 to 7.6 mmol/mol Mg/Ca). Magnitude and style of zonation was correlated with crystal diameter (Figure 1). Large crystals, 5-10 microns in diameter, tended to have low Mg/Ca content cores (0-7 mmol/mol) and a higher Mg/Ca rims (6.6-25.2 mmol/mol). Crystals, 1-5 microns in diameter, tended to have higher Mg/Ca cores (6-34 mmol/mol) and either no rim or lower Mg/Ca rims (3.3-11.8 mmol/mol). This suggests that diagenesis involved multi-stage precipitation of microcrystals creating abrupt Mg/Ca zonation in the microcrystals. Current work seeks to document magnesium zonation in complex depositional and diagenetic environments.

These data support the progressive burial cementation model for occlusion of microporosity by calcite microcrystals. In addition, they show that cementation occurred in at least three stages. The data also show that microcrystals surfaces may have different Mg/Ca than microcrystal cores, which may affect reservoir wettability. Understanding the chemical zonation and surface chemistry of these microcrystals will enable more effective ionic water calculations for water flooding and other enhanced oil recovery methods in the Tor Fm and other similar reservoirs.

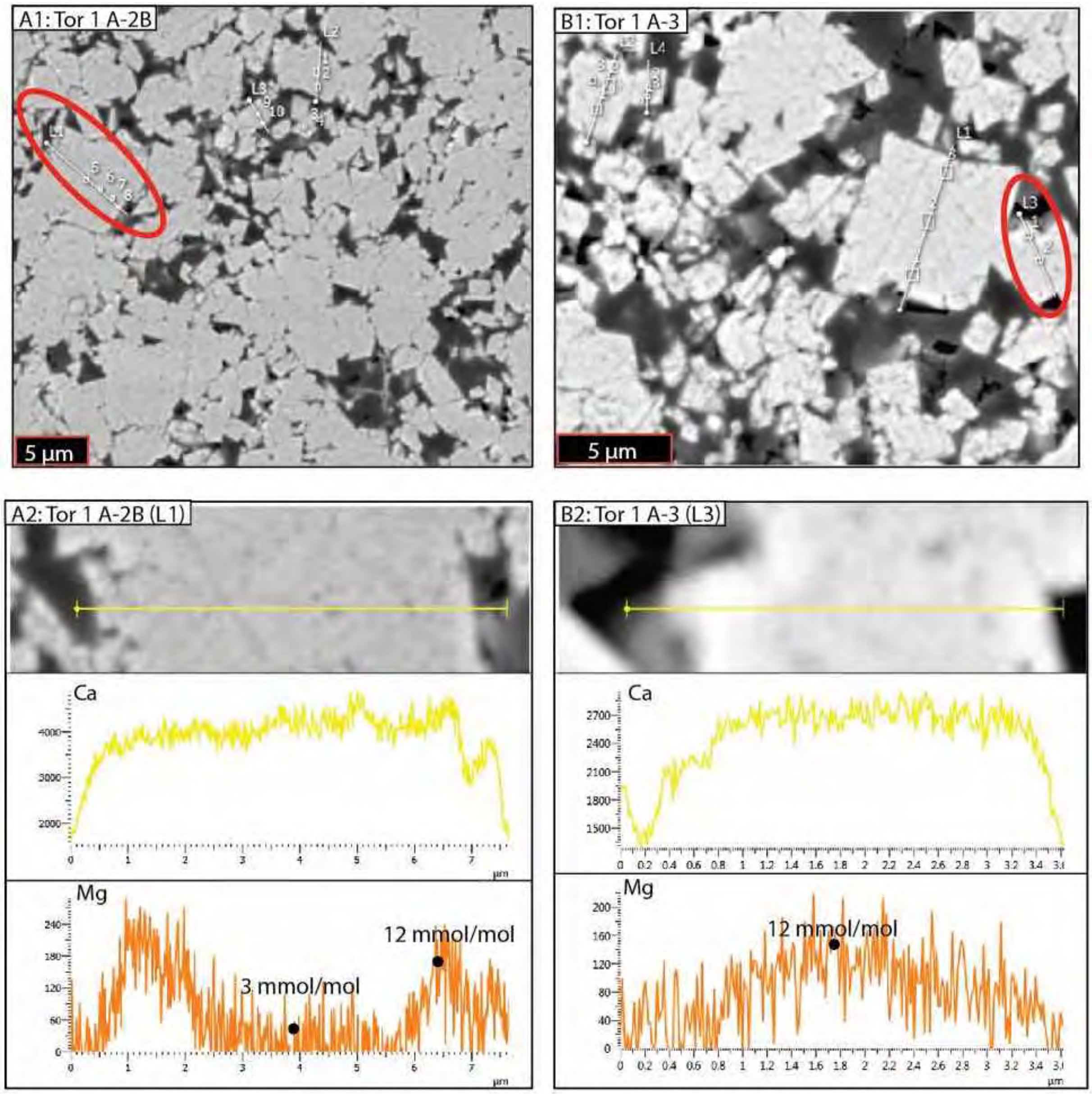

Figure 1. A1) SEM Image showing line-scan location for site A-2B on sample Tor1. A2) Close-up view of Tor1 SEM image slowing line-scan location and plots of Ca and Mg intensities along the line-scan. Quantitative point analyses are also included. This large crystal (7 µm diameter) showed zonation: low Mg/Ca core (3 mmol/mol) and higher Mg/Ca rim (12 mmol/mol). B) Similar figures for site A-3 on sample Tor1 that show a small microcrystal (3.1 µm diameter) with a higher Mg/Ca core (12 mmol/mol) and no rim.

imaging the interface between organic molecules and carbonate precipitants in lab and in nature to better understand their relationship

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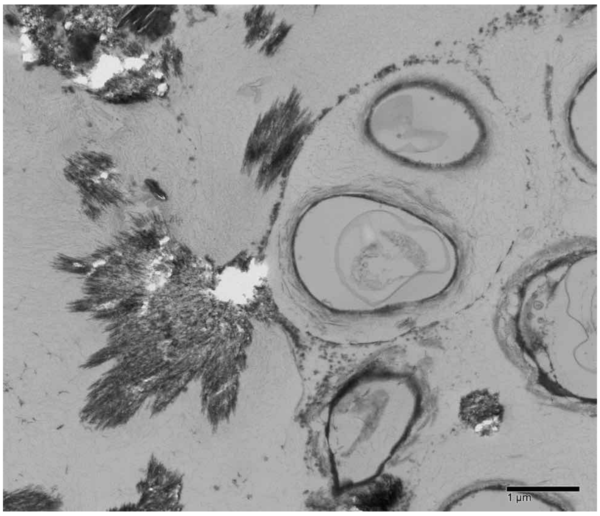
algal, carbonates, cyanobacteria, microbial, organics

The details of the mechanisms by which microbial activity and carbonate mineral precipitation are not yet clearly documented; however, the association of organic molecules and microbial structures with authigenic carbonates is clear and cannot be ignored. The goal of this project is to better explain the relationship between organic compounds and many carbonate precipitates found in nature by documenting the organic to carbonate mineral interface with scanning electron microscopes (SEM) and transmission electron microscopes (TEM). Samples imaged include specimens collected in the field and precipitates created under controlled conditions in the lab.

The interface between cyanobacteria and aragonite precipitates was imaged in samples of a microbial mat collected in December 2009 from a salt pond near Lagoa Vermelha, in Brazil. The sample was originally collected and kept alive as a teaching aid. Calcification has increased as the mat aged. TEM images show aragonite crystals appear to have nucleated from a single spot on the cell wall or within the mucilaginous sheath of cyanobacteria in the algal mat.

To test the hypothesis that carbonate mineral growth is induced by organic molecules that act as nucleation sites for mineral growth, precipitation experiments were conducted by growing carbonate crystals along with organic molecules. Palmitic and stearic acid were the organic molecules chosen because they are abundant in biofilms. The experiments were conducted in 18-, 24-, and 48-hour sets. In SEM these organic molecules image as spheroidal structures that are visibly different from smooth calcite crystal faces. EDX and XRD analysis of the amorphous spheroidal structures in the precipitation experiments prove the structures show no calcium and suggest that they are primarily organic. TEM analysis of these precipitates shows the carbonate minerals using the palmitic and stearic acid as substrates for nucleation and the organic molecules appear to be incorporated into the crystal structure. Though the mechanism is still poorly understood, the association between organic material and carbonate minerals is better established by visual documentation.



TEM image shows the aragonitic crystals nucleating on the mucilaginous sheath surrounding cellular walls of cyanobacteria the microbial mat from Brazil.

Variations in modern carbonate hardground formation in Abu Dhabi in relation to associated biogeochemical drivers

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Keywords: authigenic; biogeochemistry; carbonates; paleoenvironment; sabkha

Authigenic carbonates, in the form of concretions and hardgrounds, are common early-diagenetic features of sedimentary rocks and have been linked directly to the global carbon, sulphur, and iron cycles. Authigenic minerals have been identified as important indicators of palaeoenvironmental conditions, however interpretation of these palaeo-proxies is challenging as we lack a comprehensive understanding of the direct drivers of authigenic carbonate precipitation. This study focusses on evaluating the physical variability of cements and associated environmental and biogeochemical processes that control hardground formation, through the analysis of porewater chemical profiles and shallow sediment cores on the Abu Dhabi coast.

The sea floor of the modern Arabian Gulf is characterised by extensive areas of recently-lithified carbonate sediments. Previous work has characterised a laterally-extensive marine hardground comprising bioclastic grains cemented by calcium carbonate. Active precipitation of acicular aragonite and high Mg-calcite cements forms a variety of firmgrounds and hardgrounds in the marine realm. Variations in cement textures and crystal morphologies are observed between study sites in the intertidal-supratidal sabkha and subtidal-intertidal lagoon. The lagoon firmgrounds are typically cemented with a relatively thin isopachous fringe of bladed to equant crystals, whilst cements in the intertidal zone downdip of the sabkha display a relatively thick isopachous fringe of aragonite needles. Environmental controls of early cementation are investigated in relation to the porewater chemistry profiles at several contrasting sites both above and below these hardgrounds.

Hardgrounds at all sites occur between 10 and 50 cm below the sediment-water interface and are associated with narrow intervals of elevated porewater pH where they are believed to be actively forming. Sediments above and below the hardgrounds in the intertidal zone show sharp contrasts in redox state, indicating that the hardgrounds form an effective barrier to fluid exchange, possibly promoting the development of underlying anaerobic conditions that may further drive hardground cementation. Porewaters at both sites are undersaturated with respect to gypsum and supersaturated with respect to dolomite. The lagoon porewaters are at equilibrium with respect to calcite everywhere, but saturation state increases and pCO_2 drops immediately above and below the firmground. In contrast the sabkha porewaters have higher salinities and display higher levels of calcite supersaturation. Further analyses of porewater chemistry (dissolved ions, nutrients, isotopes, DOC and CH_4 content) accompanied by complete sediment and hardground characterisation will explore how and why growth mechanisms vary between sites, and the environmental controls that may promote or limit modern hardground formation. This will allow development of a process-based model for the formation of these marine hardgrounds to aid the exploration of how the signature of past ocean conditions are recorded in these minerals.

An experimental investigation of the chemical controls on fabric development in $CaCO_3$ systems

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Keywords: carbonate geochemistry; crystal growth; heterogeneous reaction; complex systems

Carbonate sediments are an important archive that allow us to probe deep into Earth's environmental history. Calcite crystals occur in a diversity of forms, and a given morphology may result from slightly different conditions in solution, adding uncertainty to interpretations based on this latter parameter alone. Thus, one important question is whether or not unique morphological or crystallographic properties can be directly interpreted as proxies. Nevertheless, the chemical controls on crystal growth and fabric development are still underconstrained.

Our study aims to address the relationship between molecular scale effects of solution chemistry on the rate and morphological/crystallographic expression of carbonate crystal growth in seeded systems. Dissolved species, variations in saturation state, and chemical inhibitors all produce different perturbations to crystallographically distinct surfaces of growing carbonate minerals [i.e., 1]. These molecular-scale interactions, therefore, should strongly influence crystal growth patterns. Accordingly, experimental investigation has the potential to enhance our understanding on the information recovered from the geological record. In particular, Achaean and Lower Proterozoic carbonates deposited in marine environments, as well as Lower Cretaceous carbonates from the South Atlantic – deposited in continental environments – share, in many circumstances, mineralogical assemblages and crystal morphologies, suggesting that similar physico-chemical controls could have been operative. If correct, this observation implies that such environmental parameters can be generalised and extended to depositional conditions of different geological environments (marine *vs*. continental) and stratigraphic age.

The approach of this study has potential economic application as well, because it can offer additional elements to support geological models and increase the predictability of finding oil-prone carbonate reservoirs. Additionally, it has also implications for reservoir characterisation, in which the understanding of the detailed conditions of crystal growth can help to provide reliable information about the occurrence of specific morphologies that may or may not contribute to the quality of a reservoir. This, in turn, impacts our understating of pore-space geometries and estimations of fluid flow within a reservoir. Finally, and more fundamentally, self-organising patterns such as crystal growth comprise a broader class of phenomena that occur spontaneously in nature as a result of disequilibrium within a medium or between two different media in contact with each other. As a result, patterns of regularity and the emergence of higher order complex hierarchies arise and evolve naturally [i.e., 2, 3, 4]. For this reason, lessons learned from detailed studies on the mechanisms leading to self-organisation might be extended and applied to treat analogous fundamental scientific problems.

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Estimation of calcite dissolution and precipitation rates in a CO_2-rich cave chamber using limestone tablets and SEM imaging techniques

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Key words: Cave atmosphere, corrosion cups, geochemistry, Postojna Cave, 3D-stereoscopy SEM.

Corrosion cups are vertical cup-shape dissolutional features, which have been identified on the floor and flowstones of the Red Hall of Pisani Rov, a dead-end passage in Postojna Cave (Slovenia). Their genesis appears to be related to the extremely high air CO_2 values recorded in this chamber, which can reach up to 9000 ppm during the summer.
To find out whether the formation of the cups is still taking place we have performed dissolution experiments placing limestone tablets in the corrosion cups and observing them using Scanning Electron Microscopy (SEM) before and after being exposed in the cave. Moreover, to identify the main controls on their genesis, we have monitored the temporal and spatial variations of cave's air CO_2, temperature and relative humidity, and episodically analysed the geochemistry of drip waters and water contained within the cups.

Limestone tablets made of a well-cemented pure calci-mudstone with very low porosity and homogeneous composition were embedded in epoxy resin and subsequently polished to obtain a flat surface. The resin was used as a "zero surface" to quantify the evolution of the dissolution. Small scratches on the resin were used as reference points to be able to observe under the SEM the exact same areas before and after exposure to natural conditions in the cave. Tablets were placed in corrosion cups and control sites —a pool located out of the area of high CO_2 and a stalagmite with active calcite precipitation— for periods varying from 6 to 20 weeks, both in the winter and summer seasons.

Dissolution features were already recognisable after only 6 weeks of exposure in the winter season, despite the most active dissolution occurring during the summer months, when the CO_2 values are higher. Using novel 3D-topographic SEM techniques, we have estimated an average dissolution lowering of the rock surface of approximately 10 µm in just 20 weeks. Dissolution proceeds preferentially through the crystal contacts and along scratches produced by the polishing. In control sites we observed precipitation of calcite crystals, strongly controlled by the substrate's crystalline habit. Despite showing net precipitation on a whole year period, the tablet placed on the control stalagmite showed "summer" dissolution features on newly precipitated "winter" crystals, indicating important seasonal fluctuations between calcite precipitation and dissolution regimes at a single drip site.

Our in-situ experiments have confirmed that on-going dissolution is currently forming the corrosion cups in the Red Hall. Cups form below low calcite-saturated drip points and the unusually high CO_2 concentrations in this chamber promote cup formation by causing re-aggression of the cup waters. Our findings on significant calcite-saturation fluctuations due to interactions of drip waters with the cave atmosphere have important implications for the seasonality of formation of speleothems used for paleoclimate studies.

Acknowledgements
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From inorganic aragonite to skeletal calcite: Climate as a major control on carbonate mineralogy during the late Quaternary, NW-Shelf of Australia (NWS)

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Keywords: NW-Australia, distally steepened ramp, Holocene climate

Inorganic precipitation of aragonite is a common process within tropical carbonate environments. Across the NW-Shelf of Australia (NWS) such precipitates formed in high abundance during the last glacial, while present-day sedimentation is dominated by calcitic bioclasts. This contradicts observations from many shallow-water tropical carbonate platforms, where interglacials are linked to the development of ooids, peloids, and aragonite mud while glacials are rich in bioclasts (e.g. Bahamas). Until recently the study of this unusual trend was limited to seafloor sediments. Here we present core data retrieved from the upper 13 meters of IODP Site U1461, which represents the sedimentary evolution of the NWS during the last ~15 thousand years.

Sediments which have formed between 15 and 10 ka BP (i.e. glacial) are predominantly aragonitic. They comprise of small needles, peloids, and ooids. These sediments developed in an arid environment where high alkalinities favored the inorganic precipitation of carbonates. At around 10 ka BP the NWS underwent a substantial change towards a humid climate accompanied by elevated fluvial influx. These changes are expressed as a shelf wide cessation of inorganic aragonite production. Sedimentation is instead dominated by calcitic bioclasts.

This example from NW-Australia displays the importance of climate on the development of shelf carbonates. It further demonstrates that shallow-water aragonite-rich sediments are not necessarily linked to interglacial periods. Instead they depend on high ocean water alkalinity and low fluvial influx. We thereby set precedent for the interpretation of similar carbonate systems found within the geological record.

Aragonite vs. Calcite seas – Aragonite seas in the Furongian (upper Cambrian) of Laurentia

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Keywords: Aragonite, Calcite, Cambrian, Port-au-Port Group.

The aragonite versus calcite sea problem has been debated for decades. One line of evidence for this comes from inorganic oolitic grains and cement morphologies, which may indicate the original mineralogy as being aragonite, high magnesium calcite or low-Mg calcite. However, mineral morphologies can suffer neomorphism due to diagenetic processes and it is very common to observe calcification or dolomitization of original aragonitic particles. In spite of these modifications, signs of the original mineral chemistry can be observed. Aragonite and high magnesium calcite contain higher strontium contents than low Mg calcite due to original crystal structures and it is possible for some of this to be retained even after calcification. This study presents preliminary data from the Port au Port Group, Newfoundland (Laurentia), to investigate original carbonate mineralogy and the possible occurrence of an aragonite sea in the Furongian (upper Cambrian).

The Port au Port Group, western Newfoundland, interpreted as a shallow marine record from the outer part of a stable carbonate platform that surrounded the Iapetus Ocean; it marks the gradual transition from siliciclastic deposition in underlying formation to carbonate sedimentation in the lower Ordovician. Shallowing-upward 'Grand Cycles' consist of muddy subtidal deposits in the lower half-cycle (parted limestones, shale, mudstone and subordinate wackestone) and a upper oolitic half-cycle (oolític grainstones, packstones and laminated carbonates) resulting from vertical and lateral accretion of subtidal, intertidal and supratidal deposits. Stromatolites and thrombolites, as meter scale biostrome and bioherms, occur through both muddy and oolitic half-cycles. Preliminary Electron Probe data shows that strontium content reaches up to 0.20 %wt (2000ppm) in isopachous fibrous fringes. Magnesium oxide is also variable, ranging between 0.37 and 20 wt % in ooid envelopes.

Comparatively, blocky calcite cement reaches up to 0.03 Sr %wt(300 ppm) and 0.73 MgO, showing lower Mg and Sr content.

Petrographic investigation reveals isopachous fibrous and scalenohendric cements surrounding grains, oomouldic porosity in some samples and different degrees of neomorphism in the sedimentary layers. These results suggest aragonite as primary mineralogy of some oolitic grains and marine cements. Additionally, the variability of neomorphism/dolomitization in the studied layers shall indicate inconsistency of sea chemistry and a high frequency oscillation.

A syn-bedform model for banded-radial ooid formation

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Recent work has improved understanding of modern ooid formation, especially in well-studied ooid shoals in the Caribbean. The rock record, however, is dominated by ooids that differ significantly from Caribbean ooids in mineralogy, crystal orientation, and size. In order to use ooids as an effective paleoenvironmental proxy, the mechanistic differences between formation of modern and ancient ooids must be reconciled.

Petrographic and Electron Probe Microanalyzer (EPMA) analyses of exquisitely preserved Late Cambrian ooids show striking optical and geochemical similarities between banded-radial ooid cortices and fringing cements formed during shallow burial. Based on this observation, we propose a model for ancient ooid growth in which, after ooids cross the growth size threshold for suspended transport (~0.5 mm) they are transported in migrating bedforms. While shallowly buried within the bedform, a 10-80-micron thick fringing cement can precipitate around each ooid. Bedform migration periodically disaggregates these weakly cemented ooids and remobilizes them, abrading the outermost generation of cement and rounding the ooid. This abrasion results in the discontinuities that characterize banded-radial ooid fabric. Thus, we suggest ooid cortices originated as fringing cements. Because in this model ooid cortical carbonate minerals are precipitated as cements during rest, rather than during suspension and transport, it minimizes abrasion and creates a consistent pathway to large and giant ooid growth.

Importantly, this model of ooid growth is only relevant in environments in which the shallow subsurface is amenable to appreciable carbonate precipitation, and thus is only valid when shallow-water oxic cycling of organic carbon is low or pore fluid carbonate saturation state, omega (Ω) is high. A compilation of ooid size trends in the geologic past suggests a preponderance of large and giant ooids in periods of low oxygen and/or high omega (Ω) (e.g. Neoproterozoic, early Triassic), highlighting the plausibility of this model.

The syn-bedform model of banded-radial ooid growth invokes an abrasion-precipitation cycle that differs fundamentally from modern carbonate environments and enables the consistent formation of large and giant ooids. Furthermore, this model suggests that banded-radial ooid cortices record the distinct biogeochemical environment of the shallow subsurface and are indicators of diminished shallow-water oxic cycling of organic carbon or high omega (Ω) in the shallow subsurface.

Keywords: ooid, banded-radial, carbonate saturation state, giant ooids

Actualistic seafloor lithification in the lagoon and intertidal sabkha of Abu Dhabi and why we need to re-evaluate hardground models

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Keywords: Actualistic hardgrounds, carbonate cements, intertidal zone, lagoonal and sabkha environment, parasequence

Here we report on modern firm- to hardgrounds from the lagoon and intertidal sabkha of Abu Dhabi (Trucial Coast, Gulf). Based on calibrated radiocarbon ages, seafloor lithification commenced in the Middle to Late Holocene, and proceeds to the present-day. Stratigraphic information and direct field observations document that seafloor lithification takes place in the context of transgressive and regressive relative sea-level change across the extremely low-angle carbonate ramp. Hence, in the terminology of sequence stratigraphy, the lithified intervals qualify as parasequence boundaries. Holocene to Recent high-frequency, low-amplitude relative sea-level change shifts the intertidal zone, as well as the zone of wave base-sea floor interaction, either sea- or landward, and induces the seafloor precipitation of aragonite, calcite, and less commonly, gypsum cements. The focus of this contribution is on latest Holocene to modern firm- to hardground formation resulting from the present-day sea level transgression. The study area offers direct access to a large range of sea-floor lithification processes and products. The morphology of hardground cements, particularly aragonitic fabrics, ranges from needle shaped to complex lath- and sheet-like crystals that have only rarely been described in the literature. Evidence shown here suggests a direct relation between aragonite cement morphology, lithification mechanisms, and degree of environmental restriction. Many of the features documented here are not well-explained by the classical models of hardground formation. Moreover, we document that marine hardgrounds and beachrock lithification are transitional, and the terminology applied is less than precise. Seafloor lithification actively occurs in open, current-swept channels, in low-lying areas between ooid shoals (lithified shrimp burrow networks), in the intertidal zone of the middle lagoon, some cm's beneath the inner lagoonal seafloor (i.e. within the sediment column), and in the intertidal sabkha. Lithification features within the sediment column may qualify as planar concretionary intervals *sensu lato* rather than as firmgrounds, but where the thin sediment cover is hydrodynamically removed, a secondary hardground stage overprints these features (composite surfaces). The modern environments of lithification in the Abu Dhabi lagoon are highly dynamic and constantly shift both parallel and perpendicular with respect to the coastline. The direct field observation allows for the assessment of land-sea spatial and temporal patterns in hardground formation coupled with direct environmental control. Observations shown here are relevant as they: (i) allow for the direct observation of aragonite-cemented seafloors that are poorly-preserved in the fossil record, and (ii) clearly suggest, that many hardground formation models, particularly those with reference to the shallow coastal zone, underestimate the complexity of the processes involved.

Hardened faecal pellets as a significant component in deep water, subtropical marine environments

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Key words

Australian Shelf, early cementation, IODP, peloid, subtropical carbonate

Non-skeletal carbonate grains are classically interpreted to form in shallow, tropical environments. Peloids deposited in deep, subtropical marine conditions are poorly studied. IODP site U1460 on the subtropical Carnarvon Ramp (Southwest Shelf of Australia) recovered a nearly continuous Pliocene to Recent record of outer shelf and slope sediments. The relative abundance of peloids varies between 0 and 67 % of the fine to medium sand fraction, and contributes on average ~ 4% of all grains. The origin and composition of these peloids were investigated using scanning electron microscopy equipped with an energy-dispersive X-ray spectrometer, light microscopy, X-ray diffraction and stable isotope analysis. The peloids have a uniform size and shape and are interpreted as faecal pellets. They are mainly composed of skeletal fragments such as ascidian spicules, planktic foraminifera and sponge spicules in a mud-sized matrix containing abundant coccolith plates. Mineralogical analysis show that the pellets consist of aragonite, calcite and dolomite. The pellets have an identical mineralogical composition and skeletal assemblage as the surrounding matrix, indicating that they have formed in situ. They occur more abundantly during interglacials when the site was situated in deeper waters below the swell wave base, presumably because the pellets were protected from disintegration and therefore available for cementation. The presence of framboidal pyrite within the pellets indicates bacterial sulphate reduction (BSR). The reduction of iron by hydrogen sulphide produced during BSR decreases the pH and likely explains the observed aragonite dissolution. Aragonite dissolution likely increases the alkalinity, and in consequence causes the precipitation of calcite and dolomite cements. It is suggested here that pellets are hardened due to this early cementation close to the seafloor increasing the potential for preservation in the fossil record.

Understanding phreatic diagenesis of mixed carbonate-evaporite systems associated with periods of exposure: hydrochemical evidence from modern groundwaters in the State of Qatar

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Dolomite, evaporites, diagenesis, hydrochemistry

Inter-bedded limestone, dolostone and evaporite sequences are typical of shallow carbonate deposits in arid climates. Their chemical reactivity makes them prone to diagenetic alteration, particularly by groundwater flow during periods of subaerial exposure. Continuous core was recovered to a depth of 130m below ground level at three locations along a North-South transect extending 70km on the crest of the Qatar Arch. Four hydrostratigraphic units are defined from shallow to deep: 1) crystalline calcite and dolomite of the Middle Eocene Dammam Formation interpreted to have been deposited in an open marine environment (upper aquifer), 2) Early Eocene Rus Formation shallow marine carbonate and clay deposits (middle aquifer), 3) crystalline gypsum/anhydrite Rus Evaporite deposited in a marginal marine environment (aquiclude – absent in the north of the country) and 4) Paleocene Upper Um Er Radhuma (UER) dolomitised shallow-marine deposits formed in relatively restricted conditions overlying fining-upward cycles of open marine deposits with clay rich caps (lower aquifer).

Data from nested piezometers allowed estimation of the vertical hydraulic gradient governing flow within and between each aquifer system. In southern Qatar a substantial thickness (20m - ~120m) of crystalline Rus Evaporite confines the underlying relative saline UER, which is fed from recharge in the mountains in eastern Saudi Arabia. This leads to an upward hydraulic gradient and potential localised leakage of waters from the UER to the shallower aquifers. In the north, the absence of the Rus Evaporite means that the different aquifers are in hydraulic continuity and there is a downward groundwater flow driven by meteoric recharge.

Chemical analysis of groundwater samples from different stratigraphic intervals indicates differences between northern and southern Qatar within similar rock types in the same aquifers. Concentrations of Ca^{2+}, Mg^{2+} and SO_4^{2-} in excess of those predicted from linear mixing were determined to understand processes of water-rock interaction within the carbonate-evaporite sequence. Sulphate enrichment within and beneath the Rus Evaporite in the south and in the UER in the north indicates dissolution of gypsum increasing with depth. The deeper UER waters of the southern wells were depleted in Mg^{2+} relative to local seawater. This suggests that along the flow path from the recharge area in Saudi they had already been involved in dolomitisation or had mixed with waters that had already formed dolomite (or dissolved halite). As these waters ascend, they become progressively less depleted in Mg^{+2} and less enriched in Ca^{2+} relative to concentrations predicted from the SO_4^{2-} enrichment. This vertical contrast suggests that the replacement of dolomite by calcite (de-dolomitisation) within the UER, likely driven by the increase in Ca^{2+} from gypsum dissolution. The role and importance of interaction with clays remains to be determined.

The mineralogical contrasts typical of these mixed carbonate-evaporite sequences means they are inherently vulnerable to diagenesis during periods of exposure. The nature and distribution of alteration is critically dependent upon the combination of groundwater chemistry and flow patterns at a range of scales.

Ambiguous origins of major stratigraphic discontinuity in carbonate platform: a case study from the late Barremian Urgonian Provence platform (southeast France)

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Incompleteness of the geological record is an intrinsic characteristic of past carbonate sedimentary systems. Resulting temporal discontinuities are most commonly expressed as remarkable stratigraphic surfaces. Understanding their origins is of key interest for reconstructing depositional processes and platform reservoir architecture.

During the Barremian–Aptian period, carbonate platforms from the Mediterranean Tethys are characterised by a major discontinuity, related to either subaerial or submarine processes. The latter surface marks a regional, conspicuous evolution of the sedimentary system (i.e. lithological and morphological changes along with faunal turnovers) as rudistid platforms disappear. In Provence (southeast France), this discontinuity is found at the top of caprinid-rich beds (Late Barremian *M. sarasini* subzone) of the Urgonian carbonate platform. Based on outcropping sections along a well-exposed platform-to-basin transect, we propose in-depth investigation of its sedimentological, diagenetical and geochemical features.

In distal inner platform settings, a metre-thick dissolution fringe, heavily affecting both low-Mg calcitic and aragonitic rudist shell layers, is observed below the discontinuity. Subsequent post-rudistid deposits (i.e. *Palorbitolina*-rich and echinoderm-dominant facies) infill the resulting voids. Those apparent epikarstic features have repeatedly been used in previous studies to infer a subaerial episode at the top of the caprinid-bearing succession, and hence to support the recognition of a major sequence boundary.

The lack of meteorically-induced cements associated with subtle or missing carbon isotopic negative excursions below the latter surface do not necessarily match the classical subaerial interpretation. As such, submarine erosion and dissolution processes cannot be excluded. In addition, ammonite findings indicate that the hiatus is of very short duration in Provence while longer sedimentary hiatuses occur in comparable, adjacent Urgonian platforms and can encompass several earliest Aptian ammonite zones. In those regions, palaeosoils, mature karsts and incised valleys developed during the latest Barremian–early Aptian *pro parte* transition. Such contrasting observations may fuel an alternative interpretation of the

Provence's discontinuity and, thus, challenge the current regional stratigraphic scenario in the context of the mid-early Aptian Oceanic Anoxic Event 1a.

Keywords: Barremian–Aptian, Discontinuity, OAE 1a, Submarine dissolution, Urgonian platforms.

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SELECTIVE CEMENTATION OF THE GRAVINA CALCARENITE (SOUTHERN ITALY)

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Key words: bioturbation, cementation, diagenesis, dissolution, trace fossil.

The Calcarenite di Gravina is a poorly lithified, heterogeneous Plio-Pleistocene limestone formed in temperate shallow-water setting. Since prehistoric times it is used for constructions, as witnessed by the Sassi, the old center of Matera (UNESCO site since 1993 and European Culture Capital in 2019). The most distal, fine-grained calcarenite is characterized by large bioturbation traces of crustaceans (Pomar & Tropeano, 2001). The burrows represent a major problem for the protection of the Sassi against degradation processes because they are preferentially cemented but are surrounded by poorly lithified sediment. The aim of this work is to understand how the bioturbation modifies texture, porosity, permeability and eventually the cementation of the calcarenite. Crustaceans such as *Callianassa* are known to sort grains (Ziebis et al. 1996). These organisms eject finer sediments from the burrows, forming mounds on the sediment surface, while coarse grains are stacked in subsurface chambers. The burrows have organic linings, smooth surfaces and penetrate at least 60 cm below the sediment/water interface. *Callianassa* burrows are characterized by homogeneous and well-sorted grains in the upper parts, while deeper chambers are filled with moderately-sorted gravel (Tudhope & Scoffin, 1984). A bioturbated calcarenite level, outcropping in the Matera Paradiso quarry, has been selected as case study. Large samples including fossil traces and surrounding rocks have been analyzed by means of thin sections, scanning electron microscope (SEM), and computed tomography (micro-CT). Macroscopic and microscopic descriptions, modal and cluster analyses were performed based on counting of 50 images (7.5 cm^2 surface each) to characterize the texture and composition of the bioturbated calcarenite. In addition, SEM observations were carried out to describe the cements and CT scans to visualize the internal structure and the connected porosity of the samples. Thin sections and SEM observations show a close connection between sediment sorting and cementation. In the well-sorted area, thin isopachous layers of microgranular cement around and inside bioclasts occur, whereas in the poorly sorted area microgranular and granular cement is less abundant. Based on thin sections and cluster analysis of point-counting results five main groups characterised by small but significant differences in the composition, cementation and porosity can be identified (Fig.1): (1) moderately-sorted but poorly lithified fine grainstone with high porosity, interpreted as the sediment surrounding the burrows; (2) well and moderately-sorted grainstone, interpreted as sediments ejected from the funnels, forming small mounds on the sea floor; (3) well-cemented and sorted grainstone from the burrow fillings; (4) very porous but well-cemented grainstone, representing portions of the burrow filling, and (5) well-cemented rudstone, interpreted as coarse fillings of the storage chamber of the burrows (Fig.1). Based on our preliminary results the burrow fillings are more strongly cemented than the surrounding sediment, probably because the traces acted as some sort of preferred pathways for tidally-driven pore-water flow of marine-derived supersaturated water.

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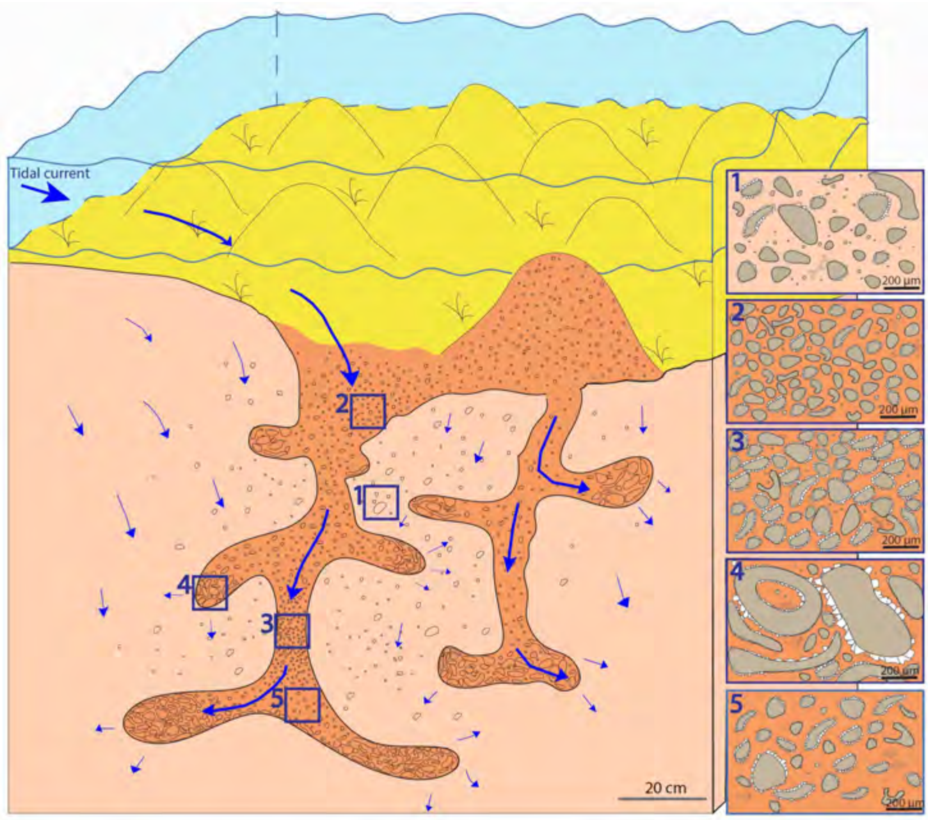

Figure 1 – Crustaceans burrows after the infilling processes, in seagrass environment. Blue arrows indicate the main water flow during tidal cycles (subtidal and intertidal sea level are reported). Burrows and surrounding area show intensely reworked bioclastic sediments with different levels of cementation and porosity as it is reported in the boxes to the right. Light brown boxes indicate the burrows while a pink box is used for the calcarenite enclosing the burrows.

Relatively Closed Diagenetic System in Carbonate Reservoir: Example from The Pre-salt Mississippian Carbonates at the Rozhkovsky Structure, Northern Pre-caspian Basin, Kazakhstan

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Pre-salt Mississippian carbonates succession of the Rozhkovsky structure is a significant hydrocarbon reservoir in an anticline structure trap located in the northern margin of Pre-caspian Basin. The previous petrologic study suggests the pre-salt carbonates are deposited in the inner-mid ramp setting with 11 lithofacies by core, thin section and SEM examinations. The paramagnetic sequence and the origin of porosity formation are defined through the mineralogical, petrophysical and geochemical analysis. Five types of calcite cement and two types of dolomite were recognized through the marine, meteoric and burial diagenesis. The pore space of pre-salt carbonate is composed of interparticle pore, intraparticle pore associated with foraminifera, dissolution pore (including moldic pore) and intercrystalline pore contributed by dolomitization. Combined the petrophyscial and petrologic data, high porosity and permeability carbonates (average porosity 6.8%, average permeability 7.12mD, below 4000m) with mainly interparticle pore are identified in high-moderate energy environment around the junction between inner and mid ramp setting, which mainly produced the peloidal/oolitic grainstone. In contrast, the poor, poor porosity and permeability carbonate (average porosity 1.1% and average permeability 0.082mD) are distributed in the low-energy environment around inner ramp, such as tidal flat and lagoon.

With over 2000 meters thick of salt strata serving as a regional seal overlying the carbonate rocks and low formation temperature (around 97℃ with the depth around 5000m), the pre-salt carbonates are in a relatively closed water exchange system with slow water-rock reaction. Therefore, the burial diagenesis, represented by minor calcite cementation and rare fracture, did not significantly alter the porosity in different lithofacies. The origin of pore space of pre-salt carbonates in the Rozhkovsky structure is related to the water energy of depositional environment: the high-energy sedimentary facies with a significant effect on interparticle pore space forming control present-day porosity generation.

Keywords: closed diagenetic system, pre-salt carbonate reservoir

Burial Diagenesis and Carbonate Reservoir Quality

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Keywords: Diagenesis, Exploration, Net to Gross, Pore type, Porosity

Burial diagenesis exerts a strong control on reservoir quality in carbonates. Increases in effective stress and temperature during burial commonly lead to chemical/pressure solution and cementation, which drive the loss of porosity and permeability. Burial trends in reservoir quality are important for oil and gas exploration, where drilling decisions are based on the hydrocarbon volumes available from a discovery, weighed against dry-hole costs. Such risk-reward propositions require a robust pre-drill estimation of the porosity of the producible reservoir and consequently of net to gross (NtG: the proportion of gross rock volume that could contribute hydrocarbons to a wellbore). The complex pore types in carbonate reservoirs commonly produce non-linear relationships between porosity and permeability, so porosity is a weak proxy for flow (producibility) and thus NtG. The permeability data necessary for robust NtG assessments are most readily available from core analyses, datasets collected routinely from most reservoirs.

A new method of generating success-case porosity and NtG assessments for exploration is here derived from a sub-set of an extensive global database of carbonate core analyses. Core data allow NtG cutoffs based on permeability thresholds, which can be calibrated to the expected fluid viscosity and recovery mechanism. Using permeability rather than traditional porosity thresholds typically leads to higher NtG values but lower average reservoir porosity. The results illustrate that for all permeability thresholds, porosity and NtG decline with increasing maximum burial depth. Depositional facies do not exert a systematic control on success-case porosity or NtG in the current dataset. Dominant pore types, reflected by the Lucia petrophysical class, do vary systematically. For a given burial depth, higher porosities are generally associated with class 2 and 3 fabrics (inferred to be mud-lean to mud-rich, or medium to finely crystalline). Additionally, class 3 fabrics (muddy/microporous) are more common in shallowly buried reservoirs and class 1 fabrics (grainy/intergranular-vuggy) are more common in deeply buried reservoirs.

The porosity-depth trends from this core-based approach differ from other published burial curves (Schmoker & Halley, 1982; Ehrenberg & Nadeau, 2005). Important distinctions are that the current method calculates porosity only for the net reservoir, applies a consistent NtG methodology, excludes pore systems not captured by core (fracture, vug), and assesses maximum rather than present-day burial depth. Future research should try to establish how facies and/or surface diagenetic processes can establish ‘entry points' for burial diagenetic trends, the impact of deep burial dissolution, and the relative importance of temperature vs. effective stress. Though facies are undeniably important at the play- or reservoir-scale and for prospect risk, it is unclear if they exert any global control over success-case porosity and NtG.

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Developing mechanism of ultra-deep carbonate reservoirs under effects of strip-slip faults and multiple fluids

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Key Words: Deep carbonate reservoir; Hydrothermal fluid; Strike-slip fault; Tarim Basin; TSR

In the Shuntuo area of the Tarim Basin, NW China, strike-slip faults and alteration by multiple fluids along the faults play a key role in controlling the development of carbonate reservoirs. Many wells drilling along the strike-slip faults yielded a high production of oil and gas stream from the ultra-deep Ordovician carbonates deeper than 6000 m. The strike-slip faults formed in the middle Caledonian to early Hercynian, resulting a series of flower-like structures in the Ordovician. Affected by the strike-slip faults, the Ordovician carbonates underwent significant structural rupture, forming fault- and fracture-type reservoir spaces. Many wells, such as Shunnan 4 and Shunbei 1-3, disclosed empty section during drilling process, revealing existence of fault-related fracture and cavity spaces. The strike-slip faults and related fractures constitute pathway for fluids, such as meteoric water, hydrothermal fluid, oil and gas fluid and TSR-related fluid, which altered the ultra-deep carbonates. In the middle Caledonian, the Ordovician carbonates in the Tahe area on the north side of the Shuntuo area were uplifted and exposed to the surface and subjected to meteoric karst. The meteoric water flew downwards along the strike-slip faults as well as the Ordovician stratigraphic slope to the Shuntuo area and then dissolved the Ordovician carbonates. The strike-slip faults became the principle channels for deep hydrothermal fluids migrating from deep to shallow layers. Affected by hydrothermal fluids, many wells in the Shuntuo area reveal typical hydrothermal minerals such as silicification, quartz crystal clusters, hydrothermal dolomite, calcite and fluorite. In particular, the Shunnan 4 well revealed a hydrothermal silicification reservoir with a porosity of 3%–20.5% in the Ordovician Yingshan Formation from 6668 to 6681m. Most of the NE strike-slip faults cut down to the Cambrian bottom boundary, connected the Middle and Lower Cambrian source rocks, and became the key channels for the vertical migration of oil and gas. The corrosive materials such as organic acids and CO_2 released during the maturity and hydrocarbon generation process of the source rocks accompanied the migration of oil and gas to the Ordovician strata. The corrosive fluids caused a certain degree of burial dissolution of the carbonate reservoirs. The drilling cores reveal a rich phenomenon of dissolution enlargement and oil immersion along stylolites and cracks, indicating the existence of burial dissolution. As the burial depth and temperature increase, the sulfate in the carbonate rock underwent TSR with the participation of oil and gas. The H_2S content in the natural gas in the wells of Shunbei 1-3 and Shunbei 1-1 is as high as 1800ppm. Extensive existence of pyrobitumen and pyrite is also observed. The $\delta^{34}S$ value of pyrite is as high as +31.1‰, indicating TSR process. Under effects of the strike-slip faults and the alteration of various fluids along the faults, the ultra-deep Ordovician carbonates in the Shutuo area developed into high-quality carbonate reservoirs.

Fracture-related diagenesis: a record of fluid flow through the Thamama Group, UAE

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Fractures, diagenesis, Thamama, cement, Cretaceous

ABSTRACT

Most carbonate reservoirs are fractured, where fractures often form either due to tectonic activity or as a result of diagenesis. Fractures are also often cemented due to fluid flow. Here we relate the formation of fractures and evolution of fluids from fracture cements to regional tectonic events from the Early Cretaceous Thamama Group, UAE.

First, fractures in outcrop were studied where the Upper Thamama Group is exposed. Second, samples were studied from the subsurface from a highly faulted Oil Field (A). Core samples were taken from wells close to major faults in the field in both oil and water legs.

Fractures in the outcrop were divided into two main generations, F1, (en-echelon) and F2, which were both either fully or partially cemented. The main tectonic events that affected the fracture formation in the Thamama Group are foreland autochthon in the Precambrian to Lower Cretaceous, a frontal triangle zone in Neogene and Dibba zone which consists of Hawasina units (Triassic to Cretaceous), and the Sumeini units (Lower to Middle Cretaceous). F1 formation is related to the NS orientation fracture system consistent to the Arabian Trend sets caused by Cenozoic compression. F2 is related to the EW orientation fracture system matching Tethyan extensional trend sets.

Petrographic analysis of the subsurface thin sections revealed the presence of three main sets of fractures. Fracture Set 1 (cemented), Fracture Set 2 (open) and Fracture Set 3 (cemented only in Lower Thamama). The fracture cement included equant and blocky calcite as well as saddle

dolomite. Cathodoluminescence (CL) analysis was used to compare the number of cement zones in each fracture cement type, and revealed more cement zones in the Lower Thamama reservoirs than the Upper. The most important diagenetic events were cementation and dissolution, which took place towards the end of the paragenetic sequence. The reservoirs also contained significant amounts of stylolites, dissolution seams and bitumen, which were associated with most of the dissolution events.

$^{m}Mg/^{m}Ca$ obtained from in situ elemental analysis showed variation through the calcite and dolomite cement zones in the different reservoirs of the Thamama Group. This was inferred to be due to temperature changes. The Upper Thamama Reservoirs (A, B, and C) show lower $^{m}Mg/^{m}Ca$ (ranging from 0.072-0.48) than the Lower Thamama reservoirs (F,G) (ranging from 0.4-1.3), suggesting that the Upper Thamama fracture calcite cements were precipitated at higher overall temperatures than the Lower Thamama reservoirs. Mn-Fe analysis allowed an understanding of the redox index through the different cement zones, in both Fracture Set 1 and Fracture Set 3. Analysis of Sr showed the absence of exotic fluids role in the diagenetic system.

In-situ (SIMS) $\delta^{18}O_{VPDB}$ values were obtained for the calcite cementation history of the two fracture sets in the five reservoirs of the Thamama Group. The $\delta^{18}O_{VPDB}$ analysis confirmed the inferred temperature differences revealed by $^{m}Mg/^{m}Ca$ analysis, and also indicated that Fracture Set 1 has a longer cementation history than Fracture Set 3, and has wider range of temperatures (58-128°C).

Microfacies, diagenesis and depositional setting of the Late Triassic mid-oceanic carbonates from Dalnegorsk area (Taukha terrane, Far Eastern Russia)

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Keywords: Diagenesis, Panthalassa, sedimentology, Triassic carbonates

In comparison with the well-known Tethyan domain, and despite of the amount of research already carried out, Upper Triassic limestones from the Panthalassa Ocean remain poorly known. For more than 10 years, the REEFCADE project, initiated and supervised by Rossana Martini, aims to improve our knowledge about these Triassic mid-oceanic limestones from Panthalassa realm (Chablais *et al.*, 2010[1]; Heerwagen *et al.*, 2018[2]; Peybernes *et al.*, 2016[3]; Rigaud *et al.*, 2013[4]). One of the best areas to pursue this project is the Taukha Terrane in Sikhote-Alin mountain range (Primorsky and Khabarovsk Kraïs, Far East Russia) where an extraordinary amount of Triassic limestones is exposed. These carbonates, showing a general good preservation, are described and analysed in detail for the first time in this study. Thus, they are of a major importance to better understand the evolution of carbonate systems in the Panthalassa Ocean during the Late Triassic.

The Taukha Terrane is a part of the South—North continuity of Jurassic to Paleogene accretionary complexes, going from the Philippines to Sakhalin Island (Far East Russia). Nine main limestone bodies, situated few kilometers around the Dalnegorsk town, have been accurately explored and extensively sampled. The foraminiferal association, mostly dominated by the genera *Parvalamella* and *Aulotortus*, indicates a Norian age. Some other genera characteristic of a Carnian age also occur. The microfacies analysis shows that all the sampled blocks display closer facies, with very minor changes, indicating a stable depositional system over a long period spanning the Carnian and the Norian. The limestones are dominated by peloidal packstones-grainstones with abundant microbial clasts and microproblematica. Oolitic grainstones and Megalodont patches are also very common. The diagenetic analysis evidences major events, from early marine diagenesis to accretion-related changes. The cathodoluminescence observations and geochemical analyses allow us to define more precisely the deposition and cementation conditions. They also permit to document, for the very first time in Triassic Phantalassic carbonates, the REE and carbon/oxygen isotopes signals of different cementation stages.

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Diapir control on platform carbonates diagenesis: constrains from the Tazoult salt wall (central High Atlas diapiric province, Morocco)

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Key words: Diagenesis, Diapiric basins, Platform carbonates, Salt tectonics

ABSTRACT

Diagenesis of platform carbonates juxtaposed to diapiric structures is complex due to the interaction between host rock and fluids related to, and not related, to diapirism. The exposure of low structural levels and excellent outcrop conditions of the Tazoult salt wall allows the analysis of the diagenesis of the Hettangian to Pliensbachian platform carbonates flanking the structure. It was possible to interpret the diagenetic evolution occurring in the studied rocks from the early stages of the diapiric activity through to the Alpine tectonic inversion of the entire rift basin.

Field and analytical data revealed the occurrence of several diagenetic phases (eight types of calcite cements and five types of dolomites) affecting the host rock. These characterise seven diagenetic stages linked to the halokinetic evolution of the Tazoult salt wall. Stage 1 (early Pliensbachian) to stage 4 (late Pliensbachian) occurred during the early growth of the Tazoult salt wall, and they were characterised by the alternation of marine and meteoric diagenetic environments. Stage 2 is of special interest as the Tazoult wall underwent an increase in diapiric activity that promoted the uplift and the subaerial exposure of the platform carbonates. The invasion of the platform top by meteoric waters caused the karstification of the host limestones and the deposition of karstic sediments. Stage 5 (Toarcian) represents the early burial of the studied units and was distinguished by the circulation of marine dolomitizing fluids downward along the contact between the diapir core and the flanks. Stage 6 (post-Toarcian) represented the maximum burial of the studied platform carbonates. During this stage, the contact between the diapir core and the flanking sediments acted as a barrier to the circulation of fluids. Stage 7 (Cenozoic) corresponds to

the uplift and exhumation event related to the Alpine compression, when all the studied carbonates were exposed and subsequently interacted with meteoric waters.

Based on analytical data the estimated temperatures of diagenetic fluids were obtained and compared to thermal and burial history of the studied basin. This multidisciplinary integration allows us to present a large-scale discussion of the timing of diagenetic events and thermal sources, not only for the Tazoult salt wall area but also in other localities with similar geological histories.

Results suggests that the Tazoult salt wall constitutes a first class example of how salt tectonics influences the diagenetic evolution of sediments flanking diapiric structures. Major controls on diagenesis are: i) the creation of fluid pathways, mostly fractures, due to the forces caused by the upward migration of salt during early stages of diapirism; ii) the local sea-level variation due to relative vertical salt movement that causes alternation of marine and meteoric diagenetic processes, which is especially relevant in platform carbonates; iii) the behaviour of diapirs and welds as preferential vertical fluid conduits, but as barriers to the horizontal migration of fluids; this is therefore partially or totally compartmentalising minibasins; and iv) the influence of salt and other evaporite dissolution from diapirs on the fluid chemistry and related diagenetic products and ore deposits.

Effects of hydrocarbon migration on carbonate diagenesis in Upper Albian reefal limestones (Basque-Cantabrian Basin, northern Spain)

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Keywords: carbonates, diagenesis, hydrocarbon, migration

The Upper Lias shale, main type II source rock in the Basque-Cantabrian Basin, achieved maturity and began to spell liquid hydrocarbons in the Early Cretaceous. The hydrocarbons migrated through the subsurface and occasionally produced accumulations when conditions were favourable. In most cases, hydrocarbons migrated through the subsurface without ever becoming trapped, seeping out, becoming oxidized and/or suffering biodegradation. During migration, the hydrocarbons interact with the carrier-beds, especially with carbonate rocks, playing a significant role in diagenesis.

The Upper Albian reefal limestone of the Eguino Formation (SE Basque-Cantabrian Basin) is a carbonate reservoir that exhibits oil shows in outcrops, but the origin and timing of the oil entrapment are still not fully understood. To date, the diagenetic and geochemical study of this reservoir has been addressed only from outcrop samples of an exhumed part (Permanyer et al., 2018). There are, however, several exploration wells in the area that have crossed this reservoir interval. In this work we study the effects of hydrocarbon migration through this Upper Albian carbonate reservoir from well-core samples of the Urbasa-2 and Urbasa-3 wells. The petrographic, cathodoluminescence and UV-fluorescence study of the core samples has revealed a relationship between the hydrocarbon migration and the local generation of secondary porosity in carbonate rocks that served as carrier beds during hydrocarbon migration. This secondary porosity is interpreted to be related to pre-hydrocarbon acidic aqueous fluids expelled, which originate in source rocks during the kerogen maturation process. The hydrocarbons that migrated through the rock samples invaded the newly created pore space, and maintained the porosity opened until migration through them was discontinued. Once migration ceased, a new generation of carbonate cement grew in the available porosity, trapping hydrocarbons as fluid inclusions and solid bitumen.

Based on stable isotope ratios of the different cement generations and data from fluid inclusions, a characterization of the evolution of the diagenetic fluids is provided. These results serve as a basis for proposing pathways and timing for the hydrocarbon migration through the carbonate formation. Isotopic and vitrinite reflectance data with present-day temperatures provide the bases for the reconstruction of the burial conditions of the carbonate formation and the maturity of the source rock at the time the hydrocarbon migration occurred.

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Cone-in-cone structures: facts and fantasies

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Key words: carbonates, cone-in-cone, genesis

Cone-in-cone structures have been known since the late 1700's. and already carefully described at the end of the XIX century (Gresley, 1887), since that time their origin have been debated and they remain spectacular and enigmatic.

There is a list a few of the popular ideas of their formation:

1. Induced pressure from burial
2. Expanding mineral growth while forming crystals
3. Inversion from aragonite to calcite
4. Association with fault structures and fractured damage zones
5. The result of seepage
6. Fluid-convective metasomatic process (Benar's whirlwinds)
7. Organic - algal-bacterial

Usually for each specific object there are explanations of the main features within one of the hypotheses but a generalization of knowledge reveals somehow an unexplained phenomena.

And yet, what we exactly know about carbonate cone-in-cone?

1. Cone-in-cone macro and micro-morphology are well studied - the internal micro-structure (thin section and SEM) of cone-in-cone features usually is well preserved as well as mineral composition (usually calcite).
2. From the crystalogenesis points of view, cone-in-cone is a radially-radiant joints of the thin splitted crystals. The phenomenon of the split growth is well known for many minerals, it is well studied and confirmed experimentally (Petrov et al., 1983; Sinay et al., 2014). All forms of split growth occur directly during crystallization at high rates.
3. One of the main reasons of splitting is the presence of impurity, commensurable with thickness of layers of increase of substance of a crystal. Clay minerals and bitumens (in organic-rich shales formations) are often found impurities. The firm particles adsorbed by the growing side, force new accruing layers to deviate parallel position. So, units of dispersing crystals such as "fans" or "sheaves" are formed.
4. Important condition of the split crystals growth is the viscous environment or free volume. Thus, the assumption of cone-in-cone formation in the stage of sedimentation - early diagenesis is the most likely.

5. By the known chemical equation: $Ca^{2+} + 2HCO^-_3 \leftrightarrow CaCO_2 + H_2O + CO_2$ crystallization of carbonates can occur with a combination of various factors leading to the removal of CO_2 from the system.

In general, carbonate rocks are polygenic, all appearance, multiple models should exist for carbonate cone-in-cone structures selfsame. Scientific imagination and professional experience allows each sedimentologist to present a whole range of conditions in which these structures can be formed, and the study of the specific objects allows to draw conclusions about the availability of a set of necessary conditions for their growth.

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Molar-tooth structure of Meso-Neoproterozoic dolomite of West Siberia: implication for sedimentological and tectonic history of the reservoir

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Key words Dolomite Fractures Molar-tooth structure Precambrian Stromatolite

The Meso-Neoproterozoic (Riphean) dolomite rocks compose the carbonate oil-bearing reservoir within the Baikit anteclise in Kuyumbinsko-Yurubcheno-Tohomsky area, western part of Siberian platform. The areas occupied by Riphean dolomites are more than 3000 km^2.

Riphean sedimentary sections mainly include dolomites, among which there are stromatolitic, granular, micritic and micritic-granular structures. Stromatolite dolomite, which occupies significant portion of the reservoir, exhibits laminated stratiform and rare colonial forms.

Precambrian sedimentation occurred within extensive, mostly shallow shelf areas. The bottom relief of the palaeobasin was characterized by insignificant ruggedness, with low relief “reefs” and bar systems. It is necessary to focus the attention on “reefs” or large carbonate constructions localisation over the zones of deep faults. Stromatolites were rapidly growing over fault areas with intensive fluid dynamics, which created favorable conditions for active development of microbial communities.

Usually stromatolites are interbedded with granular rocks forming succession up to several meters thickness with erosional surfaces, breccia intervals and syneresis cracks, which indicate a shallow water environment of sedimentation.

The uniqueness of the carbonate sedimentation mechanisms in the Precambrian basins and the absence of skeleton fauna determine the essential willfulness of the structural and textural characteristics of rocks. Molar-tooth structure (MTS) firstly described by Daly R.A. in 1912 is original sedimentary structure which is broadly limited in the Meso-Neoproterozoic section.

Fig. 1. Example of MT structures in Riphean dolomite of West Siberia
MT II – subparallel to layering, MTL – perpendicular to layering

Molar-tooth structure is the sedimentary structure made up off series of variously shaped voids (wriggle lens, pod like shapes) and ptygmatic cracks that were filled with calcite from the Precambrian which generally occurs in dark colored dolomite (fig. 1).The origin of these MT structures is not obvious. There are several views of its mechanism, which can be divided into three categories: physical origin under external mechanical forces, biological origin due to actions of bacteria and algae, biogeochemical origin due to decaying organism.

In Russia MTS are described for Precamrian sections of the South Ural, Uchur Maya, Turukhansk Uplift and Yenisei Ridge. This work describes variability of the MT structure of Riphean dolomite on the base of core data of Kujumba field. MT structures are characterized in turn of its mineral compositions, morphological diversity and position in the section.

FENESTRAL STRUCTURES IN EDIACARAN DOLOMITES: ANCIENT RESERVOIRS OF EAST SIBERIA PLATFORM

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Siberian platform is the oldest petroliferous basin in Russia (East Siberia) where ancient Riphean and Ediacaran reservoirs contain industrial oil and gas fields. Hydrocarbons mainly situated in fractures but significant zones of fenestral structures also have been discovered (Fig 1a).

Dolomite is main mineral of Precambrian reservoirs with minor content of siliceous and ferrous matter. Amount of fenestral matrix can reach tens of meters and can be described as fenestral dolostone or loferites in dolomite matrix (Shaldybin, 2017). Most of fenestral forms have the horizontal appearance and propagation in core, size of which can reach usually millimeters but sometimes can exceed more 2-5 cm. They have isolated distribution pattern and rarely interconnected.

Observation of thin sections made from core allowed describe these structures as open-space structures (Shinn, 1983). Most of cavities are usually typically flattened, open or closed cavities with an apparent zonal structure and with characteristics of diagenetic redistribution of unevenly crystallized material to the center increasing the purity and size of crystals in dolomite matrix (Fig 1 b). The study cavernous cavities under the scanning electron microscope showed that their walls are composed of perfect euhedral crystals with dolomite rhombohedral shape (Fig. 1c). Application of microprobe analysis revealed that the crystals give high content of iron in the spectra in contrast to the dolomite of the rock matrix.

Traditionally, the formation of fenestral structures in carbonate rocks associated with gas bubbles formed during early diagenesis. Simultaneously with the release of gas saturation the process of sediment desiccation (drying or shrinkage) develops in sediments, which leads to the appearance of additional compensated volume, which fenestral cavernous form in place of gas bubbles.

Horizons of the distribution of fenestral structures in core of deep wells in Siberian platform obviously find "stratigraphic distribution", i.e. appear in layers. Individual caverns have a flattened ("compressed") form, and their smaller clusters with millimeter dimensions are subject to subhorizontal stretch of layered textures.

In the space of the carbonate rock the open-space structures (fenestral or loferite origin) can build a powerful, up to several meters of high-hollow horizons, which are able to have a high response to fill by natural fluids. So some of them can be good reservoirs for oil and gas fluids as significant part of these caverns contain solid bitumen substance.

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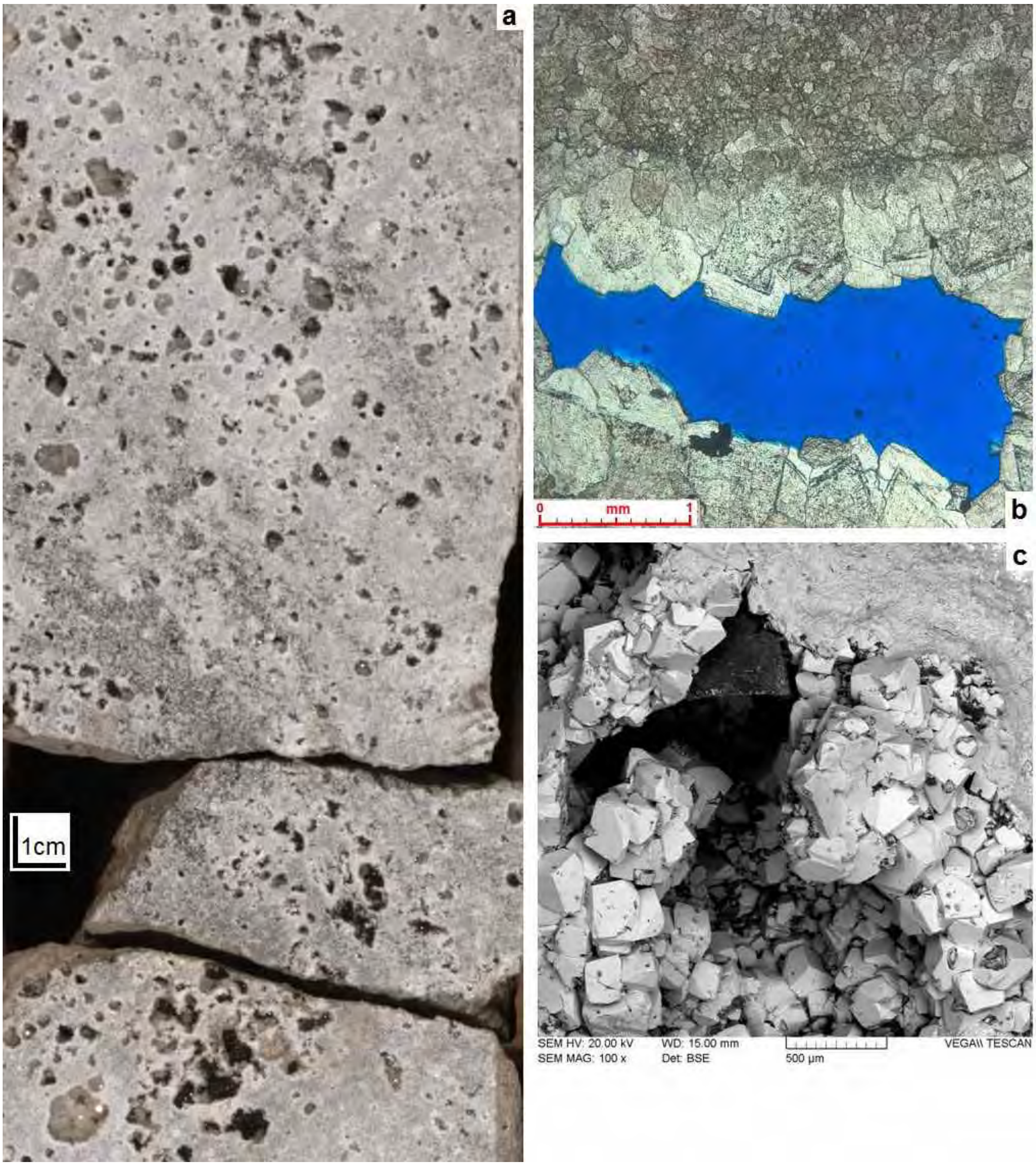

Figure 1. a) dolomite in the core with open-space structures (empty and some with bitumen); b) thin section via single fenestral dolomite in rock; c) SEM photos of the surface of fenestral cavern (gray – dolomite, black – organic matter or bitumen).

Illuminating paragenesis with hyperspectral imaging

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Keywords: diagenesis, hyperspectral, paragenesis, dolomite

Initial assessment of diagenetic phases and paragenesis in outcrops relies on a visual assessment of crosscutting relationships. In drill core, diagenesis is even more difficult to unravel with only a limited window into the subsurface. Mimetic replacement and a lack of colour differences between mineral phases can result in incomplete sampling or misinterpretation of paragenesis. Hyperspectral imaging (HI) can detect individual phases, based on composition and crystal size. This helps separate complex diagenetic processes that are typically referred to as one stage of paragenesis, such as the formation of zebra dolomites. In this study, we demonstrate the utility of HI to determine the number of phases and paragenetic sequence in a complex, structurally influenced dolomite outcrop and in a drill core containing dolomitized burrows.

An exposure of the Cathedral Formation in the main ranges of Alberta's Rocky Mountains was imaged using a hyperspectral camera capable of collecting shortwave infrared reflectance spectra between 1000-2500 um. Five images were collected along a 500 m transect at a distance of approximately 50 m. To guide the analysis of outcrop imagery (<5cm/pixel), several representative samples were taken along the outcrop and imaged using a drill core scanner equipped with the same camera (<2mm per pixel). For the field and laboratory acquisitions, measurement of dark current and of a 99% reflectance white panel were used to calibrate imagery to reflectance. Spectra collected from the samples and the outcrop were classified into 16 groups representing changes in composition and crystal size. Compilation images of spectral groups reveal a limestone-dolomite transition only detected in the field through closely spaced HCl testing. At least three phases of saddle dolomite cements are identified in the images, and highlight pore-lining and filling phases. Clasts within a brecciated zone, surrounded by dolomite cements show alteration halos or complete alteration from the initial replacive dolomite phase. Altogether, the images collected from this exposure imply that there was an initial replacement of precursor limestone facies, followed by several phases of cementation that resulted in significant alteration of host rock margins. The results provide crucial information regarding the paragenesis and a map of phases to be sampled for further analysis.

In another example, imagery was collected from a drill core through the Wabamun Formation in north central Alberta. Sedimentary structures and burrows were visible in certain parts of this core without the aid of HI, due to bitumen staining. In the absence of bitumen staining, the limestone appears massive with faint mottling. HI reveals persistent bioturbation, with dolomitized burrows and sharp dolomite-limestone contacts across burrows. Stylolites are concentrated in burrowed intervals that have not been dolomitized. Sharp, in-burrow dolomite-limestone contacts and sutured limestone-filled burrows suggest that dolomitization occurred after deposition but prior to burial.

In each of these studies, HI identified mineral phases and boundaries that result in a more complete paragenesis. This type of data acquisition may be used at different scales and is a valuable tool for highlighting mineral phases that cannot be identified without petrography.

Quantifying diagenesis in pre-salt carbonates using supervised classification machine learning

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Key words:

diagenesis, image classification, machine learning, pre-salt carbonates, quantification

This study presents an innovative methodology and its application for quantitative petrographic thin section image analysis of rock samples using the pre-salt carbonates. This is achieved using image processing and supervised classification machine learning to identify, classify and quantify the main components and their diagenetic processes, including depositional carbonates, associated porosity and solid bitumen (Figure 1).

Side Wall Core rock samples (1 inch diameter) were cut, impregnated with blue dyed epoxy resin and prepared for petrographic thin sections with final high-quality (metallographic grade) polishing. Automatic high-resolution thin section scans were performed under plane polarized light illumination with a 10X magnification. The obtained whole thin section images were gigapixel images (i.e. multi resolution image pyramids) with a maximum resolution of 0.44 microns per pixel. The petrographic study of the thin sections allowed the definition of six main categories: i) depositional carbonates, ii) clays, iii) porosity, iv) carbonate cement, v) silica cement and vi) bitumen. “Depositional carbonates” correspond mainly to “in-situ growths” and reworked microbial shrubs and spheruliths including large shrubs, small shrubs, bands or layers of spheruliths. “Clays” correspond mainly to talc-stevensite? fine-grained, silty, argillaceous and carbonate mud. “Porosity” is manly interparticle, intraparticle, vuggy and intercrystalline. “Carbonate cement” corresponds to calcite and dolomite. “Silica cement” presents different textures and generations, mainly opal, chalcedony and megaquartz, being all of them grouped under a unique category. Finally, “bitumen” corresponds to present-day solid hydrocarbons impregnating the rock.

Open-Source software was used for whole thin section image analysis to perform machine learning based classification making use of multi-resolution image pyramids. A Support Vector Machine (SVM) based classifier was used for pixel classification based on multivariate intensity and structural input parameters. Training data was generated by manually drawing several representative annotations per defined category. The classification step then worked automatically: the features for each pixel of each category were computed and the SVM outputs the corresponding category class. The accuracy of the applied classifications was visually evaluated for each thin section image. One of the main misclassifications detected is silica cement that occasionally can be overestimated, but the overall quantification results for the defined categories are representative for each sample.

In conclusion, this innovative approach allowed the identification, classification and quantification of the main components including porosity, bitumen and depositional carbonate (a total of six categories) in pre-salt carbonate rocks samples using image processing and supervised classification machine learning. Additionally, this fast approach could be applied to all the thin sections available from one or several wells to perform less biased petrographic estimations and supervised automatic diagenetic products classification and quantification.

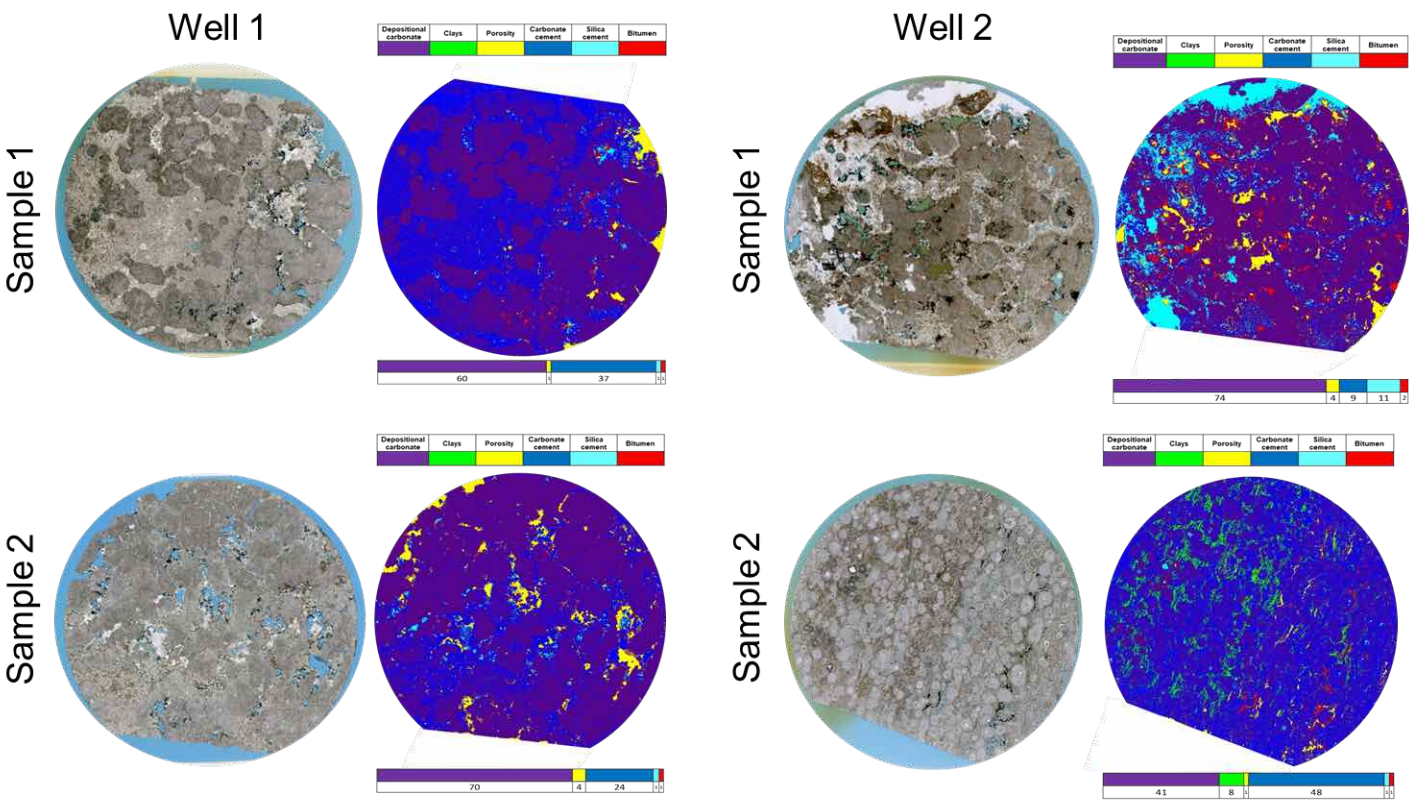

Figure 1. Example of four scanned whole thin sections from two wells, prepared from one inch diameter Side Wall Core rocks, with identification (six categories), classification (distribution map) and quantification (color bar chart and % indicated below) for the depositional carbonate and main diagenetic products, using image processing and supervised classification machine learning.

Scattered K-feldspars in shallow-water carbonates: a possible proxy for paleoclimate studies

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Keywords: K-feldspar, paleoclimate, SEM, Apennines, Iran

A basic tenet of shallow-water sedimentology is that carbonate and siliciclastic sedimentation are typically mutually exclusive (and, by the way, that is the reason why the Bathurst community exists!). Even though "mixed" sediments are more and more studied, as scholars of carbonates we know that in most shallow-water carbonate rocks if we want to look for silicates, we turn our attention to the "insoluble" residue (insoluble, of course, to HCl).
While studying the insoluble residue of some samples of Cretaceous shallow-water carbonates, we noticed the presence of small quantities of K-feldspar in early-diagenetic dolomites. According to the monumental, posthumous reference book of Erik Flügel, the occurrence of feldspar is almost never reported as insoluble residue, except in a few cases, generally corresponding to "impure" limestones
. We may assume that this should be a consequence of the intense weathering under warm humid conditions in the subtropical climate belt to which shallow-water carbonates are typically associated.
Nevertheless, after a careful SEM examination of many samples from our collection, we have found that scattered and tiny K-feldspars do occur in several dolomites of different age, either as small (a few µm) irregular to rounded grains or as euhedral crystals filling cavities. Based on a preliminary assessment, the stratigraphic distribution of these occurrences seems significant: so far we have found K-feldspar in Norian dolomites of the southern Apennines (Italy) and of the Zagros (NW Iran), and in Barremian and Albian dolomites of southern Apennines. Conversely, it is not present in Rhaetian-Jurassic and Aptian dolomites of the same localities. The intervals containing K-feldspar correspond, based on previous petrographic and geochemical investigations, to relatively arid phases, compared to the more humid phases that seems to be associated to the dolomites devoid of K-feldspar.
A similar paleoclimatic interpretation was given by Sandler et al. (2004), who found authigenic K-feldspar in the insoluble residue of Cenomanian-Turonian shallow-water carbonates of Israel. According to Sandler et al. (2004, Sedimentology, 51: 323–338), the euhedral K-feldspar crystals formed as overgrowth around detrital, wind-blown grains. Their and our findings clearly relate the presence of K-feldspar to early diagenesis and possibly to the dolomitization process itself.
According to literature, the most common feldspar in shallow-water carbonates is albite, sometimes accompanied by K-feldspar. Generally, these minerals are linked to incipient metamorphism and deep brine circulation. Regarding our samples, a late-diagenetic origin can be excluded, given the available geological and petrographic data, even though the exact genetical process is presently under study. A full understanding of the factors controlling the occurrence of K-feldspar in shallow-water carbonates could offer a new proxy both for early diagenesis and for paleoclimate studies.
Ongoing systematic analyses on many more samples from other localities will clarify if the presence of these minerals in our samples is a true oddity, or if K-feldspar has gone unnoticed by many researchers up to now simply because it is hard to see…if you are not looking for it.

Halysites chains up rhythmicity – implications for time and diagenesis

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early diagenesis, environmental reconstruction, preservation bias, reefal deposits, taphonomy

Limestone-marl alternations are often interpreted to reflect cyclic changes in the depositional environment, with time spans for the deposition of a limestone-marl couplet between thousands of years (millennial cycles) and the Milankovitch frequencies (e.g. 20 or 40 ka). Data from *Halysites catenularis* colonies from the Silurian Lower Visby Formation from Gotland (Sweden) crosscutting several layers of their circumambient limestone-marl alternation indicate a diagenetic origin of limestones and marls indifferent to primary sedimentary differences. We analysed thin sections and micro-CT scans to document (1) the life span of the coral colonies, (2) the spatial extent of the corals, limestone, and marl, and (3) the chronological order of sedimentation and subsequent diagenesis. Our results indicate a sedimentary infill of the corallum's interspaces while the coral was still alive, which is typical for halysitid corals. Growth banding in *H. catenularis* indicates growth rates of about 3.8 cm per year. Due to the typical compaction of marl layers caused by the abrupt mass loss due to aragonite dissolution during differential diagenesis and the sediment overburden during progressing burial, the coral is partly fragmented in these layers, whereas it is well preserved in the limestone. Despite the clear lithological change of limestone and marl, which is normally interpreted to reflect changes in terrigenous input, the growth of the coral does not react to these changes. Growth interruptions, density banding and the death of the coral colonies seem to be completely independent from the lithological pattern. Furthermore, the sediment baffling character of *Halysites* implies that the sedimentation rate within the coral is higher than outside the colony. As the individual limestone and marl beds have a more or less constant thickness inside and outside the coral colonies, the spatial heterogeneity of sedimentation rates within one bed leads to different time spans of sedimentation for a single bed, depending on the spot of observation. The life span of the coral colony and its corresponding matrix with only a few decades imply that most of the time of the deposition of the Lower Visby Formation with its rhythmic lithology is not recorded by any sediments but rather by long phases of non-deposition.

Basal aquifers and their role in fault-related basin-scale dolomitisation

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Keywords: dolomitisation, faults, hydrocarbons, WCSB

Although faults are often inferred to control sedimentary architecture and fluid flow on carbonate platforms [1], demonstrating this from subsurface datasets can be difficult. Previous research [2] indicates that authigenic albite in carbonate rocks can be employed as a tracer for deep-burial brine migration. Here we 'fingerprint' diagenetic fluids by assessing the spatial distribution of certain mineral and chemical phases in the Western Canada Sedimentary Basin (WCSB). Cored intervals of dolomitised Devonian strata were selected based on their proximity to mapped platform margin faults and/or Precambrian shear zones (Fig. 1).

The Swan Hills, Leduc Formations and Wabamun Group contain multiple phases of petrographically similar replacement dolomite (RD). Stylolites crosscut all RD phases, suggesting precipitation during shallow burial. Stable isotope and rare earth element (REE) data indicate that RD formed from Devonian seawater. Saddle dolomite cement (SDC) in the Wabamun Group (Fig. 1B4) crosscuts stylolites and based on geochemical data, also formed from Devonian seawater. Conversely, SDC associated with hydrocarbons in the Swan Hills Formation (Fig. 1B1) is more isotopically depleted than Devonian seawater, suggesting precipitation during deep burial, perhaps during the Laramide Orogeny (Middle Jurassic-Eocene).

Authigenic quartz and albite found in the West Shale Basin and Peace River Arch in the Swan Hills Formation (Fig. 1B1) and Wabamun Group (Fig. 1B4-1B5) suggests that basinal fluids interacted with clastic aquifers beneath carbonate strata prior to dolomitisation, with upward fluid migration along faults. Conversely, the absence of quartz/albite in the Swan Hills and Leduc Formations in the East Shale Basin (Fig. 1B2-1B3) suggests that dolomitising fluids only interacted with carbonate strata. Additionally, high-concentration lithium-bearing formation waters in the Swan Hills and Leduc Formations in the West Shale Basin and Peace River Arch area are more prevalent than in the East Shale Basin [3], suggesting a relationship between basal clastic aquifers and dolomitisation via faults in these areas.

Replacement dolomitisation of the Swan Hills, Leduc Formations and Wabamun Group likely began with modified Devonian seawater during shallow burial. Saddle dolomite cement, authigenic quartz and albite formed during deep burial from fluids that originated in areas where basal clastic aquifers are present. By assessing the spatial distribution of authigenic quartz, albite and lithium in groundwater, our approach to 'fingerprinting' diagenetic fluids is particularly applicable to tectonically and hydrologically complex basins.

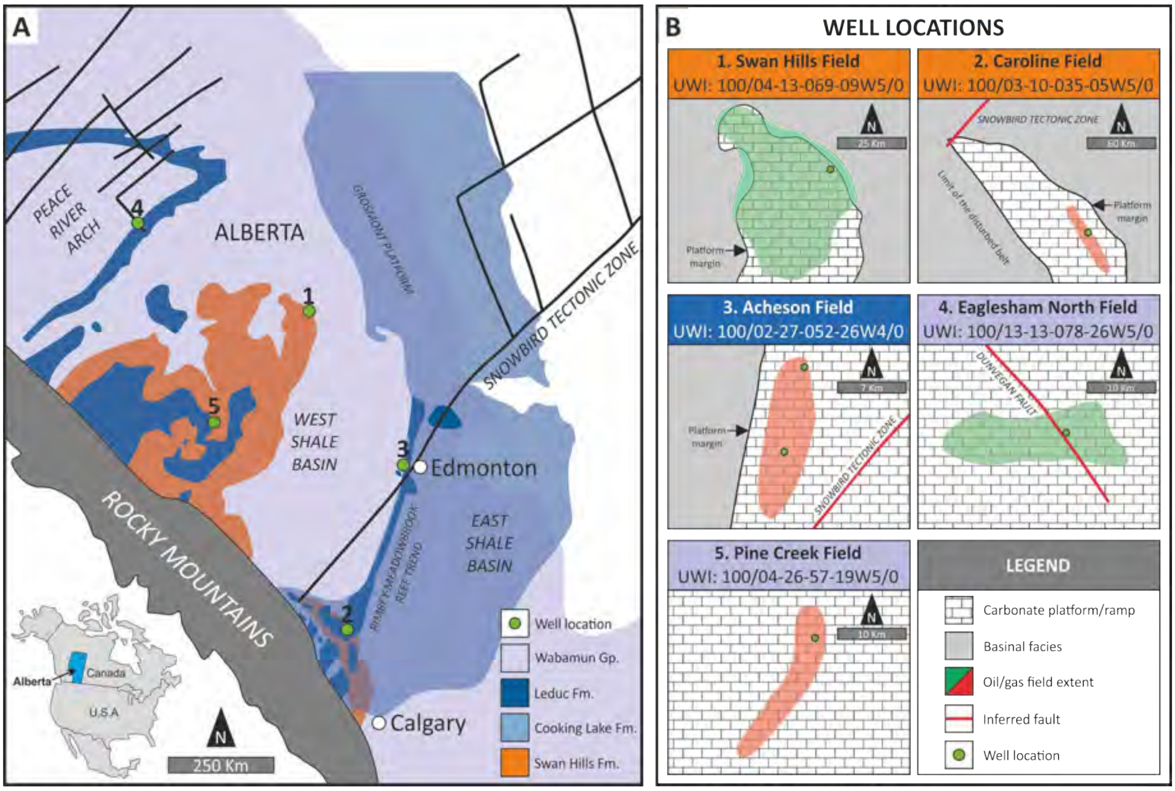

Figure 1: (A) Location of studied cores in the WCSB. (B) Relationship of cores to inferred Precambrian faults (Alberta Geological Survey data).

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fluid compartmentalization, evolution and dolomitization of the Palaeozoic successions, Huron domain of southern Ontario, Canada

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Key words: fluid flow, dolomitization, Huron domain

Laterally extensive carbonate formations occur throughout the Paleozoic sequences of the Huron Domain of southern Ontario, Canada. These sequences representing Cambrian mixed carbonate-siliciclastics, Ordovician carbonates, Silurian carbonate-evaporite sequences and Devonian carbonates. Core samples from multiple deep boreholes within the Huron Domain were analyzed for petrographic, stable and Sr isotopic composition, fluid inclusion microthermometry and major, trace and REE to characterize diagenetic history, fluid composition and sedimentary provenance.
Cambrian and Ordovician data suggest two possibly isolated diagenetic fluid systems: i) an earlier fluid system that is characterized by a pronounced negative shift in oxygen and carbon isotopic composition, a more radiogenic ratios, warm (84-156 ^{o}C for dolomite and 87-141 ^{o}C for calcite;) and saline signature (23.2 to 27.2 wt.% NaCl eq. for dolomite; and 23.6 wt.% NaCl eq. for calcite); and ii) a later Ordovician system, characterized by less negative shifts in oxygen and carbon isotopes, hypersaline (22.4 to 30.1 wt.% NaCl eq. for dolomite and 27.5 to 29.7 for calcite), comparable homogenization temperature (T_h =85-132 ^{o}C for dolomite and 66 to 153 ^{o}C for calcite) and a less radiogenic fluid system.

In contrast, the isotopic data of the overlying Silurian and Devonian carbonates show overlaps between δ^{13}C and δ^{18}O values. Dolomite samples from both age groups show similar δ^{13}C values compared to those of carbonates deposited in equilibrium with seawater of respective age. However, δ^{18}O values show evidence of dolomite recrystallization. Negative shifts of δ^{18}O in early-formed dolomite can be due to alteration during burial. Ordovician, Silurian and Devonian Sr isotopic ratios show seawater composition of their respective age as the primary source of diagenetic fluids with minor rock/ water interactions. Pervasive replacive medium crystalline dolomite matrix show T_h ranges from 49.7 to 134.1 °C and salinity of 22.0 to 25.2 wt. % NaCl) and from 69.9to 102.3 °C, and salinity of 18.9 to 21.8 wt. % NaCl for the Silurian and Devonian samples, respectively. Higher homogenization temperatures (101-193 ^{o}C) and salinity (25.9-32.6 wt. % NaCl eq.) Characterizing fluid inclusions hosted in saddle dolomite in the Silurian sequences cannot be justified by burial only; which may suggest the involvement of hydrothermal fluids during its formation. Hydrothermal fluid migration and its influence on later saddle dolomite, likely occurred during Paleozoic orogenesis. However, Evidence indicate that diagenesis is horizontally uniform across the Huron domain, displaying few signs of significant vertical connectivity beyond formation tops, except in areas with local heterogeneity (faults).

Dolomitization of the Middle Jurassic limestones at the Vajont Canyon (Southern Alps, Italy): fault-controlled dolomitization by hypo- to mesosaline fluids

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Keywords: dolomites; stable isotopes; timing

Abstract

The Middle Jurassic limestones of the Vajont Formation, which constitute major parts of the flanks of the Vajont Canyon (Southern Alps, Italy), have been subjected to pervasive dolomitization. The dolomites are localized within fault damage zones. Based on the field and petrographic characteristics, two dolomite groups can be differentiated. Group 1 dolomite, being the most prevailing, corresponds to the matrix replacive dolomites. They form non-stratabound plume-like geobodies, and occlude the infrequent veins outside but adjacent to these

replacive plume-like dolomite bodies. Group 2 dolomite, that is less common as matrix replacive, constitutes saddle dolomite cements in breccia and veins or makes up zebra dolomites. The latter cements frequently affect the replacive ones. Fluid inclusion analysis of both dolomite groups indicates comparable salinity values of 1.2 to 5.3 eq. wt.% NaCl with homogenization temperatures of 70 to 108°C, which in addition to $^{87}Sr/^{86}Sr$ ratios (0.70811 to 0.70846) reflect similar parental fluids. The estimated salinities, in combination with $\delta^{18}O$ values (-5.5 to -14.8‰ V-PDB) indicate significant contribution of ^{18}O-depleted fluids postulated to be of meteoric origin. This origin is supported by the low trace element concentrations typifying the studied dolomites. These data support the hypothesis that the fault-controlled dolomites precipitated from hot hypo- to mesosaline fluids. We suggest that the Mg-rich dolomitizing fluids most likely were derived from underlying Upper Triassic Dolomia Principale strata that were modified by descending meteoric waters. Although, inherited Mesozoic syn-rift fault and fracture corridors could have been (re-)used by the circulated fluids, the fault systems that developed during the Neo-Alpine Orogeny (Miocene) are believed to have predominantly served as efficient deep-seated fluid migration conduits as well as relatively shallow ones facilitating the downward infiltration of meteoric waters.

Multi-stage diagenesis and dolomitization of Jurassic shelf-margin carbonates, Essaouira-Agadir basin, Western Morocco

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Key words: Dolomitization, hydrothermal, seawater, Jurassic, Morocco.

The Jurassic of the Essaouira-Agadir Basin (EAB) of Morocco is dominated by thick carbonate platforms alternating with siliciclastic sediments, overlaying the Central Atlantic Magmatic Province (CAMP) basalt. These platforms were periodically dolomitized and constitute proven, but poorly understood reservoirs, offshore Morocco. Extensive outcrop, petrographic and geochemical analyses in the EAB was performed to determine the controls on dolomite distribution in three successions:

<u>Sinemurian:</u> which crops out in the salt cored Amsittene Anticline as massive then thinly bedded, heavily fractured dolomitized oncoidal-oolitic wackestone-packestone and mudstone. The transition from dolostone-limestone is striking in the field, defined by a marked colour contrast displaying gradual transitions vertically and sharp and irregular, fracture-related lateral boundaries. Dolomite comprises euhedral-subhedral, bright luminescent crystals and is nearly-stoichiometric (av. 50.8 mol% $MgCO_3$). The $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values (av. -3.49‰ and av. 1.61‰, respectively) display a constant value that is slightly enriched in comparison with the host limestone. Clumped isotope data indicates dolomitzation at 66°C to 90°C, which implies dolomitization from isotopically enriched fluids ($\delta^{18}O_{water}$ = 3.01 to 7.45‰SMOW). Dolomitization is interpreted to have occurred at two different stages: 1) as a result of seawater reflux (i.e. slightly evaporated seawater), and 2) by interaction with the underlying Triassic salts during salt diapirism and formation of the anticline.

<u>Toarcian:</u> shallow open marine- restricted marine carbonates crop out in the Barrage Aquesri area as stratabound, laterally extensive dolostones of mudstone, oolitic and peloidal wackestone-grainstone texture alternating with non-dolomitized limestone beds. Petrographically, these dolomites appear as fabric preserving replacive euhedral-anhedral crystals. The $\delta^{18}O_{VPDB}$ and $\delta^{13}C_{VPDB}$ values (av. 0.72‰ and av. 3.85‰, respectively) are enriched in comparison to the host limestone and dolomitzation is interpreted to have occurred by reflux of seawater in the shallow subsurface.

Lower Oxfordian: discontinuous coral build-ups show complex lateral and vertical facies variations. Dolomitization occurs predominantly in coral rich floatstones and rudstones and comprises anhedral and saddle dolomite textures with a dull luminescence under CL. Isotopic data is wide-ranging ($\delta^{18}O_{VPDB}$ = -4.39 to -9.56‰; $\delta^{13}C_{VPDB}$ = 1.84‰ to 3.55‰) suggesting formation by two different fluids (i.e. seawater and hydrothermal fluids). Clumped isotope data from saddle dolomite measured temperatures of av. 124°C compared to av. 80°C in the host limestone suggesting formation by hydrothermal fluids migrating along strike-slip and thrust faults created during the Alpine orogeny. It is possible that the concentration of Mg^{2+} within the fluids was increased by interaction with olivine and pyroxene within the CAMP basalts.

In summary, the results demonstrate a variety of dolomitization processes that can occur within a single basin at different stratigraphic levels as a result of variability in the climate, depositional architecture, composition of the underlying stratigraphy and basin-scale tectonics.

Mechanism of multiphase dolomitization in the Jurassic Carbonates (Samana Suk Formation), Himalayan Foreland Basin, North West Pakistan.

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The Jurassic Carbonates of Himalayan foreland Basin, Pakistan are extensively dolomitized. The integrated field, petrographic (conventional, CL, SEM), isotopes, fluid inclusion, major and trace elements techniques are applied to unravel the possible mechanism of dolomitization. Field observations show both bedding parallel strata bound and patchy hydrothermal dolostone geobodies are present at regular interval within the host limestone. Petrographic studies reveal the seven phases of dolomites and three phases of calcites were identified based on texture, crystal size and morphology. These phases are: Matrix dolomites (MD-I to MD-IV), Repalcive Hydrothermal Dolomites (RD-I to RD-III), cementing dolomite (CD-I) and cementing saddle dolomites (SD-1 and SD-2) and calcites (CC-I to CC-III). Stable isotope data show that matrix dolomite have $\delta^{18}O$ values (-0.99‰ to -2.94‰) coeval with the Jurassic carbonates. The hydrothermal dolomites show a depletion trend in $\delta^{18}O$ isotope values (-4.68‰ to -6.88‰) V-PDB suggesting the deep burial and higher temperature of these dolomites. The fracture filling calcite shows more depletion in $\delta^{18}O$ trend (-8.87 to -12.32). The $\delta^{13}C$ values of the host limestone, dolomites are consistent with the Jurassic sea water. $^{87}Sr/^{86}Sr$ ratios of dolomite, calcite ranges between 0.70734-0.710448 showing late diagentic alteration of limestone and the fluids coming from more radiogenic source. Mn, Fe, Na concentration of the matrix dolomites is relatively less than replacive dolomites suggesting the hydrothermal source of replacive dolomites in reducing conditions. Late calcites showing depleted trend in all elements suggesting the water from meteoric source.

Homogenization temperature of the primary fluid inclusions present in saddle dolomites ranges between (110-130°C) and late calcite ranges from (45-63°C) with average

salinity of saddle dolomite ranging from 13 wt.% NaCl eq. suggesting the hot basinal brines from the basement rocks coming through fracture corridors are responsible for the replacive dolomitization.

Field observation, petrographic and geochemical data suggests that there are two distinct events of dolomitization. Matrix dolomite forms at shallow depths by the interaction of rocks with modified sea water while the replacive and saddle dolomites forms by deep burial by the interaction of hydrothermal fluid from basement rocks.

The importance of this study is that field analogue of the heterogeneities in the carbonate succession can be taken as an example for the exploration of hydrocarbons in the complex carbonate units in foreland basins of Himalayan ranges of Pakistan.

Key Words: Carbonates, Hydrothermal, Stable Isotopes, Salinity

Dolomitized geobodies in the late Jurassic – lowermost Cretaceous limestones (Maestrat basin, Iberian Chain)

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Key words: Dolomitized geobodies, late Jurassic – lowermost Cretaceous, Maestrat basin

Late Jurassic-lowermost Cretaceous limestones and dolomites are the reservoir rocks in the western Mediterranean offshore. The onshore Maestrat basin, located in the southeastern part of the Iberian Chain, underwent the same dolomitization processes and, therefore, a thorough understanding of the fluid circulation patterns and resulting dolomitization in this basin is of great interest for predicting the reservoir quality.

The late Jurassic-lowermost Cretaceous syn-rift deposits are characterized by shallow marine carbonates with $\delta^{18}O$ values ranging from -8.1 to -0.1 ‰ V-PDB, and $\delta^{13}C$ values ranging between -6.6 and +2.3 ‰ V-PDB.

Dolomitization was mainly controlled by fractures, but also by unconformities, the precursor limestone textures, stratification planes and heterogeneities. The dolomitized bodies are decimetric to kilometric in length and up to 150 m thick, displaying wedge morphologies associated with faults. The dolomites are Ca-rich, with low Mn, Sr and Na contents and variable Fe content. The $\delta^{18}O$ values of the replacive dolomite and dolomite cements range from -9.8 to -1.3 ‰ V-PDB and the $\delta^{13}C$ from -3.9 to +2.4 ‰ V-PDB. The $^{87}Sr/^{86}Sr$ ratios of replacive dolomites are more radiogenic than those of the limestones, ranging from 0.70740 to 0.70798.

Although younger Cretaceous dolostones occur in the Maestrat Basin, the timing of dolomitization in this study is between 142 and 134 My ago, constrained by the age of deposition of the limestone unit affected by dolomitization (between 148 and 142 Ma) and the age of the Upper Hauterivian marine deposits on top non-dolomitized freshwater limestones (134 Ma). The dolomitized section is affected by an erosive surface, above which non-dolomitized freshwater limestones with dolomite cobbles within were deposited.

Dolomitization occurred soon after limestone deposition, affecting still porous and poorly compacted limestones, simultaneously with the development of horsts and grabens during the late Jurassic-early Cretaceous rifting stage and during subaerial exposure of the uplifted blocks.

Exposure of the uplifted and titled blocks, during the rifting, favored the entrance of topographically-driven meteoric waters into the basin downwards towards a good permeable horizon represented by the highly karstified Lower Muschelkalk carbonates. This fluid became enriched in Mg when passing through Triassic and Jurassic carbonates and evaporites, producing partial dissolution, and it was probably mixed with Mg-rich fluids derived from the expulsion of crystallization waters during clay transformation and dewatering. The deduced isotopic composition of the fluid (-5 to +10 ‰ SMOW), together with fluid temperatures between 70 and 120ºC and salinities ranging from 16 to 23% NaCl weight$_{eq.}$, support the contribution of deep basinal brines.

In this extensional setting, large convective cells, related to a thermal anomaly, heated and drove the infiltrated meteoric fluids towards shallower levels along fractures until they reached a more surficial and permeable horizon, triggering dolomitization. The potential of dolomitization diminished away from fractures. Accumulation of ascending fluids in fault zones at pressures and temperatures greater than those of the surrounding pore fluids produced the replacement of the host limestone, preferentially in the hanging wall of faults.

Hydrothermal-sedimentary dolomites in a continental rift basin: petrographic and geochemical evidence from the Lower Cretaceous Erlian Basin, Northern China

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Abstract

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Dolomites occur extensively in the lower Cretaceous along syn-sedimentary fault zones of the Baiyinchagan Sag, westernmost Erlian Basin, within a predominantly fluvial-lacustrine sedimentary sequence. Four types of dolomite are identified, associated with natrolite, analcime and Fe-bearing magnesite as hydrothermal minerals. The finely-crystalline dolomites consist of anhedral to subhedral crystals (2–10 µm), evenly commixed with terrigenous sediments that occur either as matrix supporting grains (Fd1) or as massive argillaceous dolostone (Fd2). Medium-crystalline (Md) dolomites are composed of subhedral to euhedral crystals aggregates (50–250 µm), and occur in syn-sedimentary deformation laminae/bands. Coarse-crystalline (Cd) dolomites consist of non-planar crystals (mean size >1 mm), and occur as fracture infills crosscutting the other dolomite types. Fd1, Md and Cd dolomites have similar values of $\delta^{18}O$ (−20.5 to −11.0 ‰ VPDB) and $\delta^{13}C$ (+1.4 to +4.5 ‰ VPDB), but Fd2 dolomites are isotopically distinct ($\delta^{18}O$ −8.5 to −2.3‰ VPDB; $\delta^{13}C$ +1.4‰ to +8.6‰ VPDB). The rare earth element content of the dolomites is highly variable (97.24–328.08 ppm) and samples define three groups which differ in LREE vs. HREE enrichment/depletion and significance of Tb, Yb and Dy anomalies. Md dolomite indicate formation from brines at very high temperature, with salinities of 11.8–23.2 eq. wt% NaCl and Th values of 167–283°C. The calculated temperatures of Fd1 and Cd dolomites extend to slightly lower values (141–282°C), while Fd2 dolomites are distinctly cooler (81–124°C).

These results suggest that the dolomites formed from hydrothermal fluid during and/or penecontemporaneous with sediment deposition. The networks of faults and fractures that bound the basin were important conduits through which high-temperature Mg-rich fluids discharged, driven by an abnormally high heat flux associated with local volcanism. It is thought that differing amounts of cooling and degassing of these hydrothermal fluids, and of mixing with lake waters, facilitated the precipitation of dolomite and associated minerals, and resulted in the petrographic and geochemical differences between the dolomites.

Keyword: Early Cretaceous, Hydrothermal dolomite, Lacustrine dolomite, Rift Basin, Syn-sedimentary dolomite,

origin of dolomite from the Lower Miocene Sanya Formation, Shidao, Xisha Islands, South China Sea

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Unlike the Tertiary carbonates from Atlantic-Caribbean area that are commonly exposed on islands, the Tertiary carbonates on Xisha Islands are completely buried in subsurface. Hence, outcrops of Tertiary carbonates are not available on Xisha Islands and access to these samples are only possible by drilling cores. In the past tens of years, several wells were drilled to various depths in the Xisha area, revealing the existence of Miocene-Pleistocene carbonate successions on Xisha Islands. The Miocene-Pliocene carbonates underwent extensive dolomitization and these dolomites have been interpreted to be formed by a variety of mechanisms such as mixing zone dolomitization, seepage reflux of hypersaline brine, and burial dolomitization. The absence of evaporites or relics of evaporites in these dolomites, however, makes the involvement of hypersaline fluids most improbable. Previous work showed that the most applicable explanations are the mixing-zone hypothesis or dolomitization by seawater driven either by reflux or Kohout convection. This study will focus on the dolomite of the Lower Miocene Sanya Formation from a core (XK#1) taken on the Shidao Island of Xisha Islands. Based on examination of the textural patterns and diagenetic events, the purpose of this study is to derive a re-interpretation of the origin of the Miocene-Pliocene dolomite from Xisha Islands. The results obtained from this study may help further understand the formation of island Miocene-Pliocene dolomite in the world.

Key words: dolomite; Miocene; South China Sea; Xisha Islands

Neogene synchronic dolomitization events. Are they real?

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Keywords: Dolomitization, Neogene, Sr-dating, Red-algal facies

Neogene dolomitization has received considerable attention in the last three decades especially since, it shows significant abundance leading to the hypothesis of possible synchronic events (Budd, 1997). Questions have been risen to address this phenomenon such as, are they real or bias to data availability? Is the dating method reliable? what are the origin of those events? To response those interrogations, we present a compilation of two detailed studies of Neogene carbonate platforms (Bonaire island and Maldives archipelago) as well as published data from 15 localities worldwide with different diagenetic histories. This dataset was used to compare several dolomitization types, host rocks and timing.
Neogene dolomites have been dated using Sr isotopes which is the most reliable method during this period. However, questions remain about the insufficient resolution of dating to precisely define the processes responsible for these occurrences. In spite of that, different authors have suggested dolomitization event and correlating succession on the Caribbean and worldwide (e.g. Budd, 1997; Jones and Luth, 2003; Ren and Jones, 2017), but with limited data.
Results of the most recent published data (535 data points) show a very consistent frequency of event during the Mio-Pliocene times. This data display only 5 main events contrasting with other proposed events (e.g. Budd, 1997). Also, the geographical distribution shows that the older events (Early Miocene) are more abundant towards the middle East and Far East, in contrast with the Caribbean and the Mediterranean Sea which events are highly concentrated during Mio-Pliocene times, finally, the younger events are located in the Atlantic Ocean (the Bahamas).
Numerous hypotheses have been proposed for origin of dolomitization events including allogenic processes such as stable sea level and global aridity (e.g. Messinian salinity crises) and (Budd, 1997). However, issues remain about the sufficient evidences that support those hypotheses due to differences in diagenetic environments producing synchronic and similar dolomitization events. For instance, Bonaire is an isolated carbonate platform that has been uplifted with little burial history, in contrast to the Kardiva Platform, The Maldives which drowned in the late Miocene close after deposition. However, those two platforms present very similar and synchronic dolomitization events which will be controversial to explain by only with sea-level arguments.
After comparing several succession and extensive literature review the results currently shows there is a gross correlation between high-Mg calcite coralline red algal facies abundance with dolomitized sections within most of the revised examples. This characteristic is the only consistent element in most of the dolomitized succession. For that reason, as an alternative, we propose the hypothesis that bioclastic (red-algal facies) contribution may have affected the dolomitization susceptibility of those platforms by

acting as dolomite seeds, which may reduce the kinetic barriers to dolomitization.
This ties neatly with Mio-Pliocene ocean ecological conditions, which favored coralline algal deposits as Pomar and Hallock (2008) suggested. The combination of ocean and climatic conditions with the presence of abundant algal deposits at platform edges and shallow slopes may have acted synchronously to trigger dolomitization events during the Neogene.

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Heterogeneous dolomite recrystallization in the Marion Plateau: a multi-scale approach.

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Much debate exists on the extent to which early dolomites recrystallize and preserve the signature of their primary diagenetic setting. Here, we combine clumped isotopes thermometry with X-ray diffraction to study dolomite recrystallization under shallow burial (<1 km) conditions. We analysed dolomite samples from two Miocene carbonate platforms on the Marion Plateau, NE Australia. Marion Plateau dolomites provide an ideal case study to examine the effects of recrystallization because of the relative simplicity of the geological setting, with simple subsidence, and several episodes of early dolomitization by normal Miocene sea water.

We investigate dolomite recrystallization at two scales. First, we investigate if some mimetically dolomitized fossils, such as red algae, have better preserved the condition of the primary diagenetic setting. Then, we look at recrystallization processes from the sea floor down to 700 mbsf.

Results show that Marion Plateau dolomites are very rich in calcium, poorly ordered and their formation temperature $T(\Delta_{47dol})$ ranges between 12 and 35°C. Shallow buried dolomites are very heterogeneous and contain different values of $T(\Delta_{47dol})$, $\delta^{18}O_{dol}$, and $\delta^{13}C_{dol}$ in the same sample. Dolomitized red algae are in general warmer than their surrounding dolomitized matrix and may be preferential spots for recrystallization.

The degree of dolomite recrystallization increases with depth and we described four dolomite types with increasing degree of recrystallization (D1, D2, D3 and D4). The computed fluid composition ($\delta^{18}O_w$) falls in the range of sea water composition, but a correlation between $T(\Delta_{47dol})$, $\delta^{18}O_{dol}$, and $\delta^{18}O_w$ exists: the higher the crystallization temperature, the more negative the fluid composition is. $\delta^{18}O_{dol}$ and Δ_{47dol} tend to both decrease with depth, whereas $\delta^{18}O_w$ increases with depth. We interpret the negative correlation between $T(\Delta_{47dol})$ and $\delta^{18}O_w$ as evidence of shallow burial recrystallization via dissolution/re-precipitation. Modelling of the $\delta^{18}O_w$ indicates that the recrystallization happened at very low water to rock ratio.

This study shows that $T(\Delta_{47dol})$ and $\delta^{18}O_{dol}$ have been modified by recrystallization. Therefore, they cannot be used to reconstruct the primary diagenetic setting. We caution that this implies greater temperature heterogeneities in dolomites from deeper buried platforms.

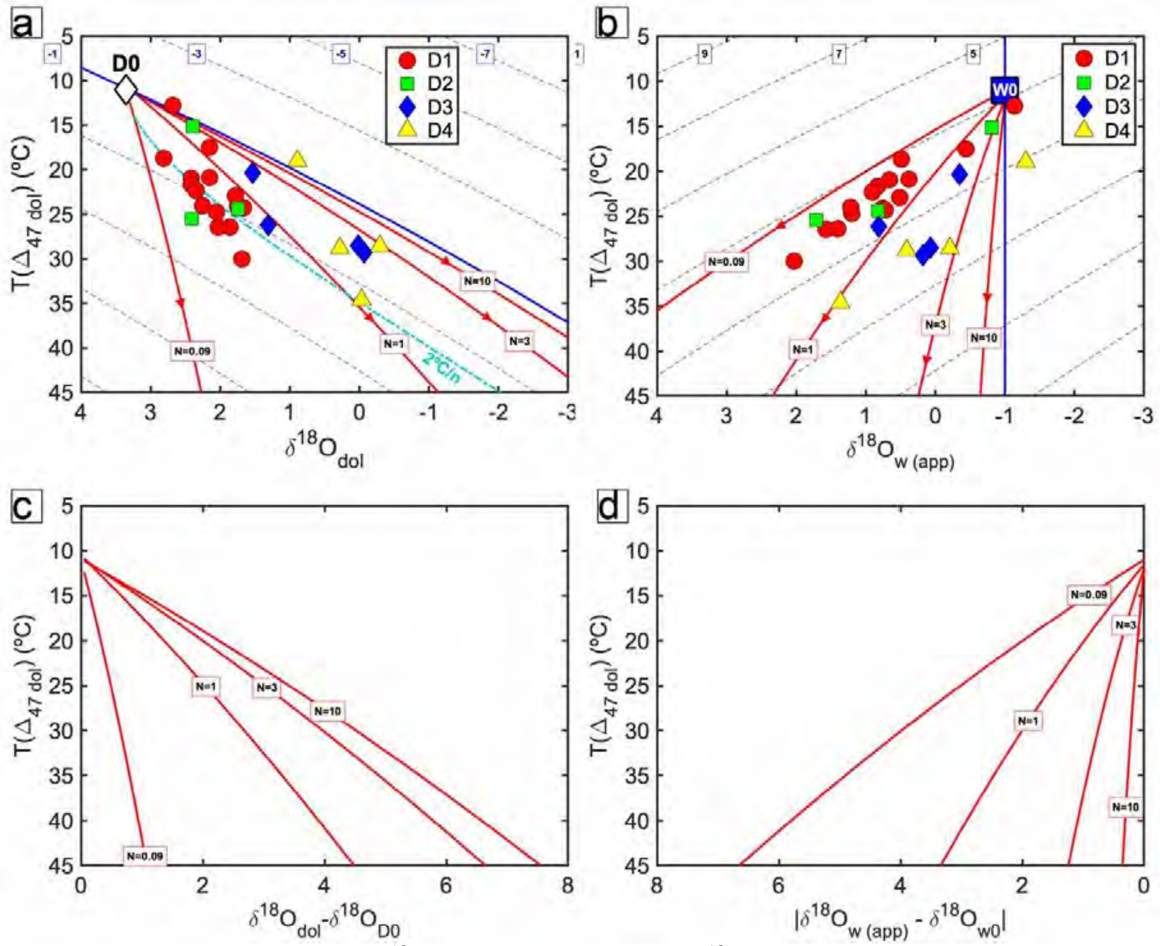

Figure 1: (a) Plot of $T(\Delta_{47dol})$ and $\delta^{18}O_{dol}$ and (b) $T(\Delta_{47dol})$ and $\delta^{18}O_w$ in Marion Plateau dolomites (D1-4) compared to the values predicted by the recrystallization model at increasing temperatures. According to the recrystallization model, D1 and D2 have mostly recrystallized at low cumulative water to rock ratio (N<1). D3 and D4 have recrystallized with about 50 m^3 of water and a temperature increase rate half that of D1 and D2. (c) Difference between $\delta^{18}O_{dol}$ and $\delta^{18}O_{D0,}$ and (d) difference between $\delta^{18}O_{w(app)}$ and $\delta^{18}O_{w0}$ predicted by the recrystallization model at increasing temperatures. The red curves are cumulative water to rock ratio of N=0.09, 1, 5, and 10. The difference between $\delta^{18}O_{dol}$ and $\delta^{18}O_{D0}$ increases when the T_{sys} and N increase. The difference between $\delta^{18}O_{w(app)}$ and $\delta^{18}O_{w0}$ increases when T_{sys} increases and decreases when N increases.

'Retreating 'dolomitization fronts: a new insight to hydrothermal dolomitization

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Keywords: Dolomitization; Fault; Hydrothermal; Reaction Fronts

Dolomitization processes are well studied, but the controls on the spatial extent of dolomitization are still not well understood. Nevertheless, although dolostone-limestone boundaries should inform us as to the controls on the termination of dolomitization, they have been considerably under-studied. In particular, very few papers document the textural, petrophysical and geochemical changes that take place across these reaction fronts, even though they could provide information on the history of fluid movement.

This study presents a new, high-resolution petrographic and geochemical dataset, collected across the stratabound termination of the Middle Cambrian Mount Whyte Formation, Western Canada Basin, with comparison to other fault-controlled dolostone bodies in the Jurassic, Morocco and the Carboniferous, UK. The petrographic-mineralogical data show a distinct change across the reaction front and can be separated into 3 different characteristics from the core of the body to the rim: (i) anhedral, unzoned, interlocking stoichiometric dolomite crystals, (ii) subhedral-anhedral, weakly zoned, near-stoichiometric crystals with minor porosity, and (iii) non-stoichiometric (calcium-rich), euhedral-subhedral, multiply concentric zoned dolomite crystals and intercrystalline porosity. The temperature across the termination is also aligned with their petrographic characteristics and spatial location, with progressive cooling towards the margin of the bodies (from 235^{o}C at the core to 132.5 ^{o}C at the margin).

Dolomite becomes stoichiometric by successive recrystallization of precursor, non-stoichiometric dolomite, and the decrease in stoichiometry and temperature at the dolostone-limestone termination implies that dolomite at the reaction front has not undergone recrystallization and stabilization to the same extent as the core. This could occur if the reaction front is the youngest part of the dolostone body, or if it is older than the core of the dolostone body but has not undergone recrystallization because subsequent flux of dolomitizing brine did not permeate as far as this contact. Since the dolostone at the core of the body has no porosity, and comprises an interlocking fabric, recrystallization appears to have closed down the pore network, which would have inhibited the flux of subsequent fluids to the dolomite front.

The data are therefore interpreted to record preservation of the oldest reaction front within the body, frozen in time. As such, the position of the reaction front is interpreted to have 'retreated'; i.e. progressive flux of dolomitizing fluid recrystallized the precursor dolomite and reduced porosity by creating an interlocking mosaic crystal texture. This lowered permeability and limited the advance of subsequent dolomitizing fluids. In most of the studied outcrops, dolomite at the reaction front is more porous than at the core, suggesting that halos of good porosity on the margins of dolostone bodies reflects preservation of an optimal phase in the dolomitization process for porosity creation.

Understanding effective controls on hydrothermal dolomitisation: insights from 3-D Reactive Transport Modelling of geothermal convection

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Keywords: dolomitisation, hydrothermal dolomite, reactive transport model, TOUGHREACT

Hydrothermal dolomite (HTD) is economically important as a hydrocarbon reservoir, and also as a host for ore deposits. HTD forms at temperatures that are elevated compared to adjacent host rock, as a result of fluid flow focussed along faults most often within extensional or strike-slip settings. However, there are a number of ambiguities in existing conceptual models for HTD formation, specifically regarding Ca/Mg ratios of deep brines and mechanisms for delivering sufficient volumes of reactive fluid to drive dolomitisation. Reactive Transport Model (RTM) simulations offer a pathway to evaluate conceptual models for HTD genesis, but prior simulations using 2-D models oriented perpendicular to the plane of the fault misrepresent important aspects of system.

Here we present preliminary results from 3-D RTM simulations of a generic single transmissive fault system embedded within a porous and permeable carbonate reservoir. Our objective is to evaluate the potential for alternative sources of Mg^{2+}-rich fluids, and the effect of flux of these fluids across thermal gradients within the fault and exchange with the host rock. We examine the evolution of fluid chemistry and distribution of diagenetic alteration, including predictions of the rate, distribution and temperature of HTD formation. Simulations are conducted using TOUGHREACT, a non-isothermal RTM capable of simulating multiphase fluid flow, heat and solute transport with physical and chemical heterogeneity.

Simulations show that when a relatively permeable fracture zone is open to the sea floor, a single pass convection cell develops which draws in cool high Mg/Ca seawaters. As these fluids become heated they precipitate dolomite within the downwelling limb of the convective cell. Following an induction period of 500-1,000 years, reaction rates are rapid, with significant dolomitisation in the baseline simulation within 10-15 Ky, at depths between 1.5 and 2 km and at temperatures of 80-150°C. Dolomitisation occurs as a gradient reaction, with only very minor alteration of calcite upstream of this zone where reaction rates are limited by advective cooling, and rates limited downstream by the elevated Ca/Mg resulting from replacement of calcite by dolomite. Whilst slow rates of fluid flow within the surrounding limestones mean that dolomitisation is confined to the more permeable fault damage zone, the distribution of dolomite within the plane of the fault reflects the advection of heat within the host rock.

The locus and temperature of dolomitisation within the convection cell shifts in response to changes in thermal input, reaction rate (initial fraction dolomite and effective reactive surface areas) and fault and host rock permeability. In particular the degree of hydraulic continuity with the overlying water body, as well as the chemistry of this water, determine the nature of hydrothermal diagenesis within the fault damage zone. Preliminary simulations suggest that injection of using fluids representative of basinal brines have limited potential for formation of HTD irrespective of temperature, although mixing within the surface fluids (seawater, or brines derived from evaporation of seawater) may increase dolomitisation potential and account for HTDs with geochemical characteristics indicative of a contribution of basinal fluids.

Depositional facies, structural setting and associated reservoir properties of hydrothermal dolomites: a case study of ooid – peloid grainstones

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Key words: hydrothermal dolomite reservoirs, depositional facies, diagenetic alteration, feeder faults and water-rock interaction

Hydrothermal dolomitisation is known to result in variable reservoir properties. This may be due to the combination of a number of parameters such as depositional facies of the host rock, diagenesis pre-dating hydrothermal dolomitisation, distance to feeder faults, texture of the dolomites, etc.

A hydrothermal dolomite body developed in ooid and peloid grainstones represents a unique example in which the depositional facies and structural setting (upper part vs. lower part of the reservoir and distance to feeder faults) are interpreted to control the secondary porosity and permeability resulting of hydrothermal dolomitisation.

In the hydrothermal dolomite reservoir studied four reservoir facies are distinguished: 3 pervasively dolomitised facies, i.e. well-sorted ooid grainstone, bimodally sorted ooid – peloid grainstone, peloid grainstone and partially dolomitised ooid and peloid grainstones. The well-sorted ooid grainstones are interpreted to represent the top and windward flanks of the ooid shoal, whereas the bimodally sorted ooid and pelloidal grainstones are interpreted as lower energy facies deposited on the shoal flanks or on its leeward margin and the lagoon.

Secondary porosity in the hydrothermal dolomites mostly consists of oomouldic and intercrystalline porosity and the grain size the precursor facies is reflected in the porosity and permeability of the dolomites. Dolomitised grainstones consisting of large and well-sorted ooids have better reservoir properties than dolomitised grainstones consisting of bimodally sorted, smaller ooids and peloids. Dolomitised pelloidal grainstones are also characterised by lower porosities, except when a sucrosic fabric developed.

In partially dolomitised ooid and peloid grainstones the ooid's cores are preserved. Much lower porosities are associated with this reservoir facies. In the partially dolomitised grainstones the hydrothermal dolomite represents a smaller proportion of the rock than in the pervasively dolomitised facies, i.e. ≤56 % for partially dolomitised facies and >70% for pervasively dolomitised facies. This suggests that the degree of dolomitisation plays a role in the development of oomouldic and intercrystalline faults.

When taking the general structural setting of the hydrothermal dolomite reservoir into account the pervasively dolomitised facies occur closer or in the higher parts of the reservoir, whereas the partially dolomitised facies is generally found in the lower part of the reservoir or further away from the main feeder faults.

The origin and features of pores of dolomites in the third and fourth member of Leikoupo Formation of The Middle Triassic in NW Sichuan Basin

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Abstract: Dolomitization is an important depositional and diagenesis process greatly affecting the reservoir quality. Based on the studies with regard to petrography, carbon, oxygen, strontium and magnesium isotope as well as the major and minor element data and ratios of bulk dolomites, seven types of dolomites has been systematic classified. i.e.①micritic dolomite with gypsum or anhydrite co-exist AD0, ②micritic dolomite D0,③ micritic and microcrystalline dolomite D1,④microcrystalline and finely crystalline dolomite D2,⑤fully dolomitized microbialite MD, ⑥ calcium bearing dolomite CDand ⑦ calcitized micritic and microcrystalline dolomite (de-dolomite) CD0、CD1.the average sequentiality(δ), is lower compared with typical dolomites in reflux dolomitization models, and the concentration of Mn and Fe are also rather lower with predominantly dark purple, purplish red, and blue purple ,less common by rose-red, orange red and yellow-red (CL). The stable isotope for values for seven different types dolomites are $\delta^{13}C_{PDB}$（1.95‰~2.46‰）and $\delta^{18}O_{PDB}$（-4.05‰~2.70‰）,while for $^{87}Sr/^{86}Sr$（0.70778~0.70807）and $\delta^{26}Mg$（-1.872‰~-2.124‰), indicating that the $\delta^{13}C_{PDB}$ and $^{87}Sr/^{86}Sr$ of dolomites within the range of globe sea-water change and minor negative offset or positive for $\delta^{18}O_{PDB}$ in the Middle Triassic. A few D0 and MD as well as AD0 are rich in the concentration of silicon, aluminum with present by a few low or high magnesium calcite, clay minerals and organic matters. Except for few of the concentration (Sr^{2+}+Ba^{2+}) is large than the (Mn^{2+}+Fe^{2+}+Zn^{2+}), and assumed as predominantly calcite and subordinate aragonite structure for proto-dolomites ; From the type of D2 to D1, or D0 and AD0， the concentration Sr and Na、most of minor-elements and ratios of bulk various dolomite, as well as $\delta^{18}O$ shows an increasing tendency ； imply that would been euryhaline, penesaline and alkaline, hyperhaline sedimentary environment .heterogeneous geochemical data prevailing in same type dolomite reveal that multi-controlling factors effect on the dolomitization process, which would be owing to shallowing upward of metre-scale cycles of deposition unites, dominantly arid and hot with occasional humid intervening climatic condition, the change lateral in lithofacies or microfacies arguably ascribed to the migration of margin or barrier of microbialite, and beach & shoal or microbial mats or bioherms. here the composite of reflux and sabakha dolomitization model has been put forward to decipher the distribution of seven types of dolomites: i.e. the AD0 or D0 most likely to been formed in a shallow lagoon, belong “Sabkha” supratidal, D0、D1 and MD(mediation of microebes) and a few AD0 in a restricted lagoon of intertidal, MD、CD1 and CD took place between the intertidal and subtidal in margin or barrier, D0、D2、CD1 and MD (in microbial mats, mounds or bioherms) in the flat (or tidal channels)or an open lagoon & the open platform, and the late-three mention cases believed to closely associate with reflux dolomitization driven by either topographic head-driven or density-difference by evaporation pump . The reservoir consists of pores and poroe-fressures types, and would be divided into deposition fabric -related pores, intercrystalline pores, intercrystalline and dissolved pores and microfissure; sedimentary microfacies such as algae mats and mounds and early diagenesis and structural fissure developed in tidal flat and lagoon are the main control factors for the formation and preservation of reservoir.

Key words：Dolomite type，Petrography，Geochemistry， Dolomitization model，types of pore; Leikoupo Formation

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Dolomite dissolution-precipitation mechanism in deep burial environment

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Abstract: In recent years, deep and ultra-deep dolomite reservoir has shown great potential in petroleum exploration. However, the prerequisite in prediction of high quality deep ultra-deep dolomite reservoirs lays on the mechanism of dolomite dissolution/precipitation. In this study, we conducted dissolution-precipitation simulation experiments under deep burial environments (semi-open and closed systems). The effects of temperature, pressure, microbial, dissolved ions (calcium, magnesium, sulfate ion etc.) and pH on the dolomite dissolution-precipitation process were investigated under high temperature and high pressure (~200ºC; ~70Mpa) with a series of petrographic and geochemical analytical methods. The results showed that thiobacillus thiooxidans accelerated the dissolution process of dolomite and calcite. The dissolution capacity of dolomite surpassed that of calcite when the temperature was over 175ºC with sulfate ion due to surface-complexation processes of sulfide and cation. Our study will provide basic theory in predicting dolomite reservoirs.

Keywords: deep ultra-deep; dolomite; microbial; dissolution-precipitation; simulation experiment;

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Why is it easier to form and maintain high quality dolomite reservoirs in deep layers?

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Abstract: Whether there is a high quality reservoir in the deep-ultra deep layers is the prerequisite in an effective oil and gas exploration and development. Dolomite reservoir in deep layer is proved to play an important role during current exploration practice. High quality dolomite reservoirs was found in depth over 8400m in the two deepest exploratory wells in China, MS1 and TS1, respectively. Why is it easier to form and maintain dolomite reservoirs in deep layers? In this study, high quality dolomite reservoirs were found to form through the combined and compound mechanisms in various diagenesis stages, based on a series of case studies and high-temperature-pressure simulation experiments. In the penecontemporaneous period and early diagenesis stage, hydrocarbon generation and TSR in an open-fluid environment and deep burial conditions provided the basis for pore formation. The dissolution of dolomites overwhelms that of limestone with high temperature fluids (with specific ions such as sulfate etc.), provides the key mechanism in the formation and maintain of high quality dolomite reservoirs. Finally, the stronger ability to resist the compaction from dolomite over limestone, makes it easier to sustain the pore of the deep layer dolomite reservoirs in a long period.

Keywords: deep ultra-deep; dolomite; reservoir; water-rock interaction;

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Relationship between iron-rich dolomite and hydrogen sulfide -an example from Majiagou formation in Danudi

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Abstract: The gas reservoir of Ordovician Majiagou formation in ordos basin contains a certain amount of hydrogen sulfide, which is formed in the thermochemical sulfate reduction. However, compared with the marine gas reservoirs in other basins, the sulfur content is relatively low, and the distribution is extremely uneven. Through investigation and comparison, we find that the reduction of hydrogen sulfide in the study area has little correlation with the distribution of anhydrite, temperature, source rock and distribution of the formation water. The strata of the ma 5 formation contain relatively high iron, which is mainly found in ankerite, powdery crystalline dolomite, pyrite and siderite. Ankerite, mostly saddle-shaped dolomite, is evenly distributed in the crystal and has a relatively negative oxygen isotope value and carbon isotope value, indicating that it precipitates in the higher temperature iron-rich fluid containing organic matter. The iron in the powdery crystalline dolomite is only distributed at the edge of the crystal. The oxygen isotope is negative, while the carbon isotope is slightly negative, which also indicates that it has been reformed by the iron-containing thermal fluid in the later period. Pyrite is often associated with ankerite. And the sulfur isotope values and hydrogen sulfide values of pyrite are similar to the seawater, indicating that they have a common source. Siderite is associated with the weathering crust, which is the main iron source of the majiagou formation. The evolution process is as follows: In the process of weathering, iron deposits in carbonate strata continuously, which forms iron-rich beds. In the burial period, the iron precipitates and infiltrates in the underlying water. When there is hydrocarbon filling, the thermochemical sulfate reduction generates hydrogen sulfide. In the process of continuing migration, hydrogen sulfide react with iron rich fluid, which generates pyrite and ankerite, reducing the hydrogen sulfide in gas reservoir.

Keywords: Pyrite; Ankerite; Siderite; Majiagou formation; Ordos basin;

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Recent vertical calcretes a possible analogue for laminar calcretes. Guadalajara, Spain

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Key words: calcrete, Central Spain, microbes, needle fibre calcite, root.

Recent calcretes develop around vertical tree (*Quercus rotundifolia*) and bushes roots which penetrate more than 3 m red Miocene continental horizontal deposits of the Madrid Basin. Calcrete thickness varies from a few mm to 15 cm and it is mostly vertical. Thinner horizontal calcified horizontal root mats connect vertically to form a grilled-like structure. The calcretes consist on white, powdery, porous and diffusely laminated carbonate, made up of micrite with some etched clasts, alveolar septal structures, calcified rootlets, coated grains and micrite grains. In detail many of these features are composed of needle fibre calcite and micro-rods. In detail, the calcrete is roughly laminated parallel to the roots/root mats. Between some laminae there is some red clastic from the host rock. Thin sections show a diffuse cm-scale banded structure, with different bands composed of: a) micrite including etched detrital clasts up to 1 mm in size along with some alveolar septal structures of about 1 mm; b) amalgamated and isolated alveolar septal structures of about 0.4 mm across and 2 mm long, with calcified rootlets and masses of needle fibre calcite (NFC), micrite and some etched grains; c) irregular and discontinuous areas (0.6 mm) containing peloids of about 50 µm across; d) etched detrital clasts showing a first regular micritic greyish etching, coated by a more discontinuous one. In cross sections calcified rootlets are rounded and about 0.5 mm in diameter; in longitudinal sections they can reach a few cm in length. They show different textures and contain calcified cells (single calcite crystals from polyhedral to round). NFC occur as a porous network commonly associated with root-related structures such as rootlets or alveolar septal structures. Most of the crystals (up to 100 µm long) are simple needles with or without nanofibres; more rarely they show rhombohedral overgrowths. Micro-rods or nanofibres (about 4-6 µm) occur on NFC as irregular meshes. Preserved organic structures within the carbonate include organic filaments, spheroidal bodies (probably bacteria) and pollen grains are also common. Non-calcified rootlets or root hairs are also seen.

The distribution of the carbonate and its characteristic features indicates that calcrete formation the result of biochemical processes driven by microorganisms that live around roots The neat preservation of all carbonate features reveals the origin of some of the most characteristic calcrete features, such as coated grains, or alveolar septal structures due to metabolic activity of fungi, causing formation of needle fibre calcite and micro-rods. In spite of the extensive of literature on root calcrete formation, up to now a modern analogue for laminar calcrete formation is lacking. The good preservation of the microstructure and the presence of living plants suggest that the Pajares calcrete is a good analogue of ancient root calcrete showing that precipitation within soils may be a relatively rapid process occurring during the life of the plant.

Biotic influence in the genesis of laminar calcretes in Vertisols of the Marília Formation (Upper Cretaceous, Brazil)

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Keywords: Calcified Roots, *Microcodium*, Spherulite, Pedogenic calcrete

The genesis of laminar calcretes has been the focus of numerous studies over the last three decades as regards the mechanisms responsible for carbonate precipitation. The most accepted model is the calcification of root systems by intracellular and extracellular processes. In addition to plants, other organisms can mediate and control the precipitation of pedogenic carbonate, such as fungi, bacteria and invertebrate fauna. This work aims to describe in detail laminar calcretes developed in a Vertisol profile of the Serra da Galga Member (Marília Formation, Bauru Basin, Upper Cretaceous of Brazil) in order to understand the role of organisms in the genesis and distribution of calcium carbonate in a non-carbonate substrate. Slickensides, wedge-shaped peds, rhizoliths, redoximorphic features and sheets and stringers of calcite are the most common characteristics of the studied Vertisol profile. Based on the distribution of macrofeatures and microfeatures (habits, paragenetic association and luminescence behavior under cathodoluminescence analysis) calcite occurrences were divided into: (1) Recrystallized *Microcodium*; (2) Recrystallized spherulites and (3) Grain-coating cements, nodules and fracture fills. The Vertisol profile is well-developed and poorly drained, developed on floodplain deposits, in the medial part of a distributive fluvial system. In dry periods, the soil shrank and developed deep cracks, while in wet periods the soil swelled, closing the cracks. The stabilization of the geomorphic surface promoted colonization by plants and invertebrate fauna during the wet periods. The sparse occurrence of vertical rhizoliths and the large amount of horizontal rhizohalos and sheets or stringers of calcite suggest that the water table was close to the depositional surface and that root mats lived at or just below it. The alternating availability of water in well-defined seasonality, promoted carbonate accumulation in Vertisols by biotic and abiotic influence, especially with the change of season, from wet to dry. When conditions became drier, roots pumped water from the soil solution, consequently increasing the concentration of ions around the roots, leading to precipitation of calcium carbonate. The distribution of carbonate in the laminar calcrete followed previous vertic features (wedge-shaped structures and slickensides), plant roots associated with microorganisms (rhizosphere), invertebrate fauna as well as water table variations. The biotic mechanisms consisted of intracellular and extracellular root calcification by changes in soil chemistry, creating *Microcodium* morphologies and rhizoliths respectively. The microorganisms play a role in the decomposition of organic matter from roots and invertebrate fauna, probably inducing spherulite genesis. Other subordinate calcite occurring as nodules and fracture fills seem to

be related to abiotic influence (evaporation) in their precipitation, since there is no direct relationship with the root traces. The proposed model supports the hypothesis that the calcification of horizontal root systems is the major contributor to the genesis of ancient laminar calcretes.

The role of pedogenic calcrete in deciphering the record of relative sea-level changes and climate conditions in mid-Cretaceous peritidal limestones of the Apulia Carbonate Platform (Italy)

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The present study analyses the stratal architecture of the mid-Cretaceous (late early Albian) limestone succession of the Giovinazzo sea-cliff section (Apulia, Southern Italy) mostly made up of peritidal facies associations whose sedimentation was frequently interrupted by repeated subaerial exposure phases. The break in carbonate sedimentation is mostly marked by abundant rhizoturbated intervals, capping high-frequency depositional peritidal sequences, and by three distinct horizons of brecciated limestones, about 2 m in total tickness, interpreted as pedogenic calcretes showing a complex polygenic and polyciclic evolution (Spalluto, 2012).
The Giovinazzo sea-cliff section exhibits intraclasts-dominated calcretes with black pebbles, microbial laminites, fenestral mudstones, rhizoturbated mudstones/wackestones and biopeloidal packstones. Some lithofacies are dedolomitized. This lithofacies assemblage represents a low relief shelf with small depressions/ponds bordering a peritidal setting; this partly subaerial and partly submerged setting was subjected to lengthy exposure and to fluctuating, very shallow groundwater tables. Climatic regime experienced by the Apulia Carbonate Platform in that time interval was semi-arid as shown by the combined record of intense calcrete development, rhizogenic structures, microbial mats and desiccation.
The unusual occurrence of calcrete in the mid-Cretaceous succession of the Apulia Carbonate Platform reveals a complex palimpsest exposure record, here interpreted as reflecting hydrological changes, caused by different phases and hierachies of relative sea-level changes. More in detail, the calcretized intervals are interbedded into peritidal and lagoonal limestones, and they have bene already assigned to a regressive peak of a Transgressive-Regressive Facies Cycle (2nd order) of the thick mid-Cretaceous shallow-water carbonate succession of the Apulia Carbonate Platform (Spalluto, 2012), corresponding to the Al7 sequence boundary in chronostratigraphic global charts (Hardenbol et al., 1998).
This case study offers a potential model for understanding facies evolution in carbonate successions corresponding to lowstand surfaces in seismic lines.

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Calcrete-palaeokarst associations: geobiological processes, climatic factors and process rates

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keywords: calcrete, diagenesis, geobiology, palaeokarst, vadose zone

Calcretes and palaeokarst phenomena are two groups of major macroscopic products of meteoric carbonate diagenesis. Although generally considered to represent contrasting styles of diagenetic processes in the vadose zone, ancient (epi)karst features and calcretes are often associated in carbonate depositional successions. Modern surface and shallow subsurface karst on carbonate rocks as well as the buried ancient karst systems are characterised by dissolutional features generally developed under prevailing humid climatic conditions and predominance of dissolutional weathering. In contrast, calcretes are typically considered as an indicator of 'arid' (semiarid to subhumid) climate, characterized by precipitation of secondary calcium carbonate in soils or within shallow, near surface vadose diagenetic environment. This palaeoclimatic generalisation has been often used in the interpretation of palaeoexposure surfaces in stratigraphic sequences. However, many calcretes form by predominance of biologically induced processes, particularly precipitation of calcium carbonate within the root systems of higher plants and associated microorganisms in soils. In its broadest definition, the depth of soil is defined by the rooting depth of plants, and this zone generally overlaps with the epikarst. We will show that certain examples of calcretes, associated with karst, reflect specific biological processes involved in the precipitation of secondary carbonates rather than specific climatic conditions. Furthermore, occurrence of calcretes within a zone of prevailing dissolutional regime perhaps seem less contradictory when we compare the rates of carbonate dissolution in karst and estimated precipitation rates for biogenic calcretes. Solutional denudation of carbonate terrains has been relatively well assessed both on global and local scales (Ford & Williams, 2007) whereas calcrete accretion is rather poorly understood and is based on few studies of (finely) laminar forms (e.g. Robbin & Stipp, 1979). Based on micromorphology of calcretes from Quaternary carbonates in the broad Mediterranean region and the Bahamas, we will show that accumulation of $CaCO_3$ in calcretes is a relatively rapid process which operates across a wide climatic range and largely overlaps with typical karst geomorphic settings. Young calcrete-karst examples will be compared with examples from the geological record.

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Stratigraphic and tectonic controls of karstic features in carbonate successions: The Achado outcrop from the Neoproterozoic Salitre basin, Brazil

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Imbricated thrust sheets and fault zones that crosscut carbonate successions are complex systems in which tectonic and geochemical processes may interact. Deformation level may be very heterogenous and related to different mechanisms, including burial and crustal thickening associated with sedimentary compaction and fluid expulsion, and tectonic thrusting along and across strike that may be accompanied by fluid and dissolution/precipitation processes.

Important questions refer to the role of these thrust and fault zones as pathways for deep-seated and meteoric fluids. While deep-seated fluids can be linked to hypogenic karstic features, meteoric ones are linked to epigenic karstic processes and usually evolve along previously formed hypogenic structures. Hypogenic fluids may be derived from the carbonate basin or from deeper regions (warmer and more chemically aggressive fluids). These fluids may fill open spaces and interact with the host-rock, promoting chemical and mineralogical transformation and changes in porosity and permeabily of the host rock.

In order to better understand the role of tectonics and fluid flow in the formation of carbonate karstic systems, we have performed a detailed investigation involving tectonic and isotope geochemistry ($^{87}Sr/^{87}Sr$, $\delta^{13}C$, and $\delta^{18}O$) of the Achado outcrop, northeast Brazil. These carbonates are well-exposed and, because of the geometry of the fault system, bedding is nearly vertical and major deformation is restricted to narrow fault zones. After performing work to define detailed stratigraphic profiles and facies distributions, our work indicates that the original stratigraphy of the Achado outcrop is well-preserved and was barely affected by meter-scale tectonic displacement, thus being an interesting area to understand the relationship between tectonics and fluid-rock interaction.

The Achado outcrops consist of laminated mudstone, dolostones with cross-bedding, phosphatic stromatolites, limestones and dolostones. Primary isotope data from calcium carbonate and dolostones across the section exhibit large variations of $\delta^{13}C$ (-8.7 to +10.3‰) and $\delta^{18}O$ (-4.9 to -2.7‰). The high $\delta^{13}C$ values are primary and correlated to highly positive carbon isotope limestones placed in the upper part of the succession. In contrast, calcium carbonate from veins and hydraulic breccias show lower isotope values, sometimes even when cross-cutting the highly positive carbon isotope limestones. The isotope data suggest that the primary carbonates were partially affected by hydrothermal fluids prior to the thrust event, thus revealing the existence of an ancient heat source within the basin. We show that karstic features are controlled by carbonate layers strongly affected by along strike brittle deformation and by millimeter-scale carbonate veins formed parallel to the maximum tectonic stress. In a next step we plan to use strontium isotopes to try differentiating fault zones originating in basin from those that reached right down to the basement.

Keywords: **Karst, tectonic, Salitre Basin, isotope geochemistry, fluid flow**

The polygenic karst that goes up and down: Upper Jurassic, offshore Gharb, Morocco.

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Keywords: carbonate platform, eogenetic karst, hypogenic karst, offshore Morocco, Upper Jurassic

A three-dimensional seismic volume from offshore Morocco displays an eastern-rimmed carbonate paleomargin of the young Atlantic Ocean during the Upper Jurassic. The carbonate platform is located on top of the footwall of a tilted block, associated with the necking fault in the offshore Gharb. This complex tectonic regime controlled the type and location of different types of karst through time. The aim of this study is to characterize and differentiate the multiphasic karst from (1) Late Jurassic rifting, (2) Early Cretaceous burial compaction, (3) Late Cretaceous – Early Tertiary compression (?), and (4) Miocene Betic-Rif compression.

Abundant truncation surfaces at top of the carbonate platform affected both the margin and the inner platform. The reflector truncations and thickness variation suggest coeval sedimentation in the half-graben depocenter, and probably subaerial erosion in the margin. The high frequency cycles with subaerial erosion and probably syngenetic karst was due the sea level falls associated with 4th order eustatic cycles and differential half-graben subsidence.

An incised valley towards the southwest was significantly developed probably through a prior inlet between the north and south shelf-edge reef complexes. The approximate 100m incision is interpreted due to 3rd order eustatic cycle variations originated during the sea level fall at Early Cretaceous. During low sea level stage, a juvenile vadose – phreatic karst was developed. High amplitude reflectors with vertical orientation suggest a locally well-developed vadose cave system. The vertical cave system is rooted in two different subhorizontal cave trends, dipping with low angle respect the bedding. Locally, the underlain aquitard on top of the tilted block acted as a hydraulic barrier, and produced low angle paleo-phreatic levels dipping toward the basin.

Concave-up reflector disruptions have high amplitudes, circular-like sections and vertical stacking are interpreted as hypogenic karst collapses. Deep-seated karst affected mostly the back-reef carbonate platform, producing a cavernous system at the top of ancient syn-sedimentary faults, and at top of the lower back-reef aquifer, or at interphase between the confining upper back-reef unit. Dip attribute maps suggest that the collapses are in clusters next to fault lineaments, independent of their strike.

Three families of hypogenic karst collapses are distinguished according to the interpreted age. a) Narrow collapses located in the inner platform reached the top of the overlaying Early Cretaceous clastic prograding complex unit. The interpreted origin was probably due to ascendant fluids coming after sediment compaction from the adjacent half-graben depocenters. b) Collapses reaching the intra-Maastrichtian unconformity were driven by mixing of connate waters in the carbonate platform and the squeezed water from the deep fine-grained siliciclastic sediment during the Late Cretaceous compression. c) Few collapses 100 to 400m width reaching the base of the allochthonous wedge of the Gulf of Cadiz, are located below the clastic infill of the southern incised valley. Some minor occurrences enhanced prior collapses in the shelf-edge reef complexes near the wedge. A possible genesis could be related with mixing waters driven by tectonism due to the compression between Africa and Iberia in Miocene times.

Influence of Long Term Exposure Surfaces on the Origin, Preservation and Distribution of Microporosity in Shallow-Water Carbonates: The Barremian-Aptian Platform from SE France

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The Urgonian limestones (Late Barremian / Early Aptian) from Provence, SE France, have been studied to estimate the influence of the regional Durancian subaerial exposure event (Albian to earliest Cenomanian) and the related diagenetic processes on the genesis, the preservation and the spatial distribution of microporosity. A high-resolution characterization of the vertical and lateral evolution of porosity and diagenetic attributes has been performed. The development of microporosity results from a complex interaction between early marine diagenesis, stratigraphic stacking pattern, early structuration of the reservoir and fluid circulation during long-term exposure events. Petrographical (sediment texture, facies) and diagenetic analysis (cement stratigraphy, porosity, permeability and isotope geochemistry) of more than 100 limestone samples revealed that early meteoric cementation during repeated subaerial exposures in autocyclic, peritidal parasequences led to the occlusion of intergranular and intragranular

pore space (=tight limestones). In contrast shallow water carbonate sediments that were not exposed during repeated subaerial exposure events, have kept a significant fraction of the intergranular macroporosity during burial. Such porous carbonates were subject to micrite neomorphism during meteoric shallow burial diagenesis during the regional Durancian uplift and associated subaerial exposure event (Albian-earliest Cenomanian). Such a diagenetic evolution resulted in a significant development of intragranular microporosity. Cementation of the intergranular space occurred during later burial diagenesis and/or telogenesis (late Cretaceous and Tertiary). Finally, circulation of meteoric fluids during exhumation led to intercrystalline microporosity enhancement and moldic porosity development. The results from the studied outcrop could be used as analogs for Middle East microporous reservoirs that developed below major unconformities.

Key words: Microporous carbonates, Unconformity, Meteoric diagenesis, Cretaceous

Sediment accumulation in paleokarst reservoirs - Analogues from an active cave system

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Keywords: Carbonate, ERT, karst, reservoir, sediments,

The presence of clastic sedimentary infills is a characteristic and often prominent feature of paleokarst. Nevertheless, there are few/no studies addressing the role of these sediments play in paleokarst reservoir in terms of volumetrics and fluid flow properties.

Karst systems may experience multiple cycles of burial, infill, uplift and rejuvenation, prior to forming sub-surface reservoirs. Exposure to surface and near-surface conditions allows vadose incision and trapping of sediments from depositional systems active on the surface (e.g. fluvial, eolian, glacial etc.). These sediments may under given circumstances fill in substantial parts of pre-existing karst cavities, in which case their petrophysical properties will control local reservoir porosity and permeability.

Sediment infill also induces lithostatic pressure on cave walls and floor, provides physical support, and constrains, redirects or dampens fluid flow in karstic systems. This affects subsequent cavity breakdown processes and development of drainage paths in the system. Cavern collapse may be prevented or delayed, as wall-spalling is contained by the sediment infill and roof collapse is hampered by sediment fill reaching the cave roof or constricting roof spans. These processes will in turn affect reservoir properties of paleokarst reservoirs originating from them.

In this study, we aim to improve our understanding of the depositional architecture and preservation potential of cave sediments in an active cave using electric resistivity tomography (ERT). The resistivity contrast between sedimentary infill, collapse breccia and host rock can be high, allowing relatively high-resolution mapping and differentiation of cave morphology and infill lithology. Thus, sediment thickness in combination with cave floor morphology may reveal depressions or baffles that can act as sediment traps and areas of elevated preservation potential for sediments.

The Maaras cave (northern Greece) was used as case study. The cave is >10 km, with an altitudinal difference of 71 m, and acts as a sediment trap for a sub-terrain fluvial system. Prior to our survey, infill was known to reach a thickness of more than twelve meters locally. An initial sensitivity test was carried out to determine optimal electrode spacing (5-meter and 3-meter spacing) and associated penetration depths. ERT data was collected at three different locations. The datasets consist of two crossing lines inside a large (60 x 140 x 50m) chamber and two single lines along the main passage; covering a total length of 369 meters.

Electric resistivity tomography proved to be a useful and time-efficient method for mapping cave-sediments and floor morphology within an active cave system. The measured sediment thickness varied from 5 meters to over 25 meters. In some areas, larger bodies with high resistivity signatures were observed and interpreted as collapse breccias. The elevated resistivity readings correspond well with measured resistivity of outcropping breccias. In the large chamber, the sediments can be seen completely enclosing collapse-related breccias. Thus, larger breccia bodies may be buried beneath sedimentary infills and overlooked during cave mapping. Results from this study significantly changed our impression of the potential volumetric significance of sediments in paleokarst reservoirs; as some passages in Maaras exhibit a ¾ fill of fluvial/coarse sediment. If preserved during burial the presence of large sediment accumulations could significantly influence reservoir properties, either by restricting or redirecting fluid flow or by providing storage for hydrocarbon/water, subsequently affecting STOOIP calculations and associated recovery factor.

Fracture Development in the Interior of a Stable Carbonate Platform: New Evidence from the Distribution of Karst Features on Andros Island, Great Bahama Bank

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Keywords: Karst, Faulting, Fractures, Cenotes, Bahamas

The Bahamas platform is widely recognised as the most stable continental block in the Caribbean. It is underlain by a series of normal and wench faults, which are inherited from an upper Jurassic rifting phase but presumed inactive since. These deep faults appear to control the geometry of the steep platform margins and deep-water re-entrants. At the surface major fracture systems, extending up 40 km, occur parallel to the platform margins and show diagenetic alteration by circulating groundwater. Similar systems are described in ancient platform margins in the Canning Basin and Guadalupe Mountains, and in the subsurface, for example in Tengiz where they are a critical control on flow. Here we present a statistical analysis of the distribution of large-scale karst features distributed across Andros island, that provides the first evidence for extensive fracturing up to 35 km from the platform margin.

Some 177 circular collapses (“cenotes”) were identified from satellite imagery. At the surface these features have a diameter of 105±60 m, with the largest spanning 370 m. Field survey shows they have a maximum depth of c.110 m, with floors of collapse boulders and soft sediment suggesting active autochthonous infill. Underwater exploration of a subset of cenotes suggest they tend to increase in diameter with depth, possibly due to the effects of mixing-zone dissolution and associated collapse. Only a few of the smaller cenotes are known to connect with lateral cave passage.

Perpendicular regression reveals the distribution of cenotes is significantly non-random, and identifies many lineations, defined by rows of up to 6 cenotes. The distribution suggests that cenote formation may be focussed at the intersections of lineations. Most lineations within 10 km of the eastern bank margin are oriented parallel to this margin, with a subset perpendicular. However, further inland, the orientation of many lineations echoes that of the N60^{o}W trending Sunniland (Bahamas) Fracture Zone, a long-lived transform feature related to Jurassic rifting that extends across the Floridian Peninsula and crosses the Great Bahama Bank to the north of Andros Island. The vast majority (98%) of identified cenotes occur within 35 km of the western bank margin. The absence of cenotes at greater distances from the margin may reflect increased infill by sediment generated on the shallow modern bank, or alternatively may be controlled by the location of margin of the underlying Cretaceous Andros Bank.

Use of GPR data to image 3D carbonate heterogeneities and karst features in outcrops, an example from Brazil: Advances in data acquisition, processing, and interpretation

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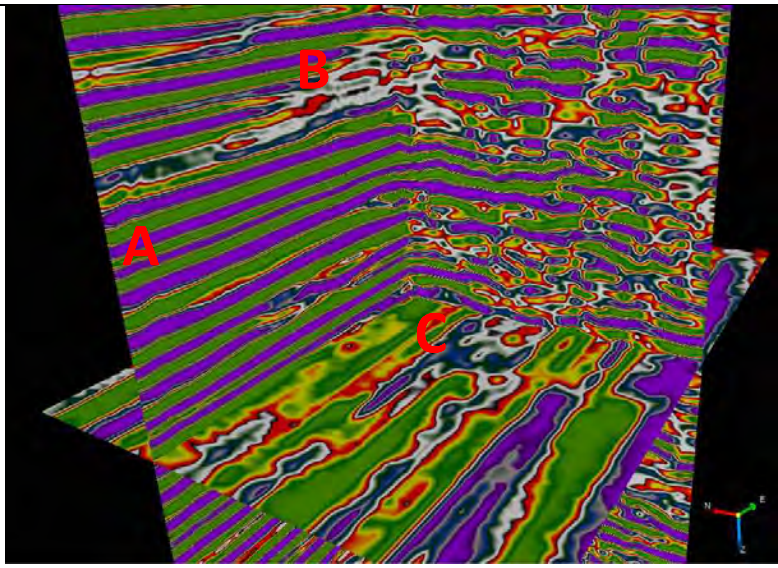
Keywords: analogue reservoirs, carbonates, karst, GPR, imaging.

In order to build porosity and permeability models for carbonate reservoirs with karst, it is necessary to establish spatial associations between primary structures, discontinuities, and dissolution features forming the karst. Advances in the understanding of this challenging problem might be obtained by imaging outcropping karstified carbonates with GPR (Ground Penetrating Radar). Our study areas are located in the Potiguar basin, where exposures of the Jandaíra Formation occur that have a large areal extent. This formation is a carbonate platform formed during sea-level transgression after the breakup of Pangea during the South Atlantic opening. The exposures show different stages of karst evolution, thereby offering excellent conditions to study karst formation processes (Fernandes Jr. et al., 2015). However, obtaining and interpreting high quality 3D GPR images is a challenge in itself, because at least three problems must be overcome: 1) Surveying on very rough karst terrains, 2) Data processing allowing high quality images, and 3) Interpreting small-scale stratigraphic and karst features. In the spirit of the Bathurst Meeting, we present preliminary results of our work in progress. We consider that problem 1) is now well solved. We developed a simple but effective methodology to perform GPR surveys on very rough terrains by using wooden pallets as shown in Figure 1. Note in this figure that regularly spaced tracks, composed of wooden slats, are set on wooden pallets providing the tracks for the GPR antenna. The operational logistics of placing and stabilizing the wooden pallets on the karst terrain is very time consuming, but the quality of the data obtained compensates for the effort required. Concerning problem 2), as the result of accumulated experience in processing GPR data (Xavier Neto and Medeiros, 2006; Medeiros et al., 2018), we have already managed to get high quality images in most karst conditions. However, as regard 3), we are just “at the start of the journey”. An example of our preliminary results (Figure 2) shows a chair display of a GPR cube showing sub-horizontal layers and dissolution features related to faults.

	
Figure 1 - A simple methodology to perform GPR surveys on very rough terrains.	Figure 2 – A chair display of a GPR cube. On the left vertical and horizontal sections, A indicates subhorizontal layers and B and C indicate dissolution features along subhorizontal layers. Note that the borders of the dissolution feature C are controlled by faults, whose traces can be seen on the right vertical section.

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Utility of $\delta^{18}O$ for paleotemperature determinations from Pleistocene (80 to 500 ka) corals: case study from the Ironshore Formation, Grand Cayman, British West Indies

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Key words- corals, diagenesis, geochemistry, paleoclimate, Pleistocene

Fossil corals provide a unique opportunity for paleoclimate research if they incorporate seawater proxies into their aragonitic skeletons during growth. Corals, however, can only produce reliable environmental information if they have not been diagenetically altered, an issue that becomes increasingly likely as the age of the corals increase. This premise is assessed by examining *Orbicella annularis* collected from the Pleistocene Ironshore Formation (Units A-F) on Grand Cayman, which range from 80 to 500 ka in age. Although thin section, Scanning Electron Microscopy, and X-Ray diffraction analyses, can highlight obvious mineralogical changes, subtle diagenetic changes in the trace element content of the skeletons may escape detection. For corals from the Ironshore Formation, elevated Mg and low Sr concentrations provide evidence of subtle diagenetic changes even in corals that have retained their primary aragonitic skeleton. Thus, coral skeletons that are formed of > 90 wt% aragonite, exhibit no cementation, have Mg/Ca ratios < 12.0 mmol/mol and Sr/Ca ratios > 8.0 mmol/mol, and $\delta^{13}C_{VDPB}$ values > – 3.0‰ and $\delta^{18}O_{SMOW}$ values > 25.0‰ can be used for calculating surface seawater temperatures. Adoption of these criteria shows that the corals from Units D-F, have not undergone extensive alteration and can therefore be used to calculate sea surface temperatures (SST). In contrast, the corals from Units A-C have been altered and cannot be used for this purpose. Based on the $\delta^{18}O$-SST proxy, the calculated SST ranged from 20 to 32°C for Unit D (~125 ka), 14 to 27°C for Unit E (~104 ka), and 20 to 30°C for Unit F (~80 ka). The calculated SST and the corresponding temperature profiles are consistent with global SST reconstructions during the Pleistocene. The corals from Unit D record an overall increase in calculated SST consistent with elevated temperatures associated with Marine Isotope Stage (MIS) 5e, whereas the corals from Unit E and F record overall cooling consistent with the end of the peak interglacials of MIS 5c and 5a, respectively.

Mg/Ca ratios of preserved echinoderm skeletal and diagenetic calcite cements provide record of ancient seawater chemistry and reservoir compartmentalization in Lower Cretaceous reservoirs, Thamama Group, UAE

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Calcite cementation, compartmentalization, Lower Cretaceous, Mg/Ca ratio, seawater

The variation of seawater Mg/Ca ratio has been widely used as an effective tool to measure the variation in seawater chemistry for the past 500 Ma. Based on Mg/Ca variation, episodes of aragonite versus calcite dominated seas were classified. The Cretaceous time is characterized as calcite sea having marine precipitates enrich in Ca^{2+}. Several studies have shown that Mg/Ca ratios of Cretaceous particularly Lower Cretaceous are low (0.8-1.8). This study shows similar low Mg/Ca ratios (0.8-1.2) obtained from four oil reservoirs from Thamama Group. These low values are concurred with low S isotopes, negative $^{87}Sr/^{86}Sr$ excursion and higher ocean crust production in Lower Cretaceous interval. The lowest obtained Mg/Ca ratio (0.8) in this study is around 118 Ma which is coincided with the major ocean crust production event through the entire Cretaceous. Based on this study and previous studies, the variation in chemistry of seawater can be inferred to the higher ocean crust production and hydrothermal brine at MORs. Moreover, the syntaxial, equant and blocky calcite Mg/Ca ratios of this study together with $\delta^{13}C_{VPDB}$ and $\delta^{18}O_{VPDB}$ obtained from other studies as well as the presence of intraformational seals and regional shale seal, show that the reservoirs of the Thamama Group are compartmentalized; calcite cementation occurred in relatively close system. Accordingly, this study suggests the used of Mg/Ca ratios of diagenetic calcite together with internal and external controlling parameters as a tool to understand reservoir compartmentalization.

Using Sr isotopes and Rare Earth Elements to correlate sequences in regions with complex facies distributions: Example from the Late Cretaceous of the South-Central Pyrenees

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Key words: Strontium Isotopes; Rare Earth Elements; Late Cretaceous; Pyrenees

Understanding the distribution of carbonate facies in areas with complex structural histories can be challenging. The Upper Cretaceous deposits of the Sant Corneli and Boixols anticlines in the Pyrenees are controlled by extensional inherited structures and subsequent inversion. The aim of the present study is to understand the timing of the structures and correlate the facies across the anticlines. The dating of the Coniacian-Santonian postrift and Campanian-Maastrichtian syn-growth sequences is based on numerical ages derived from $^{87}Sr/^{86}Sr$ ratios. Additionally, elemental analysis and rare earth elements have been used to characterise seawater signatures, environments and diagenetic overprints.

A total amount of 162 samples were collected across the two anticlines. Geochemical analysis by using ICP-MS permitted an evaluation of the elemental concentrations of the samples in order to discriminate the suitable ones for strontium isotopes. Numerical ages derived from strontium isotopes show that the Santonian carbonate systems were coetaneous across the Sant Corneli anticline. Rudist-rich facies in the northern flank of the Sant Corneli anticline correlate with the carbonate platforms in the southern flank. The uppermost Santonian shallow marine carbonates sampled in the southern flank in Collades de Basturs might correlate with the silty clays and marls of l'Aubagueta Member in the northern flank.

The obtained numerical ages derived from strontium isotopes together with magnetostratigraphic, and biostratigraphic data have been used to constrain the timing of growth of the anticlines. The syn-growth succession shows ages ranging from middle Campanian in the uppermost Herbasavina Formation to early Maastrichtian in the Castell d'Orcau Unit. Those results point to older ages than previously published works.

The analysis of rare earth elements and Yttrium (REEY) has shown flat shaped REEY profiles that are typical for the Late Cretaceous; and may indicate low diagenetic alteration. Preliminary results based on the Y/Ho ratio has revealed changes on paleobathymetries and environments. Therefore, the use of rare earth elements could be used as a proxy to support sedimentological observations.

The sedimentological and geochemical fingerprint of peritidal sediments from the Northwest Shelf of Australia and Abu Dhabi

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Sabkhas are important settings for understanding early earth biological environments. Algal mats associated with these sabkha sediments are thought to be potential source rocks for hydrocarbon production. In comparing a deeply buried example from the Miocene with a well studied example from the Holocene of Abu Dhabi, we want to identify their sedimentary, diagenetic and geochemical fingerprint to facilitate their recognition in the rock record. Site U1464 drilled during IODP Expedition 356 and locate in the Roebuck Basin on the Northwest Shelf of Australia contains a well dated Miocene sequence containing three distinct black layers in close association with evaporites and dolomites. A similar association of organic matter rich layers in carbonate and evaporite dominated sediments can be found in the coastal sabkha of Abu Dhabi. A modern analogue study including petrographic and geochemical analysis was conducted to show if the Miocene carbonate-evaporite deposits at Site U1464 were deposited in a sabkha environment and will explain the related processes of dolomitisation. The lowermost black layer was deposited during an overall rise in sea-level, whereas the upper two were deposited following a sea-level fall. The carbonates interbedded with these upper two black layers host sulphate minerals (celestite, gypsum, bassanite, anhydrite) and halite also typical for the costal sabkha of Abu Dhabi. Bright luminiscent dolomite at Site U1464 with a lighter oxygen isotope signature likely formed from normal marine Miocene seawater. Dull luminiscent dolomite with a heavier oxygen isotope signature likely formed by reflux dolomitisation from circulating brines. Furthermore, we show that there are distinct patterns of glycerol dialkyl glycerol tetraether (GDGT) distributions in the modern sabkha and that these patterns are well preserved in both the buried Holocene and the Miocene algal mats. In summary, Miocene sabkha sediments at Site U1464 are more similar to the hyperarid coasal sabkha of Abu Dhabi than to the modern more humid sabkha sediments of Australia. The sedimentary, diagenetic and geochemical fingerprint of sabkhas is unique and can be used for their interpretation in the rock reord.

Integrated chemostratigraphy of a Late Jurassic reef complex (Jura Mountains, France)

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Key words : Chemostratigraphy, Geneva Basin, Late Jurassic

Fluctuations of stable isotope ratios, especially those of Strontium (Sr), Carbon (C) and Oxygen (O), represent insightful stratigraphic proxies for Phanerozoic marine carbonate series. While these geochemical signals are highly sensitive to diagenetic alteration, in shallow-water environment specific precipitation conditions may also induce a significant perturbation of the global isotopic ratios at depositional time. This project presents a new high-resolution chemostratigraphic framework for two sections covering Upper Kimmeridgian and Tithonian strata in the French Jura. During this period, the Geneva basin was characterized by a wide shallow-water carbonate platform including coral-dominated patch reefs developing on top of pre-existing structural highs. In addition to stable isotope analyses ($\partial^{13}C$, $\partial^{18}O$), $^{87}Sr/^{86}Sr$ ratio was measured, along with various elementary concentrations to better assess potential effects of diagenesis and depositional environment. Regional-scale correlations were first constrained using the available biostratigraphic data set as well as key stratigraphic levels such as maximum flooding deposits and emersive sequence boundaries. Coupling both petrographic and geochemical approaches, our study highlights some deviations of the geochemical signals from well-established global reference curves. Diagenetic alteration appears to be the main factor responsible for this deviation. Nevertheless, chemostratigraphic proxies provide interesting correlation tools in complex reefal shallow-water carbonate settings of the Late Jurassic period and permit to discuss the previous regional chronostratigraphic and lithostratigraphic framework of the French Jura. As commonly evoked in previous studies, this work demonstrates the importance of constraining diagenesis prior to interpreting isotopic composite curves in altered carbonate strata. Furthermore, the comparison of the new $\partial^{13}C$ curve from the French Jura with existing Kimmeridgian to Tithonian records in the Tethyan realms provides new insights to discuss the long-term global carbon cycle during the Late Jurassic.

U-Pb dating of dolomite from peritidal cycles of the Early Eocene Oldsmar Formation of the southeastern Florida Platform

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U/Pb dating, mesogenetic dolomite, peritidal cycle, Florida Platform, Eocene

Dolomite from peritidal cycles of the Early Eocene Oldsmar Formation of the southeastern Florida Platform replaced stabilized (micritized) limestone depositional textures, revealed by ghosts of grains and micritic matrix preserved as inclusions (Fig. 1). Discrete individual crystals encased and partially replaced grains and filled intergranular porosity. Dolomite rhombs and anhedral mosaic dolomite also span cycle boundaries that separate underlying tidal flat wackestone and overlying subtidal grainstone. The anhedral dolomite has a most common occurrence within the wackestone, as compared to a less common euhedral dolomite, which more typically occurs as a replacement of grainstone. In some instances, the dolomite replaces *Microcodium*, a calcitic microstructure associated with calcretes and subaerial exposure (Fig. 2).

Laser ablation inductively coupled plasma mass spectrometry analyses of the dolomites was used to examine their potential for U/Pb dating. Uranium concentrations range from 0.6-3.6 ppm, while Pb ranges from 0.05-0.4 ppm. The $^{238}U/^{206}Pb$ ratio has a range of 9-164, with a corresponding range of $^{207}Pb/^{206}Pb$ from 0.25-0.75. The initial $^{207}Pb/^{206}Pb$ ratio is 0.75. A slightly radiogenic initial isotope composition is consistent with derivation from long-lived aragonite components. Aragonite does not exclude U and primary marine aragonite would have had a high U/Pb ratio. The radiogenic initial isotope composition suggests the source of Pb evolved over millions of years prior to incorporation in the dolomite.

A preliminary dolomite age of Late-Middle Eocene to Early Oligocene (36 ±5 Ma 2σ) determined groundwater younger than the Oldsmar Formation was responsible for mesogenetic dolomitization at a depth of about 895 m below the present-day surface. Based on back-stripping of minimal burial, this age places the studied specimens of the Oldsmar Formation at approximately 600 m below the land surface at the time of dolomitization. There is a strong relationship between subaerial exposure surfaces at peritidal cycle caps and dolomite. The depositional textures, early microkarstification, and cyclostratigraphy appear to influence and control the dolomite distribution and presumably the flow of the dolomitizing ground waters. Perhaps a more common occurrence of dolomite just below the cycle tops suggests a focused groundwater flow through a megaporous touching-vug porosity of the tidal flat cycle cap and a diffuse flow through the subtidal grainstone fed by the higher focused flow from the underling cycle caps.

The standards used for the laser ablation measurements were the NIST612 glass standard and WC-1 (Roberts et al., 2017), neither of which is matrix matched for dolomite. Samples are being processed for isotope dilution which will give a more precise and accurate age. We will combine clumped isotopes and the resulting C and O, Sr and B isotopes, and element ratios to better characterize the fluid and conditions of dolomite formation.

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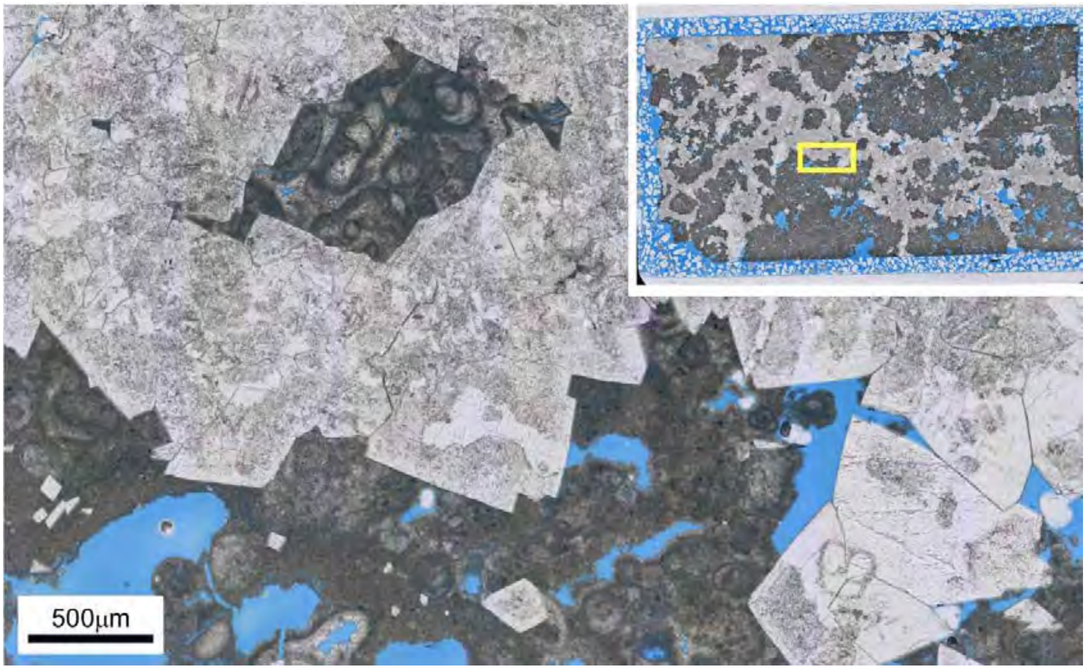

Figure 1: Plane polarized light image of cycle top sample imaged with a thin section slide scanner. The inset shows the texture at the thin section scale and the blue box within that inset shows the position of the zoomed in view of dolomitized wackestone. Note the textural preservation of the stabilized limestone within the dolomite.

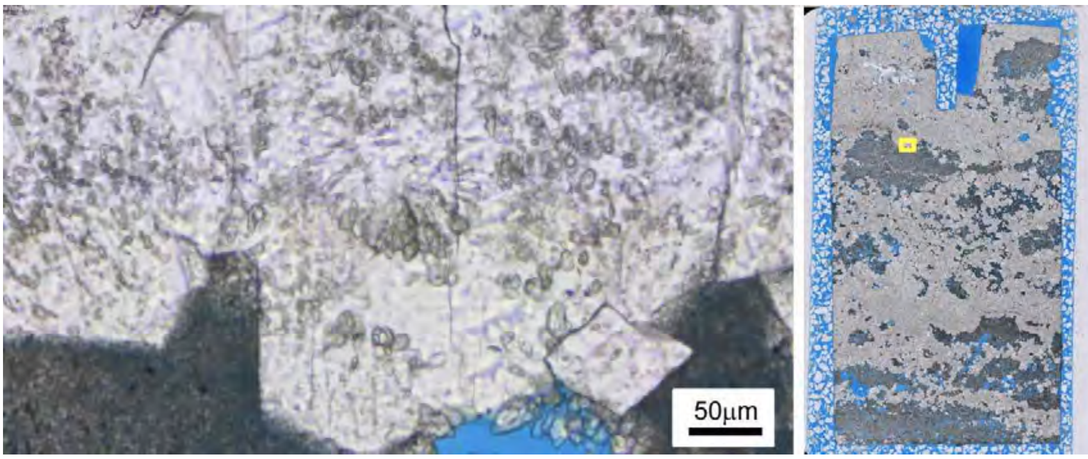

Figure 2: Plane polarized light image just below a cycle top imaged with a thin section slide scanner. Inset shows the pervasive dolomite in this sample (lighter color). The small blue rectangle shows the position that the zoomed image comes from. Note the ghost *Microcodium* within the dolomite.

16th Bathurst Meeting

Abstracts Volume

Posters

Theme 3: Core to Seismic Interpretation, Upscaling and Pore Systems

P-131 to P-150

Integration of petrographic and petrophysical data – an alternative way to create litho-sedimentological models of carbonate reservoirs

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Keywords: carbonates, litho-sedimentological model, petrography, petrophysical data, rock types

Creation of any lithological model is usually based on the detailed core description, laboratory analysis of rock composition, texture (rock fabric from petrography analysis) and interpretation of log data. During the study of carbonate reservoirs the following principle points should be taken into account. Firstly, the influence of primary and diagenetic processes on reservoir flow properties should be studied. Secondly, the correct evaluation of carbonate net pay intervals with high values of porosity and permeability is required.

Nowadays litho-sedimentological models, created for carbonate reservoirs, are frequently qualitative. Besides, definition of quantitative characteristics for lithotypes or facies is rarely performed. As a result created litho-sedimentological models can often be nominal and do not provide any useful information, which can be directly implemented into 3D geological models.

This work considers the methodological approach for lithological and sedimentological differentiation of carbonates, based on the integration of petrographic and petrophysical data, which provides the opportunity to analyze vertical and lateral heterogeneity of such complex reservoirs. The workflow was tested on the Upper Devonian - Lower Carboniferous carbonate reservoirs of one of the fields in Volga-Ural region.

The reservoir quality control algorithm consists of several steps. Firstly, the preliminary analysis of lithological and petrophysical features of carbonate reservoirs is performed. During the stage core photos, taken in ultraviolet, should be examined in order to detect the possible reasons for non-uniform luminescence of intervals in the cross-section. Then, the highlighted intervals are compared both with log curves behavior (standard logs, FMI, NMR log) and production flow tests. At this stage the methods, most sensitive to alteration of rock properties (ratio of grains to micrite, diagenetic processes etc.), should be defined. The next step comprises log hierarchical clustering using self - organizing Kohenen maps for each well from the field. This method provides rock types definition taking well log resolution into account. On the final step the comparison between log rock types and results of quantitative petrographic analysis can be made in order to perform the lithological definition and explain the changes in porosity and permeability. These data is unified by dint of special template, developed in Gazpromneft STC.

It should be mentioned, that the workflow allowed clarification of litho-sedimentological model of the oilfield. The approach provided definition of three petrotypes, observed both in core and on logs. Main rock textural features, influencing reservoir flow properties, were detected: grain content of any genetic type, ration of grains to micrite, grain size. The most influencing diagenetic process was the appearance of micro fractures, which cut rock elements and connect oil saturated intervals.

Finally, the obtained results can be directly implemented into the 3D geological model since the defined rock types are identified with core and log data, which allows the spatial correlation of petrotypes in the model as well as analysis of rock heterogeneity for the whole oilfield. This fact will provide more correct evaluation of perspective drilling zones and creation of effective development plan for challenging carbonate reservoirs.

First results from using artificial neural networks to integrate image log information with seismic data to identify vuggy porosity areas in a pre-salt carbonate field

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Keywords: artificial neural networks, image logs, seismic attributes, upscaling, vuggy porosity.

The reservoir characterization of pre-salt carbonate requires an understanding of relationships between geological features, their petrophysical properties and how this is distributed. In order to achieve a 3D distribution of properties we need to integrate different datasets, which are at different scales and resolutions, to predict heterogeneity away from the well-bore. Among the currently available methods that could help with this, the method that stood out the most for us, are the artificial neural networks (ANN). Such algorithms can correlate several variables in non-linear ways without the need of complex mathematical equations. With the objective of investigating if we could use ANN in the characterization of seismic facies with 'vuggy porosity' we developed a three-step methodology that combines data from Ultrasonic Borehole Image logs (UBI) with well logs and 3D seismic data. The set of seismic attributes used in this study were selected after performing various tests and experimenting with different attributes and combinations of reflectivity, envelope and root-mean square amplitude, all of them associated with lithological changes. The ANN algorithms used have two different approaches: the unsupervised method Self-Organizing Maps (SOM) is used for identification of patterns guided by the data, without the need of *a priori* information, and the second one, Multilayer Perceptron (MLP) uses labels to learn by experience and adapts the network adjusting its parameters until it converges to the desired output. In the first step, SOM is applied to the UBI image, in order to extract the vugs and fractures from the remaining 'matrix background', identified by pattern recognition of reflection amplitude values from the UBI dataset. In the second step, MLP is trained with the seismic attributes to predict the 'vuggy porosity' seen in UBI, previously interpolated (4 nearest traces). After training, the cubes of seismic attributes are used to predict "vugginess" for the entire 3D seismic volume of the reservoir. Finally, the seismic facies identification is performed by SOM, in order to distinguish 'chaotic/fractured' texture from 'homogeneous' regions. The quality and the user-defined choice of the input used to train the neural network are critical for the accuracy of the result that is strongly dependent on the input data resolution. Therefore, the results could be compared with other well logs, such as effective porosity or Production Logging tool (PLT), to guarantee its efficiency, whether the method is guided by well data, or not. We show that the ANN based results proved to be effective in integrating between well and seismic data, not requiring *a priori* knowledge to be implemented.

Furthermore, the results showed a high heterogeneity reservoir distribution, honoring the observed well heterogeneity that seems to pick out interesting trends and features.

Vuggy porosity analysis in dual-porosity carbonate reservoirs from borehole image logs using a machine learning-based method

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Keywords: Carbonate reservoir, dissolution features, image logs, image segmentation, vuggy porosity.

The Brazilian pre-salt non-marine carbonate reservoirs were formed during the rift and sag phases of the opening of the South Atlantic Ocean. These carbonate reservoirs are highly affected by diagenesis, which has a major impact on reservoir quality, resulting in a complex porous system with varied distribution of porosity across different scale, including large vugs and fractures visible on Borehole Image (BHI) logs. Such different porosity scales also adds complexity to the flow characteristics of the reservoir. A key challenge is to understand the 3D distribution and connectivity of the fault/fracture and vuggy porosity system for dual-porosity carbonate reservoirs. The high resolution of the BHI logs makes them a valuable tool for analyzing such heterogeneities at the well-scale. Image segmentation techniques have been applied to BHI logs to extract quantitative data that can be associated with vuggy porosity. We apply the SOM (Self-Organizing Maps) neural network method for image segmentation of acoustic image logs to extract fractures and vugs from the "background" based on pattern recognition of the acoustic amplitude variations. We used the extracted features to build a vuggy porosity log, representative of a quantitative index for predicting its distribution in the reservoir. We applied this method in a pre-salt carbonate reservoir from the Santos Basin. The sag interval is characterized by a complex network of vugs and fractures, which seems to have a stratigraphic control on distribution at the well-scale. Extensive vuggy porosity was observed for the whole Upper Sag unit, which shows large to very large vuggy features (up to metric scale) with a heterogeneous pattern of spatial distribution. We observed in one well the alternation of zones with dominant "background matrix porosity" and zones with high vuggy porosity seen on image logs, associated with higher fracture density, which could be related to distinct mechanical units controlling these reservoir zones. The vuggy porosity log highlights zones with higher incidence of vuggy features, which may indicate important pathways to fluid flow when connected to the enhanced fracture-network. The image segmentation technique applied to high-resolution image logs proved to be useful for vuggy porosity characterization in dual-porosity carbonate reservoirs. The vuggy porosity log computed from BHI logs highlights zones with vugs and captures the vertical heterogeneity. Investigation of the connectivity of vuggy layers with open fractures is relevant to predict potential high-permeability zones, supported by production tests.

Get on the ARQ: Aggregate rock quality is affected by microporosity in crushed carbonate rocks: Evidence from carbonates in Iowa, USA

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Key words: aggregate, micrite, microporosity, reservoir, rock quality

Micron-size pores ("micropores") are common in carbonate rocks. In subsurface reservoirs, they are known to lead to overestimation of recoverable hydrocarbon volumes because 1) common production (e.g., water-flooding) methods may bypass oil-charged micropores or 2) column height may insufficient to charge micropores in smaller fields. Previous work in limestone oil reservoirs (Fullmer et al., 2014) has shown that micropores dominate fluid flow when they account for >80% of total pore volume. In micropore-dominated limestones, porosity, permeability and the size distribution of pore throats are correlated to the morphology of the calcite microcrystals ("micrite") that host the micropores (Kaczmarek et al., 2015). Geochemistry suggests they are abiotic and form during shallow burial (Hasiuk et al., 2016). They exhibit zonation with respect to Mg/Ca suggesting cementation is not a uniform process. Microporosity has been reported in both limestones and dolostones from every depositional environment, facies, and from every period of the Phanerozoic.

While microporosity's occurrence in subsurface reservoirs is well documented, its occurrence in crushed carbonate rocks used for pavement construction affects more companies, governments, and people on a daily basis. The Iowa Department of Transportation (DOT) noted in the 1980s that finer-grained carbonate rocks tend to have lower resistance to winter-season deterioration (e.g., d-cracking at joints, the ice-lensing that causes potholes) leading to significantly shorter service lives for pavements (7 years vs. 30+ years for coarser-grained rocks). The Iowa DOT engineered a water intrusion porosimeter to characterize the pore systems of crushed rocks used in pavement. This "Iowa Pore Index" device measures the water absorption by crushed rock after 1 minute and 15 minutes. Recent work has shown that absorption in the first 1 minute is positively correlated with helium porosity as well as with coarse grain size in dolostones and grainier Dunham textures in limestones. Absorption between 1 and 15 minutes displays little correlation to helium porosity, but is inversely correlated to the modal pore throat size (smaller pore throats lead to higher absorption). This "secondary" absorption is also correlated with finer grain size in dolostones and muddier Dunham textures in limestones. These findings suggest that the Iowa Pore Index device effectively measures a macropore-to-micropore ratio. In addition, these data show that microporosity is limited neither to deposits currently at reservoir depths nor those exhumed from such depths.

These cases support the importance of including the petrographic and petrophysical characterization carbonate microporosity when assessing both "reservoir rock quality" and "aggregate rock quality."

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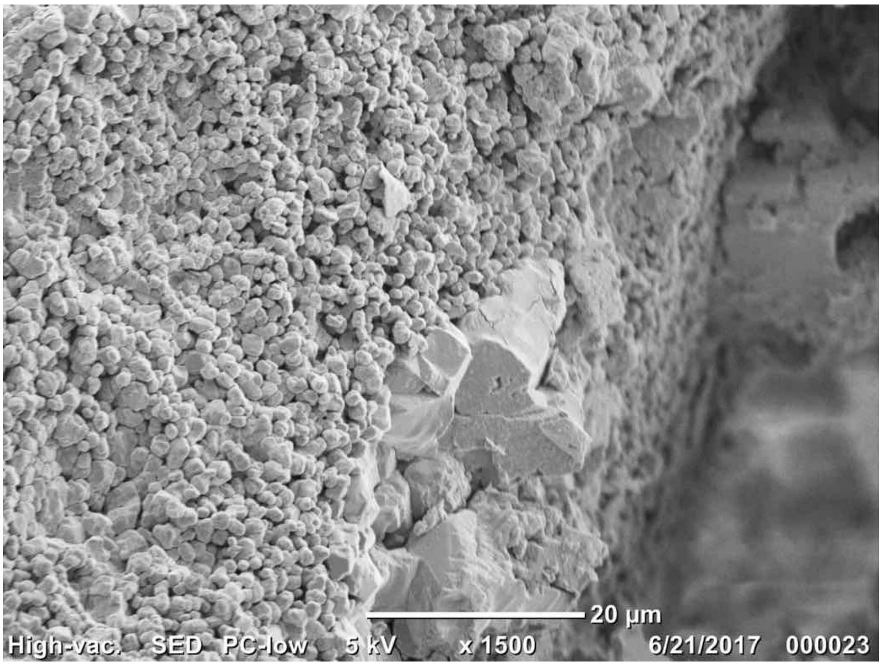

Figure 1. SEM Image of surface of crushed microporous limestone used as “coarse aggregate” in manufacturing Portland cement concrete pavement.

Microporosity in shallow water carbonates: the role of fractures

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Keywords: Micrite, fractures, porosity, shallow water carbonates

Microporous networks form many important carbonate hydrocarbon and water reservoirs in many regions of the world and, therefore, the understanding of the mechanisms of microporosity evolution during diagenesis are or great importance. Furthermore, microporosity in carbonate reservoir appears to have excellent preservation potential during burial, existing to greater depth then does macroporosity. Microporosity is formed by pores with diameter < 10µ and it is commonly associated to pelagic limestone (chalk). Similar types of "chalky" microporosity is also observed in shallow water carbonates and various processes have been proposed to explain its development and/or preservation. Those include I) diagenetic transformation of the lime mud fraction according its mineralogy (aragonitic or high Mg-calcitic), into low Mg calcite (LMC) µ-rhombic crystals (micrite), II) dissolution during burial III) dissolution/aggradation of micrite crystals in undersaturated fluids with respect to calcite. Despite the abundance of genetic diagenetic models to generate and preserve microporosity in carbonate reservoirs, very scarce data are available on the role of fractures in the creation or distruction, preservation and distribution of microporosity in carbonate rocks. Fractures are commonly seen as conduits for fast circulation of diagenetic fluids. The common association with veins indicates that fractures constitute an active site for mineral precipitation. In addition, leaching haloes are also often observed both in subsurface and outcrop examples in carbonate rocks.

In this work we will present a detailed petrographic, geochemical and petrophysics study, at cm scale, across selected carbonate plugs, obtained from a fractured reservoir, in order to understand the diagenetic processes and the type of fluids responsible for the present micrite porosity. The carbonate facies of the plugs is characterized by a skeletal wackestone and SEM petrographic observations show that the matrix is formed by a framework of euhedral/subhedral micrite crystals punctic to partially coalescent intercrystal contacs. Micrite rhombs, although well developed, show rounded edges, indicating that limited dissolution was active. In the proximity of the joints, the micrite evolves towards a tight subhedral to anhedral mosaic characterized by fully coalescent intercrystal contacts. Porosity via DIA (digital image anlysis) and He-porosimetry shows a gradual increase moving away from the joint plane. Finally, we show how the isotopic signals (C, O and Sr) as well as elemental concentrations evolve with increasing distance from the fractures and discuss about the presence of closed Vs open system.

Shell GameChanger Project: Microporosity Quantification – A novel approach to quantify pore types, pore volume and pore connectivity

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Key words: Carbonates, microporosity, connectivity, imaging, deep learning

The evolution of porosity and associated permeability and pore-connectivity of carbonate rocks is affected by biological, chemical and physical processes while they form in a wide range of depositional environments and alter continuously post deposition.

To predict pore and rock properties in subsurface carbonate reservoirs, the E&P industry uses well logging tools, which are ideally calibrated with laboratory measurements and microstructure analysis from core samples. However, extensive logging programs and especially taking core are expensive and time-consuming exercises and therefore only opted if considered essential. Generating and predicting reliable property data of reservoir rocks at low costs are nowadays the norm for making de-risked business decisions in the E&P industry. In this project, the search for novel techniques, such as quantifying properties obtained from cuttings instead of expensive coring programs, are explored if they can be technically reliable enough to drive these decisions.

This Shell GameChanger Project envisions a deep learning based tool that automatically identifies and classifies pores, textures, fractures and properties in carbonate reservoir rocks from microstructures. The classification of (un-)connected pores at multiple scales and various pressures will be obtained by integrating digital images from three novel technologies: (1) Virtual Petrograph (ViP), an automated petrographic microscope that acquires and visualizes high-resolution cross-polarized image-maps of ultra-thin sections. The ViP covers a pore size range from 10 microns to several centimeters. (2) Broad Ion Beam – Scanning Electron Microscopy (BIB-SEM), a 2D preparation and imaging technique that preserves the most delicate microstructures and images microporosity in detail over representative areas. The BIB-SEM covers a pore size range from nanometer scale up to 10s of microns. (3) Liquid Metal Injection (LMI) followed by BIB-SEM, a porosimetry technique to visualize and quantify connected and unconnected pores at different pressure steps.

To make this Shell GameChanger Project a success, it will be key to provide the algorithm with vast amounts of imaged and labelled pore data. Once the data is accessed, the algorithm is designed to automatically segment and label image maps and eventually predict rock properties. In what follows, the more QC-ed data is provided upfront for training, the better the ultimate, unsupervised prediction will be.

Two carbonate samples, each with a different fraction and type of microporosity, have been analyzed and their preliminary results were used to obtain a proof of concept. The first sample demonstrated that 100% of the detected micropores in the matrix were reached by LMI under very high-pressure conditions (400 MPa). The analysis of the second sample, however, showed that only 41% of the observed intra-particle and intra-cement micropores were filled after injecting under the same high-pressure conditions. These types of observations allow to make an assessment of the implications they have for the recoverable volumes of hydrocarbon-bearing carbonate reservoirs and may play a key role in the decision-making process that companies go through to decide how to continue developing the reservoir.

Evolution of pore types and petrophysical properties of fault rocks in low porosity carbonates

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Fault rock properties – fault rock textures and microstructures - diagenesis

In carbonates, fault zone architecture, distribution of different types of fault rocks in fault cores (e.g., breccias, cataclasites), and the interplay between deformation and diagenesis must be considered to predict the flow properties of a fault zone. We present the results of an integrated structural and petrophysical study of two carbonate outcrops in central Italy, where faults are known to act as dynamic seals at depth causing ≈70m of hydraulic head drop in a karstified groundwater reservoir.

The architecture of these fault zones is very well-exposed, allowing for detailed mapping of the along-and across-strike distribution and continuity of fault cores and associated fault rocks over a distance of ≈8 km. More than 150 samples, comprising several fault architectural elements and carbonate host rocks, were collected in transects orthogonal to the fault zones. Fault rock porosity and permeability were measured on 1-inch plugs and then linked to characteristic microstructures and fault rock textures. The results of this integration consisted in ranges of porosity and permeability for each type of fault rock.

A trend of increasing comminution and decreasing pore size is evident from the outer toward the inner portions of fault cores. Three types of breccias (crackle, mosaic and chaotic) and various types of cataclasites were identified. Crackle breccias show the highest plug permeabilities (up to 100s of mD), whereas the ultra-cataclasites have the lowest plug permeability (down to 0.01 mD, which is roughly equivalent to unfractured host rock). These data reveal the interplay between various fault rocks and host rock permeability and the development of permeability anisotropy of fault zones in carbonates (Figure 1).

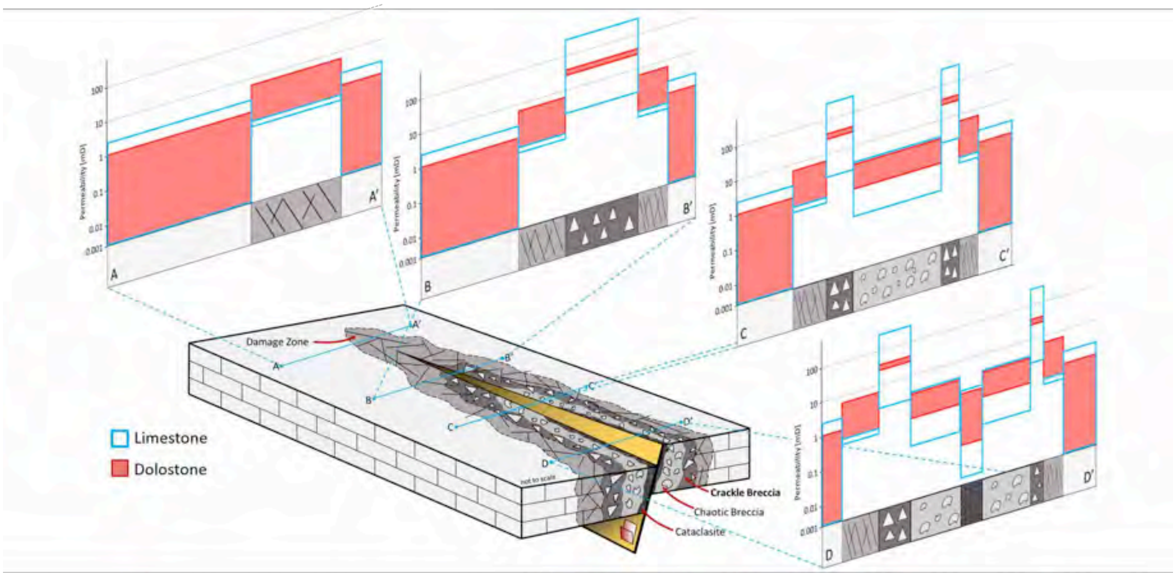

Figure 1: Conceptual model of a fault zone with normal kinematics showing fault-dependent geobodies. Four cross-sections display the ranges of permeability measured within each architectural element (permeability values are derived from plugs and do not consider meso-scale porosities and possible effects of prolonged deep-reaching meteoric dissolution). Blue empty boxes represent the permeability of limestone samples, full red boxes the permeability of dolostone samples.

A. Cilona, J.G. Solum, F. Balsamo, A. Lucca, F. Storti, C. Taberner, (in press) Evolution of pore types and petrophysical properties of fault rocks in low porosity carbonates , SEPM Special Publications, Carbonate Pore Systems

Integration of different porosity scales using multiple point statistics and artificial neural networks

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Key words: Carbonates; Multiscale Porosity; Multiple Point Statistics; Neural Networks

Pore systems in carbonate rocks are generally multimodal and present a high variation in pore size (fractures, vugs and microporosity). One of the current challenges for the characterization of carbonates is the definition of a porosity model that integrates the different porosity scales. In this work, we developed a porosity model that includes different scales by using image log and core computed tomography at different scales and resolutions. Multiple Point Statistics (MPS) was used to simulate porosity and the neural network SOM (Self-Organizing Maps) was applied for image classification. The workflow is composed of two simulation steps, in which the core and pore scales are included in the model, thus encompassing three porosity scales: pore (high-resolution CT), core (low resolution CT) and log (FMI – Fullbore formation microimager). The workflow is divided into three main steps, also summarized in Figure 1: 1) The first step is the pre-processing of image log: the inpainting process of FMI and the full image classification into 3 flow facies by artificial neural networks; 2) In the second step, the FMI is wrapped and filled by MPS simulation. The CT images are firstly classified into 3 flow facies by artificial neural networks and used as training image to simulate the empty image log cylinder; 3) In the third step, the high-resolution CT is used as training image to simulate porosity inside the volume, adding a fourth flow facies. The simulated porosity by high-resolution CT was responsible for creating the connection paths between the larger pores previously simulated from core and log scales. Therefore, the integration of the three scales becomes essential for the calculation of petrophysical properties. The vug porosity calculated by FMI segmentation was also an important factor controlling the rock connectivity, since the regions with the highest concentration of flow lines corresponded to the regions with high vug porosity, honoring both datasets and validating the results. It is worth highlighting that, according to the results obtained in this work, the petrophysical analysis of carbonate rocks cannot be calculated using a narrow range of image resolutions. The impact of the presence of vugs (in macro scale) as the influence of microporosity need to be integrated in order to correctly estimate the porosity and permeability in carbonates.

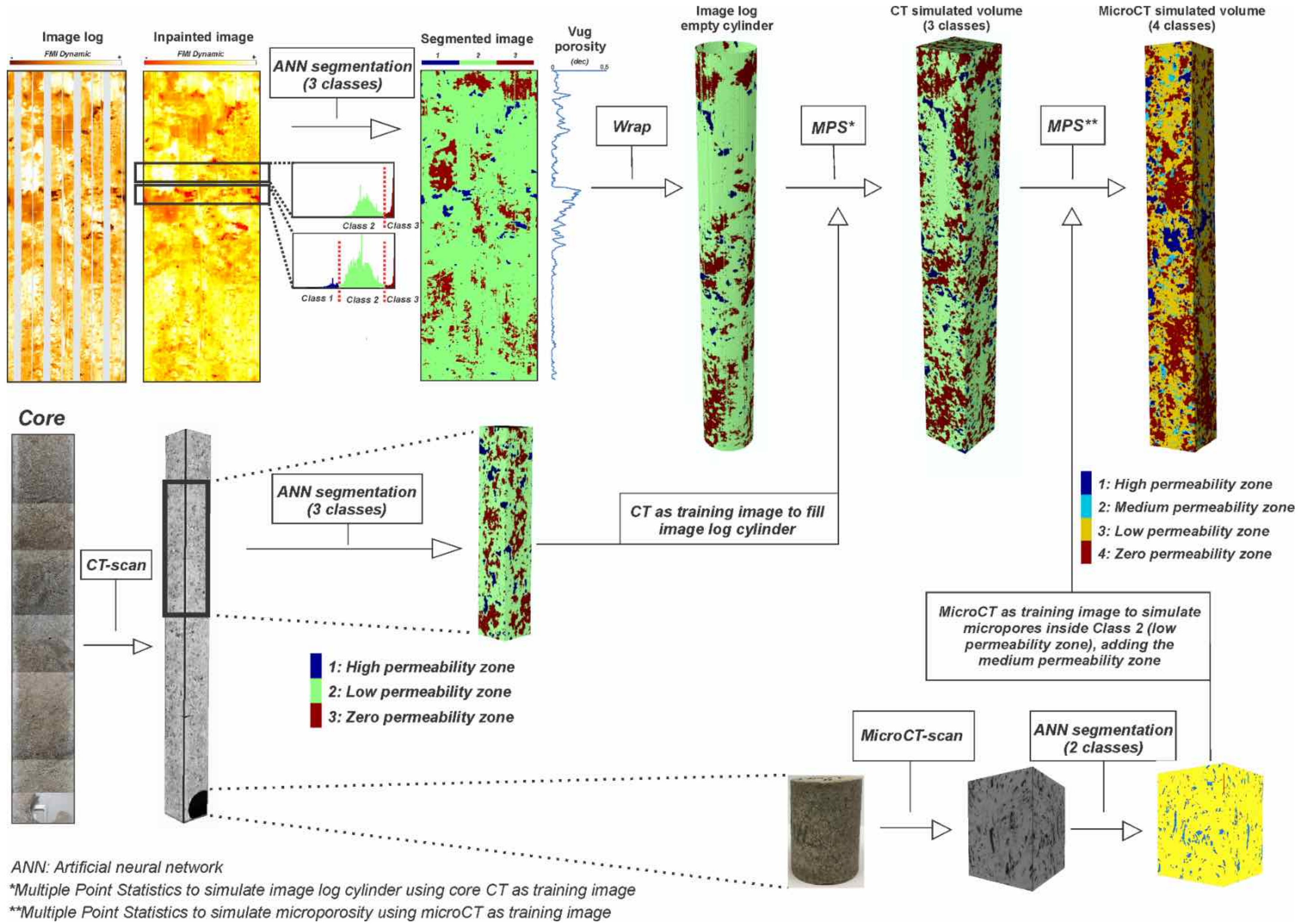

Figure 1: Workflow to integrate three scales of porosity from pore to core to log.

Upscaling of permeability fields in carbonates.
A broad scale solution for managing the effect of support in 3D.

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Keywords: Permeability, Upscaling, Power averaging, Carbonates, Support

The prediction of permeability at a larger scale than the one at which data is obtained is usually a very challenging activity in all types of reservoirs. In carbonates, the difficulty is enhanced by the extreme heterogeneity of the permeability fields, related to the multiple origin of the porous media.

It is known than for the porous medium – with a definition including intergranular, intragranular, moldic, and intercrystalline porosity, as well as large vugs – the equivalent permeability value for a given domain is strongly dependent on the geometric organization of the permeability field within this domain. When a well test interpretation is available and gives the large-scale equivalent permeability value, an analytical formula relates the horizontal permeability in the volume investigated by the well test and the original small-scale permeability distribution in this volume. The power averaging coefficient used in the analytical formula is calibrated by comparing the data at the two scales, and characterizes the geostatistical properties of the small scale permeability field.

However, for 3D heterogeneous reservoirs as carbonates, assessing the vertical permeability is as much important as quantifying the horizontal permeability. Then, it becomes necessary to deconvoluate the power averaging coefficient in two values, corresponding to the vertical and the horizontal members of the permeability tensor. The theoretical model developed in this work reveals that the two power averaging coefficients are related to a common description of the small-scale permeability field. A very simple new formula is proposed which links the two coefficients. Undoubtedly validated through numerical experiments of partial penetration effects, it has been successfully applied on tens of field cases for the evaluation of permeability.

As carbonate reservoirs are frequently characterized by the co-existence of two media : 1) a matrix with good porosity and low permeability, 2) a second medium composed of fractures, or originated by dissolution, highly permeable but with a low porosity, an early evaluation of the reservoir behavior is needed to optimize the data acquisition. Data integration and scaling issues through power averaging provide a definitive solution for delivering a comprehensive diagnosis of permeability fields – possibly with dual porosity behavior - before populating models.

During the reservoir modelling stage, one key concern is to assign realistic values of permeability to each of the meshes of the grid, for volumes not directly assessed by petrophysical measurements and well tests interpretations. As the gridblock volume is usually smaller (~10^4 m^3) than the volume investigated during a well test (~10^6 m^3), the permeability of a cell corresponds more to an apparent permeability than to an equivalent reservoir permeability. Consequently, the way to populate grids with permeability values has to take into account the effect of support, i.e. the volume of the cell for which permeability has to be estimated. This support effect has been integrated through a correction applied to the power averaging coefficient. Used intensively in reservoir operational studies, this new methodology has considerably improved the matching of dynamic data during flow simulation models.

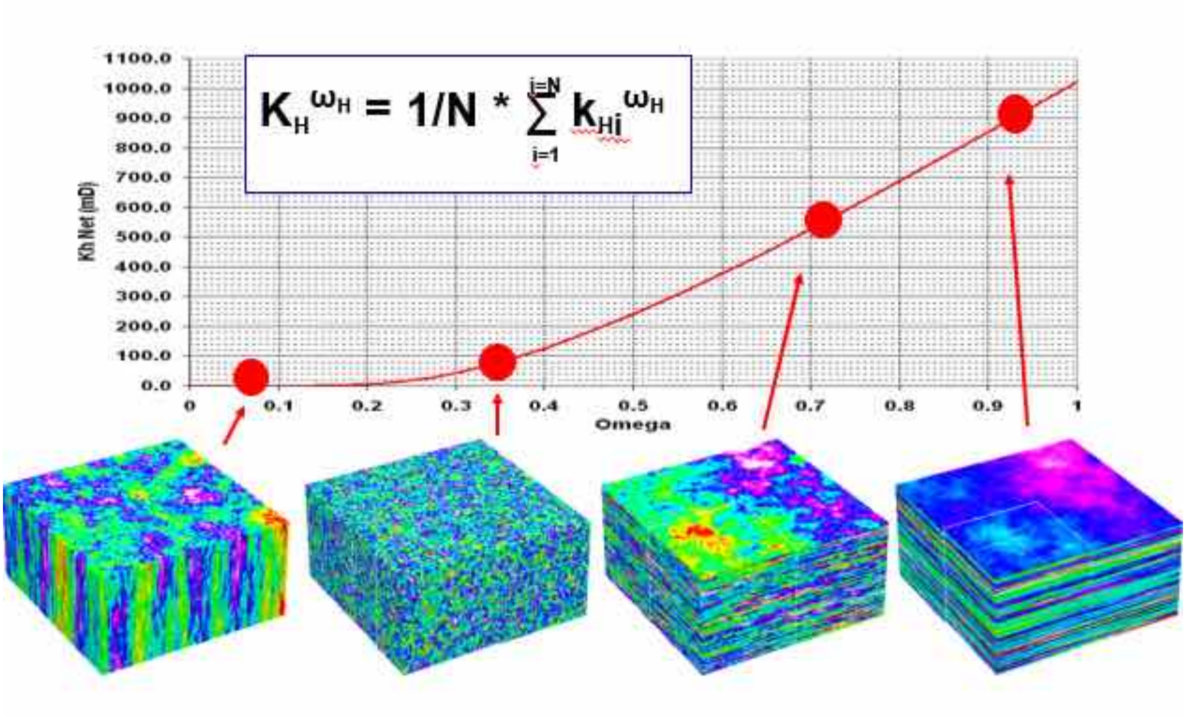

Figure 1: *Correspondence between values of power averaging, equivalent horizontal permeability, and organization of a permeability field.*

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Taphofacies and their relationship with petrophysics, coquinas of the Itapema Formation, Santos Basin-Brazil.

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Key words: coquinas, petrophysics, porosity, taphofacies.

The lacustrine coquinas, or shell concentrations, of the Itapema Formation (Barremian-Aptian age) are an important hydrocarbon reservoir rock of Brazilian pre-salt. These carbonate rocks are composed by bivalve shells and their fragments, and exhibit a diverse textural feature related to depositional environment and diagenetic processes. Due to the textural heterogeneity, different petrophysical conditions are observed, owing to the variety of pore types and their influence in permeability. In this way, interpreting the distribution of facies will aid in understanding the petrophysical variety in coquinas deposits. The interpretation of sedimentary processes in coquinas can be supported by the use of taphonomy associated with sedimentary and stratigraphic aspects. In this work we introduce a taphofacies model for an interval of the shell beds of the Itapema Formation based on taphonomic patterns such as valve orientation, degree of abrasion/rounding, sorting, packing and fragmentation, and also their relationship with porosity and permeability. The porosity was classified by the analysis of thin sections, core tomography scan (CT) and high-resolution CT (H-CT) from plugs. Six taphofacies (T1-T6) were interpreted by the analysis of core and thin sections and were separated as sorted (T1, T3 and T5) and unsorted (T2, T4 and T6), and subdivided between shallow to deep deposits. Taphofacies T1 and T2 are classified as sorted and unsorted grainstones/rudstones with oriented and packed shells with braded valves. Taphofacies T3 and T4 are classified as sorted and unsorted grainstones/rudstones with oblique oriented shells, generally well preserved but sometimes with high shell dissolution. Taphofacies T5 and T6 are classified as sorted and unsorted grainstones/rudstones without valve orientation and presence of preserved shells. In general, the sorted taphofacies do not show shell fragments smaller than 0.2mm, the granulometry of valves varies from 0.5-5mm and shell fragments are the smallest components. The unsorted taphofacies have grains smaller than 0.2mm, most of them are peloids and very small shell fragments. The sorted taphofacies are interpreted as shallow coquinas where storm currents and waves are capable of removing the thinner grains above the fair weather wave base (FWWB). The unsorted taphofacies are interpreted as storm coquinas, deposited bellow to FWWB, where the currents don´t have sufficient energy to remove thinner grains. In sorted taphofacies, the primary pores are preserved, the total porosity varies from 9% to 21%, they are mainly interparticle, intraparticle, moldic and vugs, and generally exhibit connected pores that result in good values of permeability (100mD to 3D). In unsorted taphofacies, the preserved primary porosity is uncommon, the total porosity varies from 2% to 15%, most pores are moldic and vugs with low pore connectivity that result in lower values of permeability (10-200mD).

Hybrid Rocks Classification – A New Approach

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The occurrence of rocks composed of mixed constituents (carbonates, siliciclastic grains and/or non-carbonate intrabasinal particles) is commonly observed in the Brazilian marginal basins, with different compositions and degrees of mixing. In an effort to refine the description and the classification of this type of rock, we propose a new approach for hybrid petrographic schemes classification, improving Zuffa's (1980) classical ternary diagram.
The modification was necessary to have a more accurate estimation on the percentage of the grain types of a hybrid rock and a better qualification of its constituents. The main alteration on the diagram include a revision of the percentage that limits the areas within the triangle and a modification on the classification used for the carbonate area/ vertex. The most widely employed classifications schemes for the carbonate rocks description are Dunham´s (1962) and Embry & Klovan (1971) and, for siliciclastic rocks are Folk (1968) and the adaptation proposed by Folk (1980), which consider grain size and textural relationship.
The proposed ternary diagram for the petrographic classification of rocks with different proportions of compositional mixture is shown in Figure 01. Each vertex corresponds to a class of constituent, thus defined: (I) Siliciclastic (Folk classification, 1968): composed of siliciclastic grains transported and deposited as particles. (II) Carbonates (Dunham, 1962 and Embry & Klovan, 1971) formed by allochemical particles and micrite. (III) Non-carbonate intrabasinal constituents (Folk classification (1968), plus intrabasinal particle composition) constituents such as syngenetic clays, phosphates, iron oxide grains etc., in the form of pellets, ooids, intraclasts and matrix.
Dunham's (1962) classification system modified by Embry & Klovan (1971) is the most widely used in universities and industry. For this reason, we designated Dunham's and Embry & Klovan's classification as the nomenclature for the carbonate area/vertex.
In this diagram, for facies with a predominance of a composition with up to 5% of the other constituents, we recommend to use the original classification from each vertex, without adding any modifier.

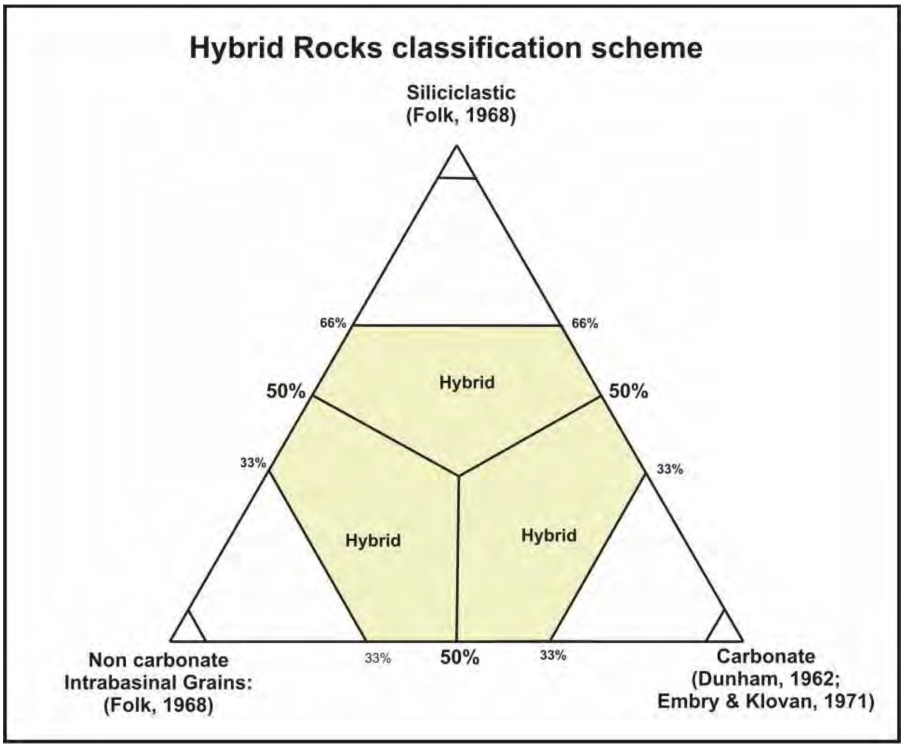

Figure 01 - Ternary diagram for classification scheme of hybrid rocks (modified from Zuffa, 1980).

The use of the name of the subordinated component is mandatory with the original classification when the amount of the subordinated grain/particle is between 5 to 33%. The word "hybrid" need to be added to the name of the rock when the percentage of the mixing components is between 33 to 50%. In this case, the term "hybrid" must be preceded by the name of the secondary constituents, in descending order of proportion (e.g, intraclastic bioclastic **hybrid** sandstone, intraclastic bioclastic **hybrid** *Grainstone)*.
We strong recommend the use of qualifiers of the major and minor composition for all vertices providing a more detailed classification (e.g., ooid/oncoid grainstone). It presents good coherence in the response in electric profiles, in the understanding of the depositional context and in the reservoir quality, being very practical on its application in the petroleum industry.

Key words: Rock Classification, rock typing, petrography, sedimentary petrology, hybrid rock

GAMMA-RAY SPECTROMETRY OF A NEOPROTEROZOIC MICROBIAL CARBONATE SEQUENCE: INSIGHTS AND EVALUATION

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Key words: Gamma-ray spectrometry, microbialites, Neoproterozoic

Gamma-ray log measures the natural radioactivity of rocks, by computing their concentrations of potassium (K), thorium (Th) and uranium (U), being widely used in the hydrocarbon industry as a tool for lithology interpretation, basin-wide correlation in subsurface, and to estimate depositional environment conditions. In carbonate rocks, concentrations of K and Th are related to the insoluble residue. K and Th ions do not substitute in the carbonate lattice implying that relatively pure carbonates posses trifle amounts of K and Th. Potassium consists in a major component of detrital minerals transported by sedimentary cycles, such as potassium feldspars, ilite and other micas, being interpreted in the carbonate strata as an index of bulk aluminosilicate. Thorium, which ions occur only as the tetravalent state Th^{+4} marked by effective insolubility and high adsorption by colloidal materials, is similarly present in detrital residues: adsorbed onto clays and oxyhydroxides or as a component of heavy minerals (such as rutile and monazite). Therefore, although not broadly enriched in aluminosilicates Th displays a linear correlation with K that is representative of shaly intervals in the carbonate strata. As a consequence, the concentrations of K and Th constitute a significant tool to infer variations in the depositional energy, since the amount of the insoluble detrital is inversely proportional to the increase of energy at the depositional site. Uranium, however, being highly mobile during digenesis, shows no predictable facies pattern, may concentrate either by groundwater movements, dolomitization, carried with the siliciclastic admixture, or during the diagenesis of the organic matter.

The aims of this study are to provide an insight into the relationship between microbial carbonate facies and their spectral gamma-ray logs, to verify their intrabasinal correlation potential, and to evaluate the reliability of the gamma-ray spectrometry in high-resolution investigation of relatively pure carbonate strata. Natural radioactivity measurements of the studied outcrop – a Neoproterozoic intertidal-to-supratidal microbialite-dominated carbonate sequence – were performed with a RS-230 Super-Spec handheld gamma-ray spectrometer (Radiation Solutions, Inc., Canada) with a 2x2” (103 cm^3) bismuth-germanate (BGO) scintillation detector. Counts per second of K, Th and U were automatically converted by the portable spectrometer to K%, U-ppm, Th-ppm and total gamma value ($ngVh^{-1}$). Measures were carried out every 0.2-m interval, starting from an initial logging point 0.1 m above the soil up to a height of 8.2 m in a vertical profile, obtaining approximately a hundred of measurements. Whenever a logging point exhibited strong signals of weathering a lateral point within the same correspondent interval was logged rather than the weathered point, with the aim of avoiding data contamination. A 60-second sampling period for each logging point was adopted. Gamma-ray log curves exhibited variations between deeper (intertidal) and shallower (supratidal) facies, the latter containing evidences of subaerial exposure, namely, tepee structures and evaporite pseudomorphs. Correlation between the gamma spectral data of two intrabasinal outcrops indicated a gentle inclination of the carbonate ramp; besides that it made possible to delineate depositional cycles from cm- to m-scales. Brazilian National Petroleum Agency (ANP) and Petrobras financed this present study.

Multi-analytical approach for the study of the porous system and water properties in carbonate facies from the Messinian deposits of Santa Pola (Alicante, Spain).

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Key words: permeability, capillarity, vuggy porosity, reef limestones, stromatolite

The Messinian record of Santa Pola cape (Alicante, SE Spain) represents one of the most relevant geosites from the Neogene record of southwestern Spain. Three carbonate facies from this geo-sedimentary enclave were studied in this work: Wackestone facies (Wf) composed of micrite with dissolved bioclastic fragments (mainly molluscs, foraminifera and rhodophyta fragments); Coral reef facies (CRf) including two subtypes according to the morphology of the *Porites* sp (stick, CRf-s; or dish, CRf-d); and Stromatolite facies (Sf). These Messinian deposits have experienced widely varying calcite cementation, dolomitization, dissolution and even several phases of subaerial exposure with meteoric diagenesis (Esteban, 1979; Esteban et al., 1996). Consequently, studied rocks are characterized by a complex porous system dominated by intercrystalline, vuggy and/or preserved intergranular pore types with wide ranges of pore size and a large degree of heterogeneity and directionality.

Porous system characterization was carried out by means of several techniques (table 1). On the one hand, Hg-porosimetry and He-picnometry were used to measure the interconnected (ϕ_{Hg}) and total (ϕ_{He}) microporosity, respectively. X-Ray Computed Tomography was employed to characterize total macroporosity (ϕ_{RX}). Porosity accessible to water (at atmospheric pressure) was also measured (ϕ_{w}).

Hg porosimetry and RX Computed Tomography are a complementary techniques for the characterization of the complex porous system of these rocks, including microporosity (from 0.001 to 200 µm) and macroporosity (from 0.1 mm to several cm). The analysis of the interparticle porosity, which excludes the vuggy porosity, shows a high difference between both total and connected microporosity (ϕ_{He} and ϕ_{Hg}, respectively), and therefore, concludes the existence of an important microporosity fraction non-connected in the whole rock varieties. Contrary, coral reef facies (CRf) present an abundant macroporosity comparing to micro interparticle porosity.

Water movement in saturated (permeability, K) and non-saturated (capillarity, C) media were also studied. Obtained hydric coefficients were interpreted after the specific porous system of each rock, taking into account the presence (or not) of large vugs affecting completely or partially the longitudinal section of the sample (V or pV, respectively, in table 1) (nV when no vugs are present in the sample). In the case of the stromatolite samples, sample orientation respect to the preferred orientation of pores was also taken into account (parallel, //, or perpendicular, T, to porosity).

Macroporosity controls completely the permeability of the rock. The presence of vugs favours the gravitational flux of liquids through the sample, but only when they are well connected and oriented in flow direction (K values of V rows, in table 1). Macropores in Wf and Sf are less frequent and, in the case of Sf, they are very low connected. As a consequence, permeability in these rocks is low and independent from the relative orientation of the sample with respect the water flux (Sf values in table 1). Contrarily, capillarity is mainly controlled by microporosity due to the fact that capillary forces are much more effective in micropores than in macropores.

Table 1. Porosity and hydric parameters of studied rocks.

		ϕ_{He} [%]	ϕ_{Hg} [%]	ϕ_{RX} [%]	**Interconnection degree**	ϕ_{w} [%]	**C** [$g/m^2s^{0.5}$]	**K** [mD]
Wf		16.23	3.31	5.80	low	12.42	26.12	9646.37
CRf-s	V	11.98	5.10	22.10	Very High	7.87	21.14	155145.72
	pV						14.49	30.51
	nV						2.51	0.86
CRf-d	V	14.67	3.61	19.35	High	11.35	9.31	23476.09
	pV						5.57	1.83
Sf	//	22.04	8.96	4.93	Very low	9.41	6.18	0.29
	T						5.41	0.12

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Will Carbonate Geologists Be Replaced by an Algorithm? Machine Learning Successfully Applied to Visual Core Description and Thin Section Identification

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Keywords: artificial intelligence, automation, data science, image recognition, neural network

Carbonate geology still in a large part relies on observational data at a range of scales. For instance, rock facies are used to derive regional stratigraphic trends from core data, and they often form the building block for petrophysical classifications. However, a recent study has shown that even experienced carbonate sedimentologists will classify the same facies using different textural names. This problem is compounded when different describers are involved in a project (or when literature data is compiled) as this can result in a heterogeneous attribution of facies to similar rocks despite the use of a common classification scheme. The reliability of descriptive data can be compromised.

In this presentation, I will discuss the potential for machine learning to help carbonate sedimentologists achieve a higher degree of consistency in their description. Behind the provocative title (you will be happy to know that I believe carbonate geologists are still useful, thank you very much!) I intend to present the potential and the pitfalls of a machine learning approach. I will start by explaining what 'machine learning' is, and how conventional machine learning is different from the recent advance of 'deep learning' and the application of neural networks to image analysis. The goal is to demystify the technology, and encourage fellow carbonate researchers to use it. I will also present some of our first results of machine learning applied to automatic identification of carbonate facies using the Dunham classification scheme. We used high-resolution core images from the Integrated Ocean Discovery Program (IODP) Leg 194 to train a model written in the Python programming language. The technology stack we rely on includes the TensorFlow machine learning library and specifically Google's Inception V3 network, a pre-trained Convolutional Neural Network (CNNs). We used 'transfer learning' to train Inception V3 to recognize carbonate core images.

Results show that our CNN can achieve up to 90% accuracy for identification of Mudstone to Rudstone and Crystalline Dolomite. The main misclassifications were between matrix and grain supported facies, and fine and coarse-grained facies, textures also commonly misclassified by control tests with geologists. Interestingly, the bias observed in core description by the algorithm is very similar to human biases: a tendency to give a greater weight to grains as they stand out from the matrix, called 'saliency'. But the CNNs were able to identify facies 60 times faster than humans, and with a much greater consistency. The results of our study demonstrate the potential of artificial neural networks to reliably interpret and quantify descriptive data, in a fast, automated, high-resolution manner. This should be viewed as an enabler for semi-supervised fast and reliable rock description, freeing the geologists and allowed them to focus on higher-order interpretations.

Dynamic analogues in groundwater reservoirs
A disruptive approach for characterizing fluid flows in outcrops
Application to a Burdigalian carbonate tidal dune system

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Keywords: Dynamic analogue, Carbonate, Tidal dunes, Burdigalian, Modelling

A new concept of dynamic analogue arose from the need for integration of hydrodynamics and geophysics in outcrop studies. Instead of single geological and petrophysical description of the reservoir before forecasting the seismic answer and the hydraulic behavior through numerical modelling, the analogue is assessed through multi-physics experiments.

The Font d'Armand quarry (Sussargues, France) is a world class site for studying the fluid flow into a tidal reservoir. The large scale tidal dunes are created into incised valleys during a Miocene transgressive event. This permeable groundwater reservoir is mainly made of bioclastic carbonates, locally mixed with siliciclastic grains. Such organization is visible in 3D from the numerous quarry outcrops. 13 wells have been drilled in which a rich set of acquisition is performed: wireline logging, cores, and a ground penetrating radar acquisition. The dynamic information is given by pumping tests and slugs tests in each well while the others wells become observers.

The small scale permeability is measured from outcrops and cores and shows a vertical and lateral evolution which is coherent with the tidal dunes architecture.
On the other hand, the large scale permeability is given by the well tests which are more integrative. The interpretation of those dynamic data demonstrates that the permeability tensor is anisotropic and follows the 3D sedimentary structures.

The 3D geometry is reproduced by a new and innovative in-house tool (T-SED™), mimicking the Miocene tidal dunes.

This methodology is now mature enough to be applied to any kind of reservoir when the sedimentary structure is the main flow driver.

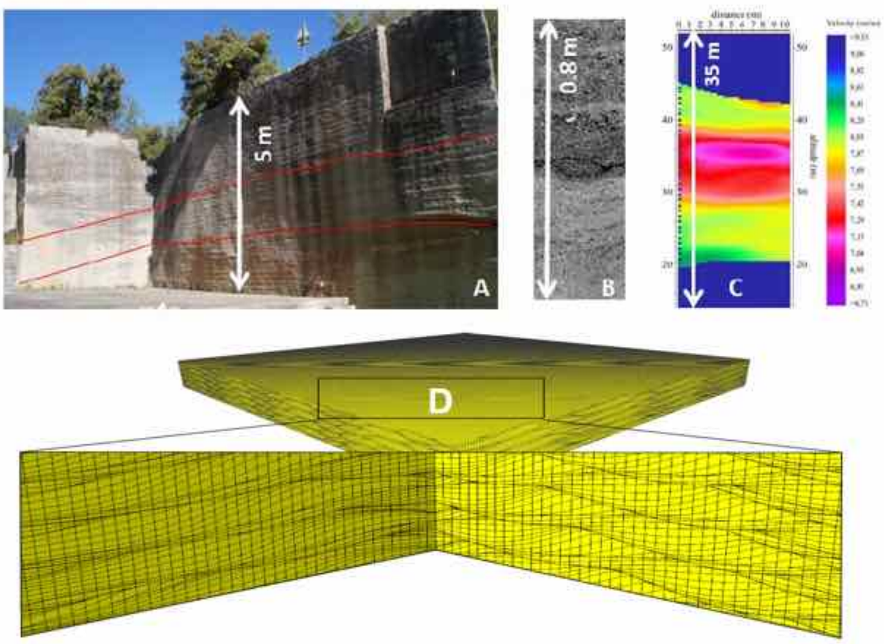

Figure: *Miocene giant tidal dunes in Font d'Armand quarry (Sussargues, France). A: 3D view of the dunes. B: CT-Scan imagery on cores. C: Crosshole radar tomography of the groundwater reservoir. In pink and red, the slowest velocity corresponds to the more permeable interval, consistent with well tests response. D: Modelling with T-SED^{TM}.*

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Geological controlling factors of acoustic properties in continental carbonates: Example of a paludal tufa succession (Messinian, Samos Island, Greece)

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Keywords: Diagenesis, Pore-type, P-wave velocity, Seismic, Tufa

Linking geological and seismic properties of carbonates is an important issue for the understanding of subsurface reservoirs. Indeed, seismic reflectors are controlled by vertical contrasts of impedance (product of P-wave velocity and density). These contrasts could be due to changes of lithology (marls *versus* carbonates) but also to contrasts of porosity (tight *versus* porous carbonates). Variations of pore types and shapes could also have an impact on the acoustic properties of carbonates, resulting in the scattering of P-wave velocities for the same porosity value, which further complicates the geological interpretation of data.

In order to investigate the geological controlling factors of acoustic properties in continental carbonates, we studied a paludal tufa succession of Messinian age, located on Samos Island. A well-exposed outcrop allowed us to describe a forty-meter-thick sedimentary succession. We collected 26 samples of 8 cm length for measuring: i) ultrasonic P-wave velocity (frequency of 500 kHz); and ii) porosity. We described the texture and microstructure using conventional microscopy.

The studied carbonates are similar to paludal tufa deposits developed in cool freshwater environments. They correspond to carbonate surface coatings on macrophytes which accumulate after the decay of the plant stems and result in phytoclastic rudstone. They are associated with phytoclastic and peloidal packstones and wackestones, phytoclastic and intraclastic floatstones, and quartz-rich mudstones. The characterization of the microstructural control of P-wave velocity and porosity is exposed on figure 1. Thanks to the recognition of textures (Fig. 1A), we observe that the rudstones and packstones show the highest velocities, whereas the floatstones, wackestones and mudstones present lower velocities. Using the empirical Raymer-Hunt-Gardner equation (RHG) which link P-wave velocity with porosity, we can compare our dataset to the classical trend of decreasing velocities with increasing porosity ($Vp=(1-F)^2*Vp_{Calcite}+F*Vp_{fluid}$). Indeed, if we take a look at the dominant pore types of the samples (Fig. 1B), we easily show their control on the distribution of the P-wave velocities: stiff pores (framework and fenestral) are associated with velocities higher than RHG, while soft pores (cracks and root molds) are associated with velocities lower than RHG. On the other hand, microporous samples tend to follow RHG.

These first results show that the P-wave velocity of paludal tufa is primarily controlled by the depositional texture (*e.g.* rudstone *versus* mudstone) and the post-depositional processes that occurred in the palustrine environment: root molds and cracks related to pedogenesis. Looking at the vertical distribution of these velocities could allow us to link potential seismic reflectors with microstructural control. Indeed, changes of impedance materialized by grey lines (Fig. 1) could be linked either with a change of texture or dominant pore-type and may lead to contrasts of impedance that create seismic reflectors.

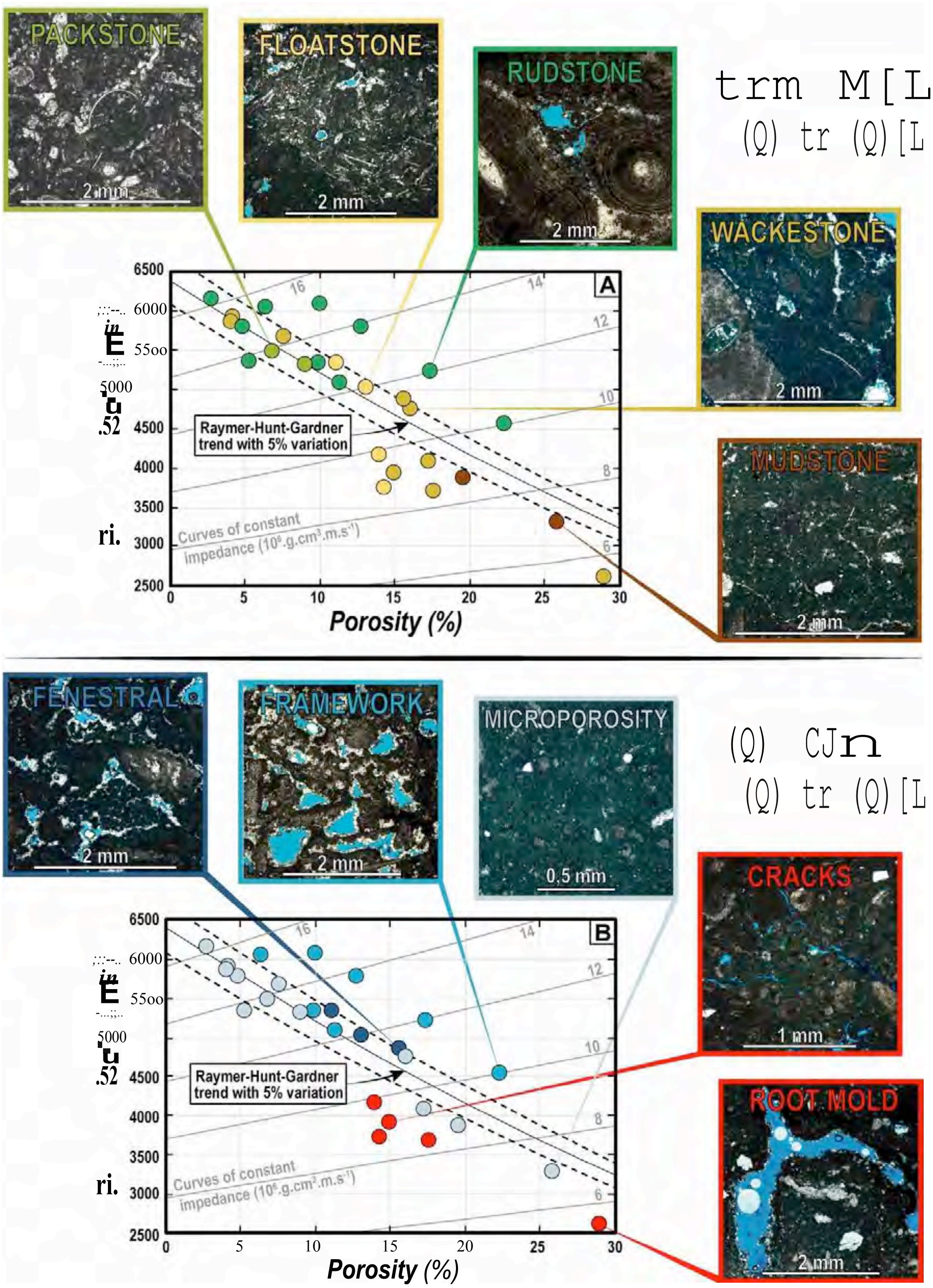

Fig. I. P-wave velocity *versus* Porosity. The RHG equation is indicated for pure calcite with 5% variation. Grey curves of constant impedance are also indicated in order to show the potential effect of microstructure changes on seismic reflectors. (A) Textura! control. (B) Pore-type control. Root molds and cracks are grouped because they are observed together on thin-sections.

Upscaling of elastic wave velocity in carbonates: A modelling approach based on a multi-scale geophysical dataset

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Keywords: Lacustrine carbonates, Modelling, Multi-scale, P-wave velocity, Upscaling

During the reservoir characterization process, linking seismic, sonic logs and ultrasonic measurements on samples is challenging, particularly in carbonates. Indeed, one of the main issues to tackle is the high petrophysical heterogeneity as well as the effect of fractures. This work focuses on Miocene formations of the Samos Island (East Aegean domain) which present two small continental basins with lacustrine and palustrine carbonate deposits.

One of the main goal of this work is to link the macro- and micro- structures of these carbonates with elastic wave velocities measured at different scales, on a single study site (Fig. 1). At the field scale, we carried out a seismic-refraction campaign to obtain wave velocities at a decametric scale (central acquisition frequency of 100 Hz). At an intermediate scale, we acquired “sonic” measurements on outcrop along a sedimentary log (frequencies of 54 kHz and 250 kHz). Following these measurements, a high resolution sampling was performed (one sample every 20 cm) in order to compare outcrop and plug data. At the plug scale, a petrographic description (conventional microscopy, cathodoluminescence) allows to describe microfacies and determine the impact of diagenesis on microstructures. In addition, ultrasonic P-wave and S-wave velocities (500 kHz) and porosity were measured on plugs.

Each scale of investigation exhibits different controlling factors on the elastic properties. Seismic data are primarily controlled by structural setting and lithology contrasts. At the log scale, the presence of cracks and fractures impacts the sonic data. The outcrop dataset is also controlled by the stacking of different facies and the diagenetic overprint. At the plug scale, microstructure changes (i.e. facies and diagenetic overprint) appear to be the first controlling factor of elasticity. Indeed, facies variations control the primary fabric of carbonate rocks and early diagenetic modifications could sharply modify this fabric and lead to huge modifications of the microstructure (early neomorphism *versus* moldic dissolution).

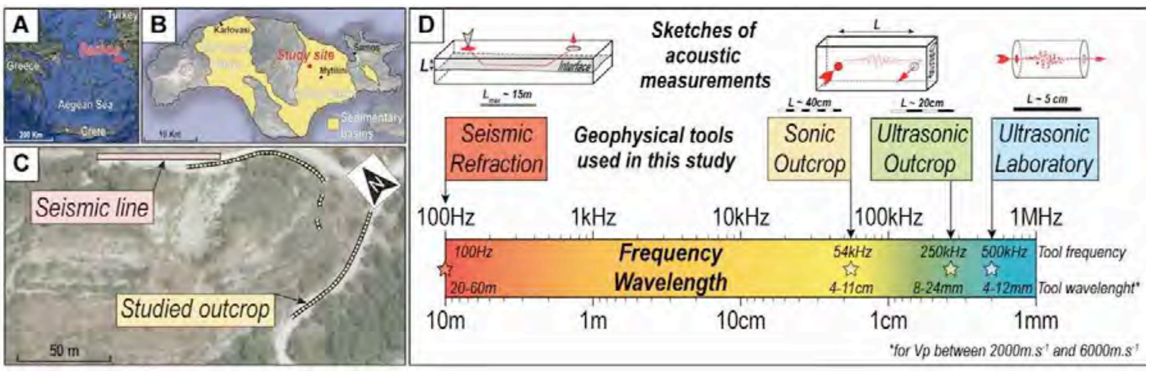

Figure 1. General framework and methodology: (A) Localization of Samos Island. (B) Sedimentary basins of Samos Island and study site. (C) View of the study area. (D) Multi-scale methodology of this work.

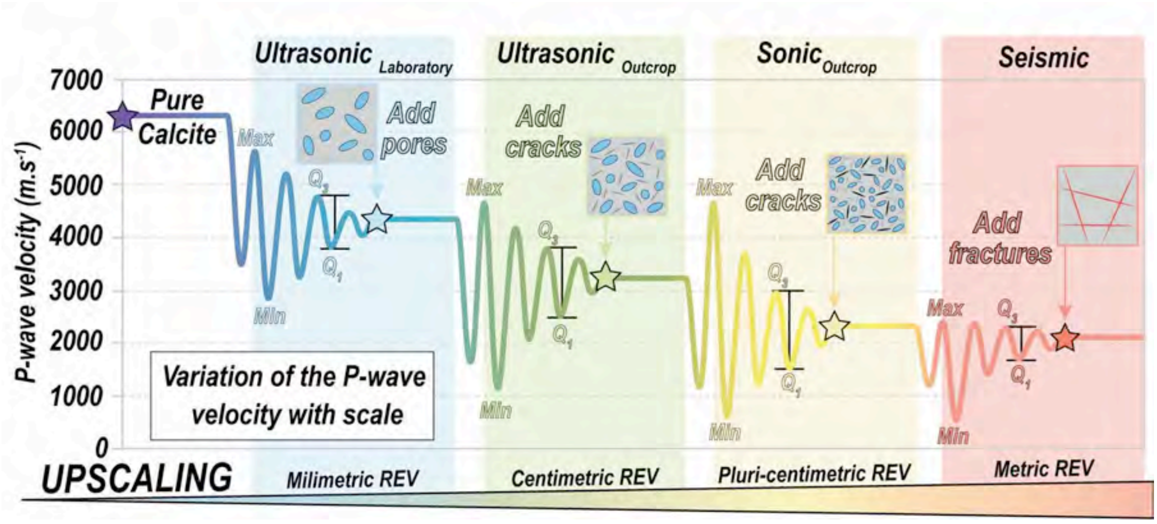

Fig. 2. P-wave velocity versus scale of measurements. The curve starts from the pure calcite value and decreases with scale. The descriptive statistics of each dataset are used to symbolize the variability of the P-wave velocity (the median is symbolized by a star). We propose to add pores, cracks and fractures between scales in order to explain the overall decrease of the velocity.

Finally, we show that the P-wave velocity decreases from laboratory scale to seismic scale (Fig. 2). To explain these variations, we relate the concept of Representative Elementary Volume (REV : volume of rock for which a physical property is constant) with the wavelength size of each scale of study. Indeed, the wavelength size varies from millimetric at ultrasonic to metric at seismic scale. Thus, using effective medium theories, we quantify the pore aspect ratio at sample scale and the crack/fracture density at outcrop and seismic scales in order to extrapolate our results to upscaled reservoir properties (*e.g.*, permeability).

Integration of petrographical and petrophysical data for seismic modelling of Late Cretaceous platform and basin carbonates

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Keywords: carbonate deposits, Late Cretaceous, seismic modelling

Abstract

Acoustic velocities are crucial for realistic seismic modelling of the subsurface. The acoustic velocity of tight carbonate rocks varies according to mineralogical composition, pore network connectivity and diagenetic processes. The influence of bulk density and pore shape is limited (Jafarian et al., 2017, 2018; Kleipool et al., 2017).

This study focuses on the well-exposed Late Cretaceous platform and basin sedimentary series in southern Albania. The shallow-water platform deposits of the Apulian and Kruja platforms reveal a succession of peri-tidal limestone-dolomite cycles, while basin sediments of the coeval Ionian Basin show hemipelagites, sediment gravity-flow and mass-transport deposits. The petrographical analysis of 85 thin sections showed the presence of nine depositional facies associations. In total, 60 plugs representative of the different depositional facies encountered, were measured for porosity, permeability and acoustic velocities (P- and S-wave).

This analysis allowed us to investigate the effect of depositional lithology characteristics (clay content, grain-size, grain arrangement and texture) and diagenetic alterations (early and late

cementation, dolomitization and compaction) on the velocity distribution of the Albanian tight carbonate, which show an average porosity of about 2%. In addition, the relationships between the petrophysical parameters and textural properties constrained the input for synthetic modelling of seismic-scale sections in the studied outcrops. This model provides a better understanding of the seismic response of platform to deep-water carbonate series of subsurface reservoir analogues.

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The identification of possible fluid-escape features associated with the development of hypogenic karst structures in carbonate reservoirs: Preliminary insights and ideas from 3D seismic and borehole image data

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Keywords: 3D seismic, carbonate reservoirs, fluid-escape features, karst.

Fluid-escape features, which can be associated with the hydrothermal activity, commonly originated from the interaction between seawater and magmatic activity. These features may provide insights into the karstic systems in deeply buried carbonate reservoirs. Examples of features associated with fluid escape include pipe-like structures, documented worldwide. We describe examples of seismic features possibly associated with focused fluid escape characterized by 'reflection-free' to acoustic blanking zones with a distinctive seismic reflector character. Their cross-sectional shapes consist of several inward-dipping reflectors resembling a shallow depression, with an abrupt transition to the horizontal surrounding reflectors. In plan view, they can be recognized by an approximately sub-circular to elliptical morphology, measuring, typically between 500 m and 1000 m wide. We interpreted the aforementioned structures in the Aptian Barra Velha Formation, the main reservoir from the Santos Basin non-marine carbonate pre-salt succession, southeastern Brazil, which formed during the sag-phase of rifting. We touch on the possible impact of hypogenic karst structures on reservoir behavior since hydrothermal fluids could cause dissolution and therefore enhance porosity and permeability. The origin of the pipe-like structures we identify and the likelihood that they acted as conduits to provide hydrothermal fluid pathways is still under investigation. We also interpreted high-amplitude seismic reflections that resemble *string-of-beads*, which have also been interpreted as evidence of epigenic karst. The main motivation of this work is the increasing need to quantify the impact of post-depositional structures on carbonate reservoir performance and the yet unclear interplay between the magmatic activity and the reservoir potential of the carbonates. The objective of this work is to share some thoughts on how some of the fluid escape features could be recognized using both borehole image (BHI) logs and seismic data. This may help the hypotheses proposed to explain the karstic influence in the Brazilian pre-salt carbonates. The 3D seismic data, BHIs, and conventional wireline logs, from a pre-salt field located in Santos Basin, were applied to analyze vertical to sub-vertical seismic pipe-like structures, similar in geometry, to those found elsewhere in the world, associated with karst, magmatic, and hydrothermal activity.

Seismic facies interpretation in an epicontinental see environment dominated by mud mounds

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Muddy deepwater carbonate factory, Seismic sequence stratigraphy, Upper Jurassic, SW Germany

Sequence stratigraphic analysis of carbonate sediments poses a challenge to a seismic interpreter. In the present work, we investigate complex heterogeneous carbonate facies, which were deposited in the epicontinental sea environment applying sequence stratigraphic methods (Emery and Myers 1996). We interpret these facies as products of the "muddy deepwater carbonate factory" (Schlager, 2005).

The study area is located in southern Germany and in the Upper Jurassic time was part of the carbonate platform on the northern side of the Tethys Ocean. In literature, it is referenced as South Bavarian reef or sponge platform (Meyer and Schmid-Kaler, 1989). The carbonate sedimentation took place from Oxfordian to Turonian time. Sedimentation cycles and systematic investigation of different reef types depending on the microfacies were reported from well and outcrop analysis (Koch, 1994; Pawellek, 2003). In the ongoing efforts in exploration of the carbonate platform for geothermal use, more 3D seismic surveys were acquired. Therefore, seismic methods can help to investigate the local geologic development of carbonate structures in an epicontinental sea environment.

A 170 km^2 large 3D-seismic survey serves as a base for the investigations presented here. To get an overview of the internal structure of the platform we applied blending of seismic signal frequencies. A classification scheme with three seismic attributes enabled delineation of different zones within a layer model of the platform. The carbonate platform was further vertically subdivided into four sequences based on the reflection strength and the distribution of seismic patterns. The sequences show distinct changes in the sedimentation and erosional events. We then produced a model of geological development on the platform with the help of the sequence analysis of vertical seismic sections and maps produced with the seismic classification.

The results show that a larger carbonate mud mound separates two depocentres. Its growth successively increased the topographic relief. The filling of troughs and the ongoing development of reef complexes and dome-like structures flattened the relief afterwards. Seismic signatures show an asymmetric sedimentation, so that one can define a leeward and windward direction of the sedimentation processes. This model helps to identify facies distribution. Small ramps and seismic onlaps characterize areas with a higher topographic relief. These areas have a parallel seismic signature and therefore are caused by other sedimentation processes than the mud mounds. This matter is still under discussion.

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Abstracts Volume

Posters

Theme 4: South Atlantic Pre-Salt Carbonates, Potential Analogs and Microbialites

P-151 to P-181

Sedimentological and stratigraphic analysis of Pre-Salt coquina, Santos Basin, Brazil

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Key words: coquina, bivalves, Pre-Salt, depositional system, lacustrine

Petroleum reservoirs composed of bivalve rudstones were formerly known in Coqueiro Formation of Campos Basin, but with smaller oil accumulation than in Itapema Formation of Santos Basin. The current study is the first one performed on the coquinas of Jiquiá local age (lower Aptian) in Santos Basin. The aim of this work was to recognize the facies, facies association and depositional system in a stratigraphic framework, where these sediments were deposited.

In this study, 373 m of cores and 957 sidewall cores of 10 wells were analyzed, totalizing 996 thin sections described. 29 sedimentary facies were identified, based not only on the composition but also on the size of the shells, degree of the shell fragmentation, sorting, roundness, sedimentary structures and packing. These facies include 12 different rudstones and 5 grainstones which are the facies with the best reservoir quality.

Four facies associations were characterized: bars and interbars, lake embayment, beach, and deep lake. They are elements of the depositional system of bars and interbars composed mainly by massive rudstones of bivalves deposited by catastrophic episodes like storms or tsunamis on the lake border. The lake embayment is characterized by low energy facies like microbial stromatolites, oncolites and mudstones/wackestones. The beach is mainly composed of peloidal laminated grainstones, occasionally, presenting low angle cross stratification. In this environment the shells suffer microbial micritization and are reworked by the daily waves of the lake. The deep lake facies is a succession of lamites, mudstones and laminites.

The Itapema Formation was subdivided in five stratigraphic intervals based on the facies and facies association distribution and the well logs. The stacking pattern of these intervals shows that there was a shallowing upward from the base (interval I) to the interval IV, when there was very little accommodation space for deposition. On the top of the Jiquiá sequence, interval V, there was an abrupt deeping, probably due to tectonic activity with deposition of lamites and laminites on the lowest areas.

The sedimentological and stratigraphic comprehension achieved has given support to the prediction and reservoir development of bioclastic carbonates of Itapema Formation.

Depositional paleoenvironment of authigenic magnesium clays in Pre-Salt of Santos Basin - Brazil

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Key Words: authigenic Mg clays, carbonates, depositional settings, Pre-Salt

The main carbonate reservoir facies in the Aptian of Brazil are "in situ" facies like stromatolites, laminites and spherulitites composed essentially by calcite and subordinately by dolomite, genetically related with biotic processes – organomineralization induced and/or influenced. Reworked facies, like intraclastic grainstones and packstones also occur. However, in some areas the carbonate facies are associated with magnesian clay minerals and in this case, a dramatic decrease in porosity and permeability is observed.

The paleoenvironment interpretation for Mg-clay minerals deposition only was possible according to an integrated approach using analytical methods (X-Ray diffraction, electron microprobe, scanning electron microscope-energy dispersive spectrometry and automated scanning electron microscopy of thousands of samples) to identify the species of clay minerals; petrography analysis to recognize the textures of clay and carbonate facies; sedimentary structures recognition, stacking patterns analysis, regressive and transgressive hemicycles characterization, facies association, upscaling to logs and seismic data, high resolution stratigraphy correlation, seismic facies and seismic stratigraphic analysis and understanding of the evolution and geometry of the carbonate platforms.

Different species of clay minerals are identified: kerolite, stevensite, saponite, sepiolite, illite and mixed layer minerals kerolite/smectite and illite/smectite and the petrographic analysis show that these Mg-clay minerals present different textures that indicate their genesis: authigenic by neoformation (sin-sedimentar direct precipitation for ionic or colloidal solutions); authigenic by transformation (early diagenesis: dissolution-precipitation from previous phases); Mg-Clay intraclasts – sand size (authigenic clay reworked); and detrital clay (Al and Mg-rich) associated with silt size siliciclastic grains. The relationship between carbonates and clay minerals shows that these clay minerals are concomitant with the carbonatic sedimentation.

This integrated analysis indicates that there are different depositional contexts with coexistence of carbonates and clay minerals: a) Low energy sedimentary environment with magnesium-rich alkaline hydrochemistry, in a regressive trend: Mg clays neoformed (kerolite, stevensite, sepiolite, MLM kerolite/smectite); b) Moderate energy, reworked carbonates and Mg clays neoformed in the more humid context, in the beginning of transgressive trend (intraclasts of kerolite, stevensite, and MLM kerolite/smectite); c) Low energy sedimentary environment and magnesium-rich to moderate alkaline hydrochemistry, more humid, in a transgressive trend: decantation processes is predominant (saponite, ilite, MLM ilite/smectite).

Finally, seismic analysis shows that authigenic magnesium clays occur in protected areas like platform interior and low energy ramps.

Unusual dolomite fabrics in spherulitic and shrubby boundstones of Santos Basin Pre-Salt deposits

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Keywords: carbonate, diagenesis, dolomite, lacustrine, pre-salt

The Pre-Salt of South Atlantic continental margin presents an entirely new world in terms of carbonate lacustrine deposits, with depositional facies that are product of evaporitic, microbial and hydrothermal processes, each one with more or less importance depending on the structural context inside the basin. A very attention-grabbing feature in these deposits is the presence of unusual dolomite fabrics which occur in the spherulitic and shrubby boundstones.

In the Barra Velha Formation, Santos Basin, at least eight dolomite phases are recognized, here identified as: (1) pseudomorphic; (2) rhombohedral; (3) medium crystalline mosaic; (4) lamellar; (5) reticulated; (6) incrusting, (7) saddle dolomite, and (8) very fine crystalline mosaic. The pseudomorphic dolomite replaces shrubs and spherulites, and seems to be the first dolomite phase to occur. The rhombohedral is the most common dolomite phase and occurs among shrubs and spherulites. It is usually zoned, with a darker core (dirty aspect). The crystals are arranged in a reasonably regular spatial arrangement, which in the 2D vision of the thing section gives an aspect of floating crystals in the pore space. The medium crystalline mosaic dolomite occurs when the rhombohedral dolomite continues to grow until it occupies most of or the entirely pore space. The lamellar dolomite, a very unique dolomite texture, is formed when very fine dolomite crystals grow from both sides of a lamellar (or laminated) shaped feature (probably organic filaments). Cathodoluminescence images show that it is formed after the rhombohedral dolomite. The reticulated dolomite consists of an irregular and delicate dolomitic network that reminds an organic shape. The incrusting dolomite is formed by anhedric to subhedric brownish dolomite crystals that occur mainly around shrubs and spherulites, as discontinuous crusts and sometimes as a meniscus. The eogenetic saddle dolomite occurrence is restricted to some portions of the basin, possibly related to hydrothermal activities during deposition. Finally, the very fine crystalline mosaic dolomite occurs as both replacing and cementing phases, being related to exposure surfaces, frequently forming dolocretes.

The dolomite phases reported above commonly occur associated with silica (microquartz and chalcedony), magnesian clays, pyrite (usually less than 1%), and locally with magnesite and some trace minerals. Most of these dolomite phases are interpreted to be formed during the eodiagenesis due to high evaporitic conditions in the depositional environment, and some of them may have its nucleation related to microbial activity. Its occurrence is variable along the Pre-Salt deposits, related to depositional cycles in its different orders. The understanding of its genesis and spatial distribution is very important due to its impact in the porous system, usually reducing porosity and pore throat size.

Linking carbonate and evaporite deposition as a basinwide event in the South Atlantic rift – The role of basalts in determining the geochemistry in these ancient evaporite basins

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Evaporite sedimentology; hydrothermal marine seepage; Pre-Salt; Santos Basin.

Recent studies (Sabato-Ceraldi and Green 2016; Szatmari and Milani 2016) have raised the exciting possibility that the sag phase carbonates of the Santos-Campos basin were deposited during the initial/transitional stage of a closed, sub-sea-level evaporite basin that subsequently reached higher salinities culminating in the deposition of halite and bittern salts (carnallite, sylvite, tachyhydrite). Regarding the Walvis-Rio Grande volcanic high as a topographic barrier during the Aptian, we propose that the reaction between seawater and the basaltic volcanic barrier at depth was the main source of calcium to the Barra Velha paleolake. The Moho, shallow beneath the hyperextended crust, increased the geothermal gradient to levels favorable for the generation of hydrothermal $CaCl_2$ brines, a process facilitated by the elevated Ca^{++} ion and minor sulfate concentration of the Cretaceous ocean. These $CaCl_2$-rich fluids would percolate through the volcanic barrier into the basin where the water level of the paleolake was lower than sea level. The high salinity paleolake in the rift becomes saturated in calcium bicarbonate/carbonate as internally drained $NaHCO_3$-bearing alkaline waters, formed by physical/chemical weathering of penecontemporaneous basaltic rocks, mixed with the $CaCl_2$-bearing hot brines percolating through the barrier, which formed a hybrid brine ($2NaHCO_3 + CaCl_2 = Ca(HCO_3)_2 + 2NaCl$), typical of large ancient evaporitic basins. With progressive evaporation, this saline-alkaline brine would generate conditions for calcium carbonate deposition mimicking evaporite deposition. Owing to the depositional framework of brine drawdown in an endorheic basin, the evaporitic pattern of deposition would be dominated by ephemeral salt pan-like hydrology indicated by bedded salt crusts. The crusts would accumulate as a stack of subaqueous aligned crystal beds through diagenetic growth of salt within saline and mud layers beneath the surface of the dry pan, followed by deposition of laminated sediments. We interpret these patterns as the cause of cyclicity between shrub-like crystal growths, diagenetic spherulites in magnesium clay matrix and laminites, typical in pre-salt cores. This working hypothesis may have important implications for the study of these unusual carbonates.

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Classification scheme for coquinas and shell concentrations: Advances since Bathurst 2015

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Shell-rich deposits are abundant around the world throughout geologic time, presenting a high variability in thickness, matrix composition and principal bioclastic components. In order to obtain the correct classification and then paleoenvironmental interpretation of coquina sequences, it is necessary to evaluate several aspects: biological (such as shell productivity, type of organisms), sedimentological (environmental energy, transport of bioclasts, terrigenous sediment supply), taphonomic (fragmentation of shells, abrasion) and the diagenesis, each of these directly relates to porosity and permeability characteristics of these types of carbonates. The classification schemes available for carbonate rocks do not meet all of these criteria and do not cover many interpretational aspects required for this type of carbonate rock. As observed in the literature, three main problems could be briefly discussed: (1) *Nomenclature divergence*: there is not a standard classification used to describe this type of rock; in fact, over 20 different names have been used to describe the same rock; (2) *Skeletal components:* As pointed out by Schäfer (1972), although shell concentrations can be formed by calcareous, chitinous or siliceous skeletons of organisms such as balanids, hydrobians and echinoderms, most components are in fact molluscs, specially bivalves; (3) *Matrix composition*: Over 60% of the described shell concentrations in the literature also contain siliciclastic matrix. Since the large majority of shells are bivalves, made of calcium carbonate, a coquina with siliciclastic components would be considered a hybrid rock. In this context, we are proposing a new suite of terms based on the classifications of Dunham and Folk, but blended with the taphonomic concentrations (biofabric) terms of Kidwell, complimented by others terms (condensed-shellstone, fitted-shellstone and sparstone) based on Wright's diagenetic classification. This classification was applied to the 200 thick succession of bivalve coquinas of Morro do Chaves Formation (Barremian/Aptian), Sergipe-Alagoas Basin, NE Brazil, predominantly composed of coquinas formed from fragmented bivalves' shells, parautochthonous to allocthonous, interbedded with sandstones and shales, representing a mixed carbonate-siliciclastic depositional paleoenvironment. This sucession has a prominent role to play in the study of analogous Pre-Salt reservoirs in the hydrocarbon producing basins of the eastern Brazilian margin. Due to the high complexity of these reservoirs, directly related to the heterogeneous distribution of the permeability and pore space, there are several challenges to modeling the petrophysical characterization of the coquinas of Morro do Chaves Formation; we use CT scan data, whole core, petrophysical logs, thin-section description; along with laboratory tests and measurements on core-plugs. The next steps in applying this classification in rocks from Itapema Formation in Libra field (Santos Basin).

How taphonomy can be used to further our understanding of bivalve rudstone and floatstone facies and stratigraphic models of the early Aptian of the South Atlantic Rift Basins

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Key Words – Taphonomy, bivalves, coquina, pre-salt, Campos rift basin, early Aptian

Abstract

The mollusc-rich limestones of the shallow-water lacustrine sediments of the South Atlantic continental rift basins, specifically the Coqueiros Formation, early Aptian of the Campos Basin, are diverse and complex. For this reason, a more detailed approach than the conventional textural classification is needed to understand their paleoenvironmental setting, the processes of coquina deposition and heterogeneities within coquina reservoirs. Taphonomy has been used as useful additional tool in the study for understanding the physical, biological and chemical processes affecting these carbonate rocks during and after deposition and through to diagenesis.

Taphonomy and taphofacies analysis has been used to further our understanding of the complex biofabrics in these limestones from the original lacustrine bivalve communities through their transport, fragmentation, and abrasion to eventual deposition. The shells that survive these various taphonomic filters build the final biofabrics and control the nature of the pore system. Subsequent micritisation and encrusting can significantly increase the preservation potential of shells but also affect the porosity development within these reservoir rocks.

The biofabrics of the Coqueiros Fm have been studied from 9 wells (400m of core) and one FMI log (400m of continuous log), and ten taphofacies are recognized. The taphofacies reflect biological and hydraulic processes that have acted on the shells in the lake margin environment including fair weather wave concentration, storm concentration, and deeper lake condensed concentration. The taphofacies represent a taphonomic grade from more or less *in situ* shell assemblages in rudstones to floatstones through to fragmented and abraded rudstones and grainstones. The taphofacies approach enables a bed by bed classification of the coquinas in successions that have in the past been classified as molluscan rudstones and grainstones, or, just coquinas. The taphofacies classification also provides evidence for high frequency, meter-scale cycles and bedding-parallel layering within these limestone reservoirs. In addition they provide input into facies models that are used to explain the geometric arrangement and characterization of these complex coquina deposits. The taphofacies also explain the variations in porosity (5 to 25%, average 11%) and permeability (<1 mD to >1 Darcy) and layering within the coquina reservoirs.

Facies classification and cyclicity in the lacustrine carbonates of the Barra Velha Formation, Pre-salt, Santos Basin

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The lacustrine carbonate rocks of the giant Pre-salt oil-fields in the Santos and Campos Basins differ in a number of important aspects from classic well-documented lake deposits. Prior work has described distinctive and unusual aspects of deposition, early diagenesis and reservoir quality, with these rocks defying classification using established schemes. In addition to their unusual textures, debate continues as how to correlate data from individual wells across the basin. This has been attempted for the Barra Velha Formation using both lithostratigraphic and sequence stratigraphic approaches. However, in the absence of a high-resolution fossil record, it has been proved impossible to date the recognized stratigraphic cycles. Rates of sediment accumulation within these lacustrine systems thus remain unconstrained.

We set out to understand vertical trends in sediment texture and evaluate whether cyclic variations in the facies can be tied to astronomical curves. However, this analysis demanded first that we develop a new facies classification scheme. This is based on the relative abundance of three end-member components – mud (micrite and clay minerals), calcite spherulites and fascicular calcite shrubs. Although focused on the main textural and mineralogical features of the rocks as seen today, the proposed scheme takes into account the relative contribution of depositional and early diagenetic components, sediment mineralogy and the degree of dissolution. It offers insight into depositional conditions, whilst also linking to reservoir quality.

Even at thin-section scale, there is huge heterogeneity in the relative abundance of the main components, and the existence of cyclic variations in texture has not previously been evaluated. We compare the observed textural variations to astronomical target curves, using the average spectral misfit (ASM) method proposed by Meyers and Sageman (2007), and the wavelet transform method to differentiate between signal and noise generated by the Fourier analysis. This approach both evaluates a range of plausible time models and also tests paleoclimate data against the expected astronomical frequencies. Despite uncertainties introduced by depositional hiatuses and controversies regarding the duration of each cycle, this approach yields information on sedimentation rate for the Barra Velha Formation.

Preliminary analysis demonstrates that these cycles in the lacustrine carbonate deposition may be modulated the orbital frequencies. The frequencies could reflect either precession or long eccentricity. Both scenarios are substantially shorter than 10 My, which has been derived from Ar-Ar radiometric ages obtained from extrusive volcanic rocks (Moreira et al 2007). This work reinforces that important unconformities are present in the Barra Velha Formation and/or the interval of time of Barra Velha Formation should be revaluated.

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Lithofacies description of Barra Velha Formation, Pre-salt, Field Y, Santos Basin, Brazil.

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The Barra Velha Formation forms an important oil reservoir of the Pre-salt province of the Santos Basin, offshore Brazil. Preliminary lithofacies analyses of a continuous core of the Barra Velha Formation in Field Y is discussed. In this core the formation consists of a carbonate succession, with variable diagenetic modifications, in which the main lithofacies are: (1) Medium to coarse, moderately sorted calcarenite, composed of fragments of crusts and mafic volcanic rocks; (2) Breccia (calcirudite) with up to 8 cm angular fragments of crust and calcarenite, and minor calcimudstone and mafic volcanic fragments; (3) Crusts (shrubs) up to 3 cm thick with arborescent form in dense, loose or dispersed texture; (4) Calcitic aggregates formed of spherules up to 2 mm diameter, with dispersed or agglutinated texture, that can be associated with a mixed micritic-clay matrix; (5) Calcimudstone with brown and green clay minerals and (6) “Microbialites”(*cf.*) with stromatolites as laminations up to 2 mm, and locally oncoliths that can be up to 6 cm in diameter. In this core the Barra Velha Formation can be subdivided in three intervals. A lower interval which consists of calcarenites and minor proportions of breccia and shrubs. A massive breccia occurs at the base of the interval. Above the base, calcarenites forms up to 1 m thick massive beds and locally thin beds showing ripples or plane-parallel lamination. Massive beds of breccia and of shrub facies are intercalated. The middle interval is composed of crusts and spheroid calcitic aggregates, and minor proportion of calcarenite, calcimudstone and breccia. A massive breccia occurs at the base of the interval, followed by a succession of massive beds of crusts and spheroid calcitic aggregates, showing abrupt or, more rarely, gradual contacts. Intercalated in the crust beds there are thick massive beds of calcarenite and breccia showing erosive basal contacts. There are also calcimudstone beds which show irregular continuous, discontinuous and plane-parallel lamination. Usually they grade upwards in to the spheroid aggregates. The upper interval consists of “microbialite” and calcimudstones, calcarenites and breccia intercalations. A massive breccia occurs at base of the interval. It is covered by an intercalation of laminae and thin beds of “microbialite” and calcimudstone forming strata. Intercalated in these strata there are oncolites, tepee breccias, calcarenites and calcirudites. Our initial work has led us to infer that the Barra Velha Formation is formed in a tectonically active setting in a shallow alkaline lacustrine environment, initially with exposure of mafic volcanic rocks in the sedimentary source area. Deposition appears to be dominated by a high rate of chemical precipitation of calcium carbonate linked to evaporative conditions, however, evidence for physical processes, with the ability to erode, transport and deposit large quantities of newly formed material, indicate that the environment went through high energy episodes.

Keywords: Barra Velha Fm., Lithofacies succession, Pre-salt, Santos Basin

Facies analysis and petrophysical properties of Pre-salt reservoir core, Barra Velha Formation, Field X, Santos Basin.

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The Barra Velha Formation is composed of continental carbonates that form one of the principal oil reservoirs of the Pre-salt province, deep-water Brazil. Core descriptions, lithofacies analyses and correlations with petrophysical data was performed on 2 continuous cores from a Pre-salt field, in order to understand the relationship between lithofacies, lithofacies succession and reservoir properties. The succession is mainly composed of laminated calcilutite and secondarily, of calcitic aggregate beds, which we term crusts. For description of the core we tried to find classification names that do not have a genetic connotation. Microscale structures observed include normal faults, convolute folds, loop bedding, boudins and diastase cracks. Seven lithofacies were recognized: 1) Calcilutite in plane-parallel lamination and very fine wave bedding; 2) Grayish calcilutite in plane-parallel lamination; 3) Calcilutite in fine wave bedding; 4) Calcilutite with wavy bedding associated with carbonate crusts; 5) Massive calcirudite; 6) Laminated carbonate crusts and 7- Massive carbonate crusts. These lithofacies show the following successions in core: 1-2-3, 1-2-3-2-3, 1-2-4, 5-6/7, and 6-7. The massive calcirudite occurs in rare layers between the laminated and massive carbonate crusts (facies 6 and 7). The carbonate crusts occur in thick restricted intervals and their structures and textures can interestingly be compared with some recent tufa deposits (as those of the Pyramid Lake). Porosity and permeability data are correlate with the lithofacies, although they can be affected by tectonic features (faults/ fractures) and silicification. Occasionally they are affected by the tectonic structures and the silicification. Approximately 80% of the core shows porosity higher than 10% and it is typically oil-stained. The interval with lithofacies 5, 6 and 7 shows very good reservoir quality and the highest porosity and permeability values. The calcilutites, in general, have moderate to good porosities and poor permeabilities. Facies 3 and 4 show, on average, good porosities and poor to moderate permeabilities. Locally, facies 4 shows good and very good permeability values.

Keywords: Barra Velha formation, Carbonate rocks, Facies, Pre-salt, Santo Basin.

Depositional texture and petrophysical analysis of Aptian pre-salt lacustrine carbonate reservoir from Santos Basin, offshore Brazil.

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Unusual lacustrine carbonate deposits mark the sag sedimentation stage of the so-called pre-salt section of the Santos and Campos Basins, offshore SE Brazil. These salt-sealed carbonate reservoirs form giant and prolific oil fields and are currently responsible for approximately 56% of the Brazilian oil and gas production. In the Santos Basin, the sag stage carbonates are represented by the Aptian Barra Velha Formation, characterized by exotic textural and compositional features, whose origin, evolution and correlation with petrophysical properties have been broadly discussed in the last decade. A geological and petrophysical study has been performed based on core samples, plugs and thin-sections of a well from the eastern Santos Basin. The analyzed core interval was grouped into six depositional facies constituted by the association of five main textural components: (1) Crystal shrub crusts; (2) Calcite spherulites; (3) Hybrid forms; (4) Crystalline dolomite rhombs; (5) Intraclasts and pisoids. The millimeter- to centimeter-sized, shrub-like growths are the most striking and common textural components of the interval. The pronounced crystal habit of the fibrous-fascicular calcite crystals may be evidence that bacteria exercised poor control on the overall shrub morphology. The spherulites are millimetric, spherical allochems composed of fibrous-radial calcite crystals, occurring as both *in situ* and reworked sediments. Generally associated to spherulite-rich beds, transitional hybrid grains occur ranging from asymmetrical spherulites to better developed and branched structures. Detrital grains are mainly characterized by intraclasts of diverse natures, such as reworked fragments of shrub crusts and spherulites. Restricted occurrences of dolomudstones were also described and are characterized by irregular laminated textures with variable mud and clay content. The relationship between the depositional framework and the permo-porosity system, as evidenced by CT-scan data and petrographic image analysis, is highly complex and non-linear. Even though each facies present specific primary porous systems, such as the shrubby boundstones dominated by high growth framework porosity and spherulitc/intraclastic grainstones characterized by interparticle porosity, the depositional control on the porous system is inconsistent. This behavior is partially explained by the extensive diagenetic and possible hydrothermal overprint, creating heterogeneous hybrid porous systems. Dolomite cementation, dolomitization, pervasive silicification, and dissolution processes are the main primary porosity modifiers. In addition, some intense fractured intervals are mainly associated to irregular silica-filled fractures. CT-scan image analysis points to a significant volume of opaque heavy minerals crystalized within these fractures and also associated to silicification spots, which may be evidence of circulation of hydrothermal fluids.

Key words: Brazilian pre-salt, CT-scan, Lacustrine carbonates, Permo-porosity.

Pore typing using nuclear magnetic resonance, an example with samples from cretaceous pre-salt lacustrine carbonates, Santos Basin, Brazil

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Key words: Lacustrine carbonates; Pore typing; Nuclear Magnetic Resonance; Santos Basin

The recent discoveries of giant carbonate reservoirs in the Brazilian sub-salt deposits from the Santos and Campos basins and the production decline of mature siliciclastic fields have made these carbonate fields the main targets for oil production. These sub-salt reservoirs are mainly composed of lacustrine carbonates, comprising the Itapema (Barremian-Aptian) and Barra Velha (Aptian) Formations in the Santos Basin. The carbonate rocks of the sub-salt interval are highly heterogeneous in terms of texture, pore systems and diagenetic history, constituting an unusual sedimentary sequence and its elements are associated to restricted depositional systems that do not have current models. This makes it difficult to adopt a distribution pattern for petrophysical properties. In this context, the nuclear magnetic resonance (NMR) emerge as one of the advanced technologies for in-situ reservoir evaluation, providing information about porosity, permeability and fluid characterization. In this study, a pore type definition based on the NMR analysis of samples from the Barra Velha and Itapema Formations is proposed, including also petrographic descriptions, porosity and permeability measurements and high-resolution X-ray computed tomography (CT). The pore typing is an important step in the petrophysical and geological characterization of a reservoir aiming to relate the petrographic characteristics to petrophysical properties. The results showed that the two sample sets from the Barra Velha and Itapema Formations have very different petrophysical behaviors and porosity controls. The Barra Velha samples showed a pore system with high heterogeneity and variability, being classified as tight, good and best reservoirs. Meanwhile, the Itapema samples were all considered as good and best reservoirs, due to their high porosities and permeabilities. Regarding porosity controls, samples from the Barra Velha Formation presented a hybrid control between depositional and diagenetic and the samples from the Itapema Formation showed hybrid controls between depositional, diagenetic and fractured. The good correlation of pore types with the laboratorial porosity and permeability values indicates that the NMR analysis were able to represent the petrophysical differences between the samples. The integrated study of NMR, CT and petrographic analysis enabled a better understanding of the pore systems and the NMR responses to the petrographic characteristics.

First steps to understand the controls on reservoir heterogeneity in the Brazilian Pre-Salt: A case study from the Barra Velha Formation

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The Santos Basin, offshore south east Brazil, contains several prolific Pre-salt oilfields. The Pre-salt interval shows very heterogeneous carbonates of different lithologies deposited in an extensive and unusual lacustrine rift system developed during the breakup of Gondwana (Lower Cretaceous). The studied area is located on a structural high, in a lithostratigraphic context of the Barra Velha Formation, which is formed by carbonates whose depositional origin is still under discussion (abiogenic or biogenic). Earlier work adopted a microbial origin for the main "in situ" facies in this interval. Recently, an abiotic model was proposed for lacustrine carbonates of the Santos Basin. The unit presents exceptional reservoir quality, being sealed by thick evaporites (Ariri Formation). Although this succession has attracted major research interest, there are relatively few published studies. In order to decipher the petrophysical property distributions and to comprehend the depositional and diagenetic controls, the logs and cores of one well were analyzed in detail and linked to seismic data to help understand tectonic controls. The main lithotypes recognized in the studied section can be grouped as in situ facies (mostly calcitic crustones) and reworked facies (mostly calcarenites and calcirudites). The crustones are composed of millimeter to centimeter-scale crusts of calcite with different textures and structures, divided into three facies: (1) Crusts of microcrystalline calcite (averaging Φ ~ 15% and k ~ 170 mD), characterized by laminated millimeter-scale crusts with peloidal and clotted texture showing mostly horizontally-oriented porosity (fenestral and vugular) and, in small proportions, microfractures and channel porosity (vertically-oriented); (2) Crustones with columnar shrubs (averaging Φ ~ 7% and k ~ 5 mD) presenting bifurcated and globular forms and internal laminations, that limited the growth of the calcite crystals. The pore system is composed of “intershrub” spaces (growth framework) controlled by the packing density of the shrubs (open to dense) and reduced by calcite, dolomite and silica cementation; (3) Coalescent fan-shaped shrubs (averaging Φ ~ 15% and permeabilities that can reach over 1 D), densely packed formed by fibrous crystals of calcite aggregate, displaying fascicular optical texture with the pore system enhanced by fractures and dissolution. The reworked facies comprises calcirudites (rudstones) grading to calcarenites (grainstones) in centimeter to decimeter-scale cycles, with porosity being highly influenced by the degree of cementation and compaction. The basal and intermediate intervals are more compacted, so this facies presents poor reservoir quality (averaging Φ ~ 5% and k ~ 15 mD), while in the upper interval a moderate reservoir quality occurs (averaging Φ ~ 15% and k ~ 130 mD). This work shows a variety of facies in a Pre-salt section, which could be interpreted as terminal fans and deposits associated with

springs, that show a strong relationship between primary depositional texture and diagenesis with the reservoir quality.

KEYWORDS: Pre-Salt, Lacustrine Carbonate, Reservoir Quality

Deposition and Early Diagenesis in the Pre-Salt "Microbialite" of the Kwanza Basin, Angola

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Key Words: Angola, Pre-Salt, Microbialite

The sag phase lacustrine carbonates of the South Atlantic, informally termed "Microbialite", are unprecedented as world-class oil/ gas reservoirs. From a sedimentological perspective, it is becoming apparent that the scale of the system is unique in our understanding of Earth's history. As more data from the South Atlantic enters the public domain, the heterogeneity within the larger depositional system is only just starting to be explored. While the characteristic shrubby and spherulitic fibrous calcite facies can be found over a large area, there appear to be variable amounts of microbial influence and re-working processes. Depositional models for the fibrous calcite facies remain contentious, not because of alternative models for fibrous calcite growth, but because of the wider implications that arise from alternative environmental reconstructions. Restrictions on publishing, data access and sparse sample sets have further hampered attempts to reconcile different observations into a wider depositional model.

The work presented here follows detailed analysis of a complete core from the Pre-Salt of the Southern Kwanza Basin, Angola. Despite being a one-dimensional data point, it has been possible to interrogate facies relationships in detail; in a way that would not be possible from widely-spaced sidewall cores. Several petrographic and geochemical techniques have been applied in order to explore depositional and diagenetic variability.

The core is characterised by a variety of shrub, spherulitic and coated fibrous calcite facies, some of which have not been published in the public domain. Microbial macro textures of silicified/dolomitised stromatolitic fabrics and coated grains are rather common. A number of different re-worked fabrics are also present. The components reveal the interaction between fibrous calcite growth, microbial activity and kinetic processes. Early silicification is evident and is believed to be triggered by a drop in pH caused by pluvial events, marine incursions or by the degradation of organic matter. Micro-porous, pseudo-chalcedonic fabrics resemble microbial textures reported from the outer Kwanza Basin, however in this core they appear to be associated with a diagenetic event.

Abiotic depositional models are based, in part, on a lack of evidence for microbial structures in fibrous calcite facies. Indeed, evidence for microbial structures within shrubs and spherulites is often ambiguous using transmitted light microscopy. Scanning electron microscopy reveals that calcified microbial structures are in fact reasonably abundant within facies that may otherwise be interpreted as "barren". Despite this, there is no evidence that microbes mediated fibrous calcite precipitation, or indeed their own mineralisation. It could be that the system was microbially *influenced* and that the structures were passively mineralised.

Coiled microfossils (cyanobacteria?) from Brazilian Pre-Salt

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Keywords: Carbonate; cyanobacteria; Pre-Salt; spherulites;.

The South Atlantic Aptian Pre-Salt reservoirs correspond mostly to crusts of fascicular calcite and to rocks with calcite spherulites in partially dissolved magnesian silicate (mostly stevensite and kerolite) syngenetic matrix. Information on the biota associated to these deposits is very limited, and the preliminary interpretation of the crusts as microbial stromatolites has been extensively questioned recently. The present work presents unprecedented information regarding singular bioclasts described in thin sections from the Pre-Salt. These features generally occur as round forms inside the spherulites and fascicular aggregates that present delicate walls commonly made of the stevensite, which may be completely calcified (Fig. 1A and B). Forms with elongate shape with similar dimensions apparently correspond to longitudinal cuts of the same organism (Fig. 1C and D). The morphology of these elongated forms is similar to that of *Obruchevella* sp., helically coiled cyanobacteria with occurrence from Pre-Cambrian to Devonian, ranging between 5 and 22µm for filaments width, and 109 and 220µm for helix diameter. *Obruchevella* is considered as related to the recent cyanobacteria *Spirulina/Arthrospira*, an extremophile organism common in alkaline soda lakes, an environment presently interpreted for the Pre-Salt lacustrine systems. Living organisms from this group also reveal specific body morphologies for particular high pH, high temperature and high light radiance. The investigation of these organisms and their paleo-environmental interpretation shall contribute to the understanding of the chemical and biological conditions prevailing during the deposition of the South Atlantic Pre-Salt extensive and prolific lacustrine deposits.

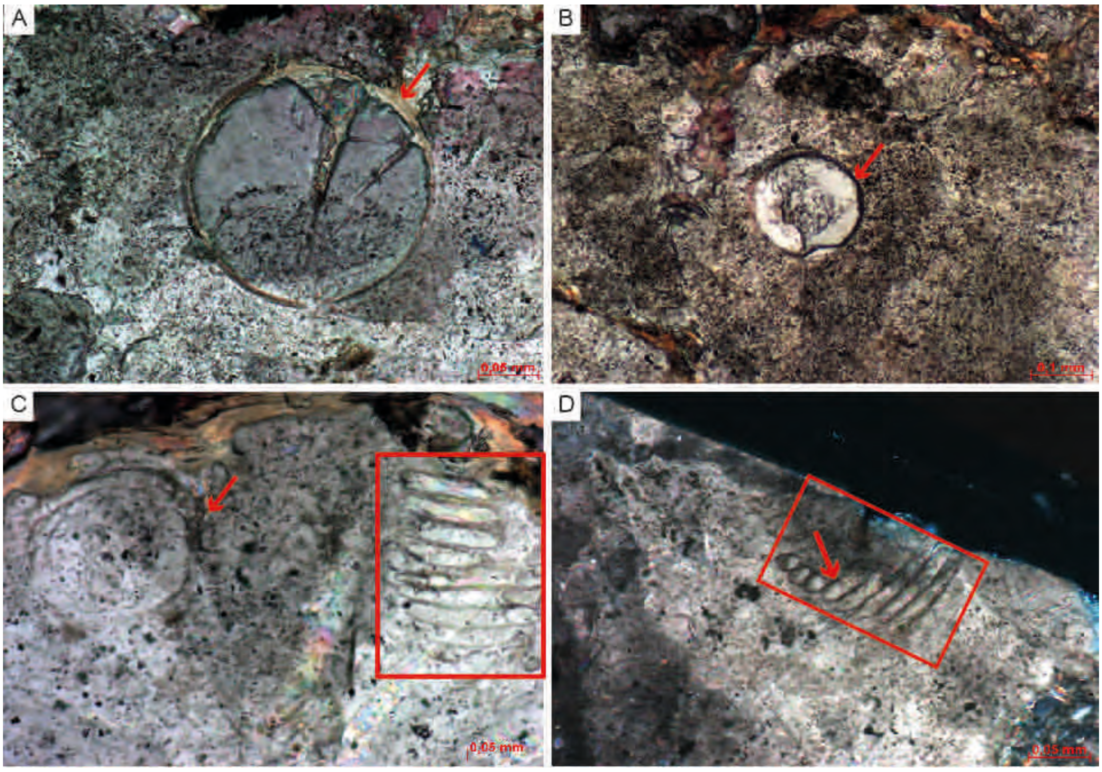

Figure 1. Photomicrographs of described Pre-Salt organisms. A) and B) Round forms with thin, partially calcified, magnesian clay walls (red arrow). C) Spherulites with round (red arrow) and elongated coiled (red polygon) forms within a spherulite. D) Elongate coiled form (red polygon) with transversal cuts of the filament indicated by the arrow.

What causes carbonates to form "shrubby" morphologies? An analog case study from a hyperalkaline leachate.

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Abstract - The South Atlantic Aptian "Pre-salt" shrubby carbonate Formations of Brazil and Angola are of major interest for the oil industry due to their potential hydrocarbon accumulations. Although the general sedimentology of these deposits is widely recognised to be within saline, alkaline lakes in rift volcanic settings, the specific genesis of shrubby carbonate morphologies remains unclear. This study reports petrographically comparable shrubby carbonates amongst other carbonate microfacies grown in a hyperalkaline (pH 9-12), hypersaline (conductivity 425-3200µS), ambient temperature (12.5-13 ^{o}C) stream affected by steel slag leachates (Consett, UK). This discovery allows us to capitalise on long-term hydrochemical monitoring efforts, demonstrating that shrubby carbonates occur uniquely within the waters most rich calcium (~240mg/L) and with highest pH (~12) and consequently with very high levels of supersaturation. We explore the likely controls on the origin of these shrubby carbonates, and show they most likely a consequence of kinetic influences on crystal growth at very high rates of precipitation. The shrubby carbonate grows in the presence of significant diatomaceous and cyanobacterial biofilms despite the highly alkaline and saline conditions. These biofilms are lost from the deposited material early, due to the high solubility of organic and silica within in hyperalkaline settings, and this loss contributed to high intercrystalline porosity. We have found no evidence of Mg-Si mineral phases in these samples.

Key words: Alkaline steel slag / Hydrochemistry / Microbial / Pre-Salt reservoirs / Shrubby carbonate

Investigation of processes producing dolomite/clay mineral associations in natural environments and culture experiments

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Key words: diagenesis, dolomite, Mg-rich clays, microbial processes.

Improving our understanding of the diagenetic processes that control the distribution of clay associations within carbonate sequences has important implications to elucidate questions related with rock reservoirs and diagenesis. Particularly important is the study of clay-mineral/dolomite associations. The genetic characteristics of clayey material, usually corresponding to Mg-rich clays, whether formed by allogenic or authigenic processes, affect the reservoir properties of rocks to a greater or lesser extent. In the case of carbonate reservoirs, the presence of clay can significantly affect the porosity and permeability of reservoir rocks. More specifically, when the clay minerals are randomly distributed within the carbonate matrix, it becomes difficult to predict the reservoir characteristics. This carbonate and clay mineral association is commonly found in carbonate formations throughout the geological record, e.g., the Cretaceous Codó Formation, NE Brazil, (Bahniuk et al. 2015) and the Tertiary lacustrine sequence, Jbel Rhassoul, Morocco (Chahi et al. 1999). Some studies relate this association to the diagenetic transformation of clay minerals into dolomite (Kahle, 1965) or vice versa (Chahi et al., 1999), but these formation processes remain debatable.

In order to understand this association in the geological record, we have undertaken a comparative study of laboratory experiments and modern environments, where clay minerals have been shown to precipitate together with dolomite. Two modern dolomite-forming environments, the Coorong lakes, South Australia and Brejo do Espinho, Rio de Janeiro, Brazil, were selected for this investigation. In addition, enrichment microbial culture experiments, using natural pore water from Brejo do Espinho as the growth medium to promote mineral precipitation, were performed. To establish the environmental parameters and biological processes facilitating the dual mineral association, the experimental samples have been compared with the natural samples, both being analyzed by X-ray Diffraction and Electron Microscopy (high-resolution transmission electron microscopy, HRTEM, with analytical electron microscopy, AEM, and Scanning electron microcopy, SEM). The results demonstrate that dolomite and Mg-rich clays apparently do not co-precipitate, but the precipitation of these minerals in the same sample has probably occurred under different environmental conditions with variable chemistries, e.g., hypersalinity versus normal salinity resulting from the changing ratio of evaporation versus precipitation. However, under burial conditions this association could indicate an active hydrologic system with changes in the pore waters chemistry and diagenetic processes affecting mineral composition, i.e., dolomite versus Mg-clays.

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Selective Dissolution of Carbonates with Mg-silicate in African Lake analogous to the pre-salt by geochemical modeling in PhreeqC

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Keywords: Pre-salt; Selective dissolution; Carbonates; PhreeqC, Mg-silicate

The mechanism of magnesium silicates formation is a subject that has attracted several studies related to the geology of reservoirs. In particular, due to the growing interest in the formation of Pre-Salt in the South Atlantic Ocean. Carbonates such as calcite and dolomite found in these formations have an important contribution to the geochemical evolution routes of these reservoirs. Scientific contributions important for the formation of Mg-silicate in the presence of carbonates can be done in the laboratory with experiments and in parallel with thermodynamic equilibrium models obtained with geochemical simulation software such as PhreeqC. Numerical simulations of selective dissolution, especially in African alkaline lakes (potential analogs for the pre-salt), are important to identify the specific condition for the occurrence of silicates of Mg or carbonates.

For this study, the Ounianga El-Kebir Lake was selected. It is located in the northeastern region of Chad, near the Libyan border, Tibesti and Ennedi. A sample of the lake ("Lake 14") was described by Darragi & Tardy (1987) and was used as a reference. Selective dissolution of carbonates (calcite and dolomite) in the presence of Mg (stevensite and kerolite) silicates were performed using the PhreeqC code. Two scenarios were investigated. First scenario, considering the variation of Saturation Index (SI) and pH with the temperature using the selected conditions of the lake. Second, the balance of carbonate/Mg-silicate in water equilibrated with carbonates (alkaline water) under varying temperature.

The equilibrium between carbonates and Mg-silicate produce alkaline water. The Mg-silicate is more sensitive than carbonates when pH and temperature suffer variation. The carbonates are forced to precipitate when the temperature is increased, and on the other hand, this effect dissolves stevensite and kerolite. The dissolution of Mg-silicates contributes to carbonate precipitation because the concentration of ionic species in the solution is increased.

Temperature is an important variable because it offers good indications that help in the understanding of the pre-salt system, especially selective dissolution of carbonates and Mg-silicates. The PhreeqC simulation shows that carbonate precipitation occurs first then the precipitation of Mg-silicate after 80 °C and as important as this result, the dissolution of the Mg silicate occurs at the same time as the precipitation of carbonate. The process ends when the pH drops to dissolve the carbonates. The understanding of pre-salt formation is complex and involves different geochemical variables such as temperature, speciation, and alkalinity and, more recently, the presence of microorganisms that may interfere not only in the reactions in carbonates but also in the clay mineral. It is important to observe that all variables strongly alter the thermodynamic and geochemical equilibrium of the lake.

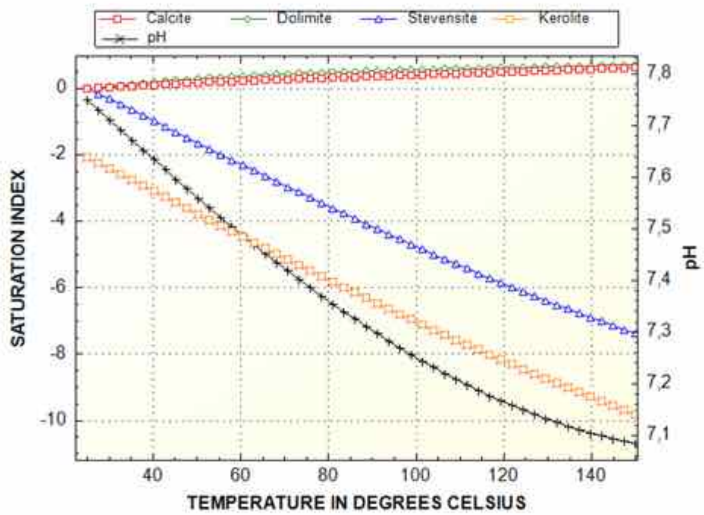

Figure 1. Curves of saturation index variation and pH as a function of temperature variation of the lake Ounianga El-Kebir in the Chad northeastern region.

A desiccated monomictic lake as analog for South-Atlantic pre-Salt alkaline carbonates: the Ricon de Parangueo Maar, Guanajuato St. (México).

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Key words: microbial carbonates, lake, maar, monomictic, karst, pedogenesis

The discovery of the South Atlantic (Aptian) pre-salt hydrocarbon carbonate reservoirs, with their unique sedimentologic and diagenetic history, renewed the interest of academia and industry on recognizing valid analogs for such an exceptional geological scenario. However, the search for the perfect analog systematically failed. Recognized present or fossil analogs only account for a part of the pre-salt lacustrine systems characteristics. Therefore, we present a new partial analog accounting not only on how pre-salt carbonates formed but, more precisely, on how they could be partially destroyed during subaerial exposition and, yet, preserve or create porosity.

In México, many monogenetic volcanic cones and maars of the Trans-Mexican Volcanic Belt (TMVB) contained and, in some cases, still preserve monomictic or meromictic alkaline lakes, often with diffuse hydrothermal influence and seldom microbial carbonate formation. Valle de Santiago (Michoacán–Guanajuato Volcanic field), contains a series of "*maars*" that have been anthropically disturbed in recent times due to excessive groundwater extraction. Among them, Rincón de Parangueo (1740 m.o.s.l.) stands out as it contained a perennial, monomictic shallow lake (≤20m depth), now almost fully desiccated; the present-day soda-lake system (pH≤10; 12% total salinity) precipitates trona halite and microbially-mediated hydromagnesite, with minor thermonatrite, natrite, eitelite, sylvite (Sánchez-Sánchez et al., 2019). Desiccation allowed the outcropping of the carbonate rimming formations as a scarp, that progressively grades into varve-like profundal sediments, towards the center of the lake.

Repsol, in collaboration with UNAM academics, completed a geological survey of the ancient lacustrine sediments, defining five informal Units, from bottom to top: (1) Volcanic unit, composed by basaltic debris and up to five microbial colonized horizons; (2) Fan Delta Unit; (3) Ocher unit (finely laminated varves); (4) White Unit (finely laminated tufas); and (5) Biohermal Unit (bioherms/biostromes) with abundant hydromagnesite thrombolites.

Figure 1: full aerial view of the Rincon de Parangueo lake with the fully exposed carbonate shoreline.

While the almost full lacustrine sediments subaerial exposition allows to literally walk from the biohermal shoreline units to profundal varved facies, despite some recent clay diapirism and subsidence of the carbonatic units, the most revealing processes occur while the microbial units are being destroyed. A diffuse micro-karst is developing on top of the biohermal unit, resulting in the formation of a loose matrix-free granular pavement (grainification?), composed by angular thrombolite fragments. Also, the lacustrine tufa exhibits common vertical columnar structures, covered by a horizontal darker horizon, with strong similitude with alkaline soil profiles.

Figure 2. Left: partially destroyed biohermal unit by a (mature?) micro-karst and possible grainification of the surface. Right: alkaline soil profile?; vertical columnar structures covered by a horizontal darker horizon.

All these eogenetic processes could account, after burial and compaction, for some of the problematic and heavily corroded carbonatic textures seen to occur in some of the Brazilian pre-salt reservoirs.

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Holocene hot spring travertine ridge-cone morphology and feeder pipe facies, Jifei, south China: insights into travertine formation processes

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Keywords: travertine, ridges, cones, internal pipes, Jifei

Ridges and cones are common depositional morphologies in hot spring travertine deposits, but the details of their formation remain unclear because their internal structure is usually not exposed. Here we describe sub-Recent travertine ridges and cones at Jifei in western Yunnan, south China, which are sufficiently eroded to reveal their internal structures, providing insights into their formation.

Thermal groundwaters emerge from fractured Neogene lacustrine sandstones to form travertine deposits near Jifei village. The main deposit is a linear NW-SE orientated fissure ridge ~120 m long, 20 m high, and up to 40 m wide. The fissure ridge is linearly asymmetric, highest in the south-east, gradually lowering towards the north-west. It does not show the typical smoothly sloping margins of crystalline crusts. Towards the south-east the ridge is composed of amalgamated cones. Additionally, up to about 30 solitary and amalgamated cones of differing size occur on sloping ground west of the fissure ridge. Most of them are < 50 cm high and 20-30 cm across. The highest, more distal examples, are up to 7 m high. Hot spring water (35-81°) emerges from the middle part of the fissure ridge and from the summit and base of some distal cones. All the cones (including amalgamated cones in the fissure ridge) have smooth outer walls and complex internal pipes. The outer wall consists of dense crystalline calcite and is mostly thinner than the internal pipes. The pipes differ in size, have complicated linkages, and can be empty or infilled by crystalline deposits oriented parallel to the (mostly vertical) pipe axes. The pipes are filled by elongated and slightly branched crystalline columns a few millimetres across, that consist of dense sparry crystal aggregates and frequently incorporate micritic and filamentous domes or patches. Where crystalline columns fill large inflated or ovoid internal pipe-spaces, they radiate outward and branch upward from the axes, resembling stromatolites built by calcified cyanobacteria.

The outer wall of the cones is initially constructed upwards and outwards by calcite precipitation around the margins of the vent. Internal pipe morphology and infillings reflect changes in spring pressure, water flow and precipitation rate. Infillings increased with pressure, whereas lower pressure reduced precipitation and left pipes empty. Abundant microbial deposits in the pipes suggest that chemically reactive vent environments were suitable for microbe growth. The Jifei travertine shows that fissure ridges can form by lateral cone juxtaposition due to vent blockage and diversion. Juxtaposed cones reflect relatively rapid sealing of vent-pathways due to enhanced precipitation. Solitary cones commonly remain unplugged because accretion stopped when water flow stopped. By comparison, ‘classic’ fissure ridges appear to reflect maintenance of fluid flow by reduced precipitation and/or increased crack expansion. These relationships emphasize the interplay between tectonics and groundwater supply/composition that broadly determine many aspects of the location and formation of hot spring carbonate deposition.

Mg and C/O isotopes of the Late Cretaceous lacustrine dolomite and travertine in the northern Tianshan, Central Asia

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A dolomite-forming lacustrine depositional system associated with travertine was established during the Late Cretaceous at the northern margin of the Tianshan Mountains, southern Junggar Basin. The morphology of the dolomite can be divided into two types. Dol-A is made up of fine, homogeneous, euhedral and densely packed crystals that are 10-20 µm in size. Dol-B is made up of euhedral, rhombic dolomite crystals that are 30-50 µm in size that occur in cavities and near calcite veins with annular intracrystalline holes. The dolostone display low degrees of dolomite order (mean = 0.48) and are Ca-rich (mean = 55.8), respectively. The $\delta^{18}O$ values (PDB) range from -4.2 to -6.6‰ and average -5.3‰ for the dolostone. The ranges of this quantity for limestone and travertine are -7.0 to -11.1‰ and -9.1 to -10.2‰, respectively. The $\delta^{13}C$ values (PDB) of the dolostone and limestone vary slightly from each other, and their average values are -4.5‰ and -5.9‰, respectively; however, the corresponding range for the travertine is 0.1‰ to 1.3‰, and its average is 0.8‰. The $\delta^{26}Mg$ values of dolostone range from -1.523 to -2.913‰ and average -2.365‰. Meanwhile, the average $\delta^{26}Mg$ values of limestone and travertine are -3.582‰ and -4.305‰, respectively. The simulation of both Rayleigh and seepage reflux models show that the most lacustrine dolomite of Donggou formation developed in a near-surface environment (25-50°C). Meanwhile, there are abundant low-temperature hydrothermal minerals that are paragenetic with the dolomite and travertine, such as authigenic quartz, chlorite, barite, siderite, pyrite, zinc sulphide and silver, as well as evaporative deposits of gypsum, halite and sylvite. These results have implications for dolomite formation in strongly evaporative, saline and alkaline inland lake environments and expand the model of dolomitization under thermal water influenced evaporative lacustrine conditions. Moreover, it's also very important for reconstructing and deciphering paleoenvironments and uplift evolution in the Tianshan area during the Late Cretaceous, as well as Central Asia.

Keywords: lacustrine dolomite, travertine, Mg isotope, hydrothermal, Tianshan Mountains

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The life and death of a tufa mound

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Key words: freshwater carbonate, meteoric, mound, tufa

Tufas are porous and permeable freshwater carbonates precipitated at ambient temperatures and forming mounded deposits at groundwater resurgences. Abiotic controls and the degree to which these are mediated by biological processes, has been a topic of active research. However, the fate of tufa after deposition is largely ignored. Here, we consider the life-cycle of a tufa mound, based on a hydrochemical reconnaissance study of the Warm Bay tufa mound. Situated 20 km south of Atlin, north-western BC, this is possibly the most aerially extensive (~2.3 km^2) of all Canadian tufa deposits but is undescribed in scientific literature.

A dozen cool (~13 °C) and warm (~26 °C) springs feed a network of streams that flow over two sets of tufa terraces (each >5 m high), and across intervening areas of boggy ground to discharge into Atlin Lake some 30 m below the resurgences. Although some flow traverses the steep-fronted tufa terraces, the majority percolates into the terraces, to resurge in a series of springs at their base. Away from the active stream channels, much of the terraces are dry allowing for succession towards dense pine tree coverage. Above each set of terraces is an area of low-gradient boggy ground, and below the lower terrace a broad low-lying area of saturated ground drains into the lake. Each boggy area comprises rimmed pools colonised by grasses, herbs, and mosses, whilst pines appear to die prematurely, and is underlain by tufa. Streams resurging from the lower terrace coalesce and cut a channel down into this tufa to reveal thin organic-rich horizons that may represent previous depositional hiatuses. [166/483]

Surface flows sampled in September 2018, show degassing of CO_2 (from 1.2% to 0.2% over 1.1 km and 0.3 km of high- and low-discharge reaches, respectively); increasing saturation with respect to calcite ($SI_{calcite}$ as log IAP/K) from 0.3 to 0.9. Decrease in calcium (Ca) concentrations with distance downstream from the springs, support observations of active tufa deposition. High discharges incise boggy ground and precipitation is concentrated in rimstone pools of the main tufa terraces. Active deposition, associated with the largest Ca decrease (80 to 65 mg/L), also occurs as low-discharge streams flow over and through bare areas of tufa-encrusted scree / solifluction lobes. Increasing CO_2 and decreasing $SI_{calcite}$ with depth, and localised calcite undersaturation evidence tufa dissolution in porewater profiles adjacent to tufa terraces and in the bog. Elevated dissolved Ca, to a maximum measured depth of 30 cm, is indicative of dissolution in reducing conditions driven by root respiration and microbial activity. Encrusted-scree likely represents incipient tufa deposition that aggrades to form terraces, behind which saturated reducing conditions arise. It is unusual for such a range of morphologies to be forming simultaneously within a single tufa system, and it is unknown how one morphology might evolve and influence the development of others, either seasonally or interannually.

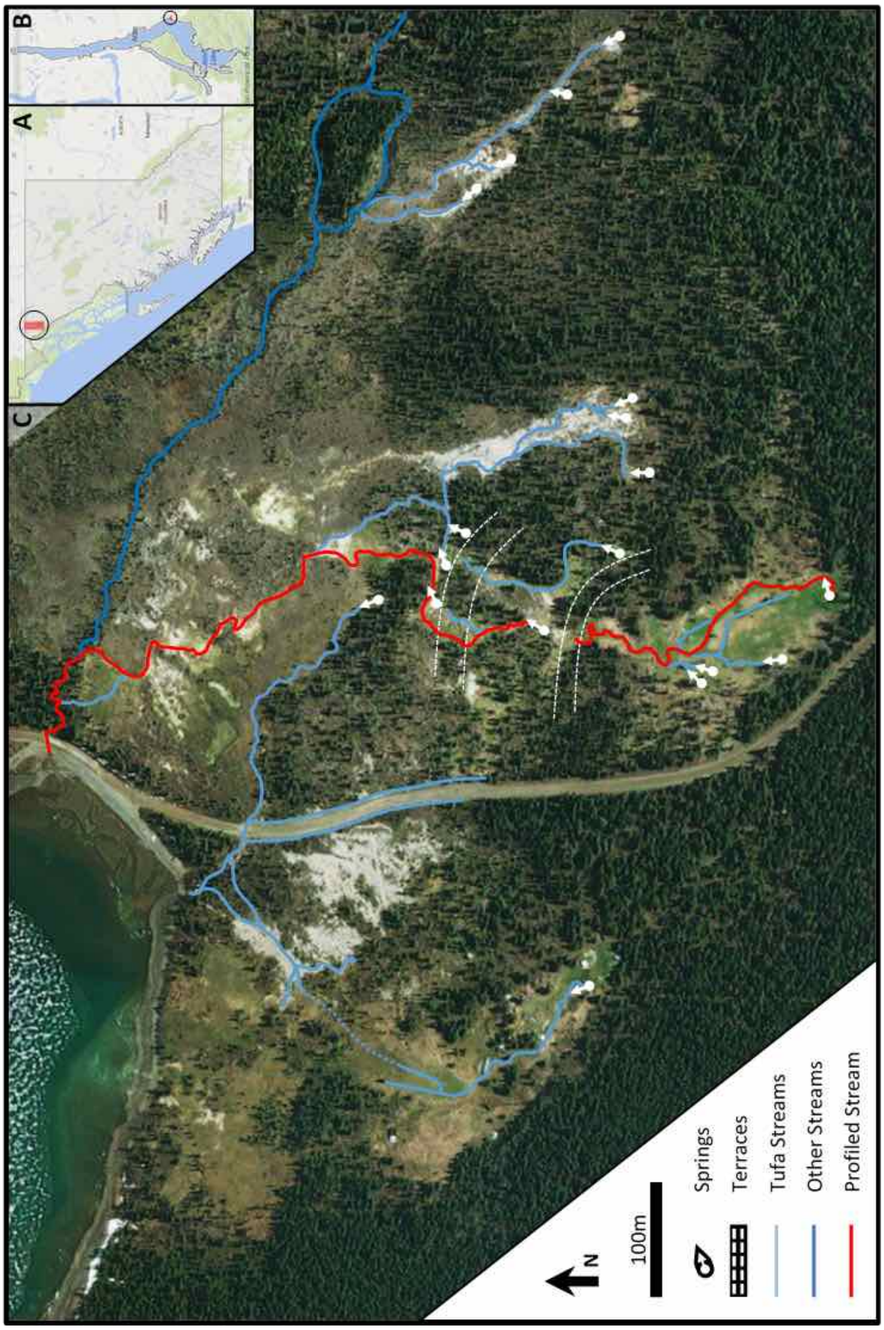

Figure 1: A) Map of British Columbia with B shaded red and circled. B) 42 km across. Map of Atlin Lake with C shaded red and circled. C) Satellite image of the Warm Bay tufa mound. A dozen springs source tufa-depositing streams that flow ~1 km north, through scree, bogs, and terraces, into Atlin Lake. All maps/images © Bing 2019.

Multi-stage approaches to spring tower formation, an example from NW Turkey

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Keywords: hot water, spring tower formation, travertine, geochemistry

Spring towers are one of the rarest and most spectacular depositional morphologies of travertine precipitation in geothermal areas (Jones and Peng 2017). In this study spring tower formation elaborated at the Hisaralan geothermal area that located to 25 km NE of the Sındırgı town, Balıkesir, NW Turkey.

The oldest units in the area are ophiolitic rocks and limestone blocks within the Izmir-Ankara Flysch Zone. The Miocene volcanic rocks such as dacite-riyodacite rest unconformably on these basement rocks. Spring towers and associated travertine depositional morphologies directly precipitated on the Miocene volcanic rocks. Most of the towers are inactive, whereas, presently only a few towers continue to form along the Serin stream to the west of the studied area.

Although the number of the spring is controversial, around 70 spring have been identified during the field campaigns. The tower-forming hot springs are those of Na-HCO_3 type. Temperature, pH, EC and HCO_3 values of the hot waters are between 54 to 97°C, 6.55 to 8.13, 1125-1429 µS/cm and 470-640 mg/l, respectively. Almost of these hot springs oversaturated in calcite, aragonite and dolomite. Saturation indices are 0.01-1.43 for calcite, 0.04-1.33 for aragonite and 0.25-1.79 for dolomite. Some of the waters saturated in quartz with a range of 0.07 to 0.44.

Approximately 60 towers were counted. The towers are up to 5 m in height and up to 4.6 m in width at the base. The vents, took place at top of the towers, are circular, oval or lenticular in shape. Internal walls of the vents were covered by radial calcite. The most leading lithotype is crystalline crust travertine in the towers that is accompanied by the laminated and microporous travertine lithotypes.

Ca is the most common element in the travertine samples with amount of 260643 to 394857 ppm. The Sr concentrations are between 11636 and 515.8 ppm. The highest Sr values were yielded from the recent and subrecent samples close to the spring orifices. The stable isotope values are –0.5 to –4.3‰ (V-PDB) for carbon ($\delta^{13}C$) and –23.6 to –11‰ (V-PDB) for oxygene ($\delta^{18}O$). The $^{87}Sr/^{86}Sr$ values display highly uniform distribution regardless of travertine lithotypes. The values range from 0.710024±9 to 0.710396 ± 19 with an average of 0.7101604 ± 13. These results indicate that the Sr isotope values were increased due to the interaction of the hot waters, which precipitated the travertine towers in Hisaralan, with the lower Miocene dacitic-rhyolitic volcanic rocks. The negative carbon isotope values most likely imply the CO_2 contribution of magmatic origin. Based on the element and isotope analyses, the spring towers were formed by the deeply circulated hot waters that oversaturated with respect to calcite and aragonite.

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Comparison between shrubs from Pre-salt reservoir cores and from travertines: Discussion and Implications for possible analogues

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Keywords: Lacustrine; Pre-salt; Shrubs; Travertines

Some unusual facies in Pre-salt reservoir cores from Brazil have been likened to travertines, giving rise to several studies looking for analogues for these Cretaceous non-marine deposits. However, other possible interpretations of these facies may have different implications for the sedimentary record in the cores.

Petrological comparisons between shrubs from Brazilian Pre-salt and those from subaerially-formed travertines are presented and discussed.

Shrubs are related to other different facies in both travertines and lacustrine deposits. In travertines, they are usually capped by microbial biofilms, rafts, coated bubbles, and less frequently by fine-grained sediments and coarse crystalline crusts. In lacustrine Pre-salt deposits, shrubs commonly developed from spherulites related to Mg-clay matrices and can be capped by different types of laminites, microbial mats, or intraclasts.

Travertine shrubs are typically low magnesian calcite (LMC) or aragonite, whereas Pre-salt shrubs are of LMC, high magnesium calcite (HMC) or aragonite, as well occasionally as of secondary mineral compositions such as dolomite.

Travertine shrubs can be (i) Micritic, displaying a clotted texture; (ii) Fibrous, including both radial arrangements and patches made of fibres and dendrites; (iii) Sparitics, including dendrites s.s. and feather-like crystals, made of rhombic platy crystalline subunits.

Pre-salt shrubs can be (i) Micritic, with a clotted texture although commonly appearing neomorphized to microsparite; and (ii) Sparitic, with a texture commonly defined as fascicular-optic, despite showing some features suggesting an original fibrous texture after cementation of the microporosity and/or neomorphism or replacement.

Diagenetic changes of the travertine shrubs include (i) Cementation by calcite or aragonite (pore-lining type) and mosaics of spar calcite partially to totally occluding the the primary growth framework porosity and the secondary vugular and intra-crystalline pores produced by dissolution; (ii) Neomorphism, including change from HMC to LMC, aragonite-to-calcite inversion, recrystallization and micritization; (iii) Cementation by calcite, dolomite and silica, among others, of the primary growth framework porosity and the secondary vugular and intra-crystalline pores produced by dissolution.

Differences in vertical arrangements of shrubs with other facies suggest that the processes and conditions were different during formation of shrubs in subaerially-formed travertines and Pre-salt. Differences in the mineralogy of shrubs and the matrices containing them, together with differences in chemical compositions of pore waters strongly control the diagenetic processes, which are clearly different between Pre-salt shrubs and travertine shrubs, even if just eogenetic modifications are considered, provided that travertine analogues did not undergone burials comparable to that of Pre-salt. Such differences in primary and diagenetic processes may lead to different final textures in both cases. In consequence (i) travertine shrubs may be not a direct analogue for lacustrine shrubs, although (ii) some depositional features and diagenetic changes found in travertine shrubs may provide clues to understand the controlling factors for shrub formation in alkaline lacustrine settings.

Hydrothermal silicification along faults and its impact on carbonate reservoir quality, Potiguar Basin, Brazil

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Although silicification has been recognized as a process for more than a century and has been documented in a few active faults in several tectonic settings, its effects on carbonate formations has not been well studied. We analyzed hydrothermal silicification along the Afonso Bezerra strike-slip fault in the Potiguar Basin, Equatorial margin of Brazil. The fault cut across the whole basin, including its crystalline basement, a late Cretaceous lower carbonate unit and a Paleogene-Neogene upper carbonate unit. Our results indicate that the fault was active from the rift to the post-rift phases of basin evolution and is composed of several parallel fault segments that exhibit dextral strike-slip motion with a normal component. Intense fault-controlled silicification caused by upward migration of hydrothermal fluids and their diffusion occurred within and around the vicinity of the fault zone. The preliminary data from fault mineralogy and homogenization temperatures of fluid inclusions indicates a fluid temperature above 140°C. The process of silicification resulted in the complete replacement of the carbonate mineralogy by quartz and amorphous Si (chalcedony, opal). The $Si0_2$ content increases from 3-15% in the host carbonate units to as much as 94-97% in the silicified carbonate units. Superposition of multiple events of cataclasis and silicification resulted in a fault zone compositionally heterogeneous along stratigraphic-lithological units (vertical variations) and orthogonal to fault strike (horizontal variations). In the lower carbonate unit, a series of faults marge and form a complex ~800 m wide zone of silicification, where reduction (~less than 1%) and increase (more than 15%) in porosity occur. The lower carbonate units exhibit evidence of dynamic silicification characterized by hydraulic brecciation at all scales. In this case, multiple phases of silicification and cataclasis were coeval or alternated in time. Silicification in the upper carbonate unit shows evidence of dynamic silicification in a narrow fault core ~10-20 m wide and static silicification in a damage zone ~50-100 m wide, where no lattice orientation or deformation occurred. The lower carbonate host rocks exhibit porosity around 5-10% and the highly silicified lower and upper units both exhibit porosity as high as 14%, which could reach higher values if the cm-scale (5-30 cm) vuggy porosity along fractures observed in outcrops are taken into account. This anomalous vuggy porosity could serve as reservoir pore space. This work may shed light on the origin and likely geometry of the fault-controlled silica distribution causing heterogeneities within carbonate reservoirs.
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Keywords: hydrothermal silicification, strike-slip fault, brecciation, porosity, carbonate reservoir quality

Processes and properties of fractured and karstified carbonates in outcrops and caves – as a key to understanding aspects of the Brazilian Pre-Salt

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Fractured and karstified carbonate reservoirs present challenges for reservoir development and production, such as extensive systems of small- (µm-mm) to large-scale (m-km) karst conduits that can impact reservoir performance during production. The main goals of our project is the investigation of (1) Dissolution (karst) systems at all scales, associated with both the sedimentary facies and fault/fracture system in a burial history context; (2) Rock matrix and diagenetic evolution and relation to karst-associated porosity; (3) Secondary porosity developed along structural features such as faults, fracture corridors and single fractures and their relationship to tectonic history; and (4) The impact of the karst system on porosity and permeability at all scales in the reservoir. We chose two carbonate outcrop/cave analogues to address these points on the basis of the high-quality and size (>1km^2) of the outcrop/cave-system, and their contrasting tectonic regimes and lithologies: (1) The Cretaceous Jandaíra Formation (Potiguar Basin, NE Brazil) with a strike-slip tectonic regime, which formed as a transgressive unit after the breakup of Pangea during the opening of the South Atlantic. This analogue is characterised by epigenic karstification caused by aggressive fluids derived from the surface; and (2) The Neoproterozoic Salitre Formation (Irece Basin, Central Brazil) with a thrust/contractional and strike-slip tectonic regime, which is composed of supratidal to subtidal carbonates, where stromatolites/microbiolites are common, which is mainly affected by hypogenic karstification caused by fluids ascending along faults. In this research we focus on the karst processes from the macro- to micro-scales that can have a major impact on the reservoir-scale porosity-permeability. Our preliminary results indicate that at the centimeter-scale (1-100 cm), karstification concentrates along cross bedding and small fractures (1-10 m) and forms large individual vugs 2-5 cm wide and 10-100 cm long in the epigenic karst example. At the metric scale (10-100 m), layers of shales behave as a seal for ascending fluids. Karstification occurs below the sealing units in the hypogenic analogue, where super-permeabilty layers showing anomalous high permeability (macro-scale, up to 10 m wide and a few km long) were formed. The architecture, dimensions and orientations of fault/fracture corridors is extremely variable in both examples. In both cases, however, fracture corridors concentrate along anticline hinges, where fractures have an *en echelon* geometry. Karstification occurs along these fractures and forms voids up to 5-10 m wide and a few hundred meters long, which are linked and form flow corridors. These flow corridors are likely to form large-scale high permeability connections within the reservoir. The combination of the sedimentary and fracture/fault related discontinuities makes the karst system complex but somewhat predictable.

Keywords: karst, analogue reservoir, flow corridors, super-perm layers, pre-salt, fault corridors

Microbial influences on tufa and travertine fabrics

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Keywords: calcification, cyanobacteria, EPS, stromatolite, thrombolite

Factors controlling the growth fabrics of microbial carbonates are still not well understood, despite of their significance for understanding their depositional processes and assessing the potentials as hydrocarbon reservoirs. For better understanding on this subject, we conducted sedimentological and geomicrobiological investigations of tufas and travertines of the present day.

Investigated tufas were categorized into stromatolite and thrombolite according to their fabrics in the mesoscopic scale, and their surface was colonized by cyanobacteria (Shiraishi et al., 2017). Major driving force of $CaCO_3$ precipitation was the same for both stromatolite and thrombolite (photosynthesis-induced $CaCO_3$ precipitation), while cyanobacterial community composition was quite different. In the stromatolite, *Phormidium* sp. secreting acidic EPS (extracellular polymeric substances) sheath was dominant, and their EPS provided crystal nucleation sites to result in uniform calcification in the mesoscopic scale. In the thrombolite, on the other hand, *Leptolyngbya* sp. secreting non-acidic EPS sheath and *Coelosphaeriopsis* sp. secreting acidic EPS capsule were dominant. The former was not calcified to form fenestrae while the latter was calcified to form peloids, resulting in heterogeneous calcification in the mesoscopic scale. These observations suggested that the acidity of microbial EPS had significant influence on microbial carbonate fabrics.

Similar EPS control was also recognized from travertine-depositing hot springs where $CaCO_3$ saturation state was much higher than tufa-depositing creeks (Shiraishi et al., 2019). In the investigated travertine sites, the major driving force of $CaCO_3$ precipitation was abiotic CO_2 degassing and/or photosynthesis-induced $CaCO_3$ precipitation. Cyanobacteria colonized on the travertine surface under the condition in low flow velocity: *Oscillatoria* sp. secreting acidic EPS sheath was calcified to form micritic fabrics, while *Spirulina* sp. lacking acidic EPS sheath was not calcified to form sparse fabrics. Cyanobacteria could not attach to the travertine surface under high flow velocity, resulting in sparitic and dense fabrics.

From these observations, we suggest that the fabrics of carbonate deposits are strongly influenced by the presence/absence of microorganisms and their EPS acidity.

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The 'sediment dilemma' in fossil microbialites: a review of the factors controlling the 'trapping and binding' process

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KEY WORDS: agglutinated, EPS, oncoids, stromatolites, thrombolites.

Trapping and binding of grains by benthic microbial communities has been considered a fundamental process of microbialite accretion since its discovery in popular present-day shallow-marine examples (Bahamas and Shark Bay). However, agglutinated textures are rare in fossil microbialites and, thus, the role of trapping and binding has been largely debated. Renewed attention on this subject has produced new findings of fossil agglutinated microbialites (those mainly formed by 'trapping and binding'), but they are still few and geologically recent (post-Paleozoic) when compared to the 3.5 Ga long record of microbialites. This discrepancy in the presence of trapped grains between modern and fossil microbialites is known as the 'sediment dilemma'.

Based on an extensive literature review, the first thorough database of modern and ancient agglutinated microbialites has been made, showing that all of them are formed in shallow-marine environments and most under tidal influence. In addition, a Lower Cretaceous case example (Leza Formation, La Rioja, Spain) provides a step forward in the understanding of the dilemma, due to its remarkable abundance and diversity of microbialites: oncoids, skeletal stromatolites, agglutinated stromatolites, micritic-evaporitic stromatolites, thrombolites and fenestral laminites (Figs. 1-2). Each of these microbialites developed in a particular paleoenvironment, from freshwater-alluvial to shallow-marine, some of which rich in grains (Fig. 2). However, only the microbialites formed in marginal-marine tide-influenced environments accreted mainly by trapping and binding (Figs. 1-2), matching the environmental pattern observed in the literature database. This allows to discuss the factors that control and enhance 'trapping and binding' (Fig. 2): a) occurrence of grains in the microbialite environment; b) frequent currents that mobilize the grains and supply them onto the microbialite surface; c) high concentration and diversity of electrolytes in water to increase the adhesiveness of the extracellular polymeric substances (EPS) of the microbialite surface; and d) $CaCO_3$ saturation state not so high as to promote early and strong carbonate precipitation within EPS, which would eventually decrease its availability to adhere grains. Therefore, this review shows that the keys to solve the 'sediment dilemma' may be environmental, because the conjunction of those hydrodynamic and hydrochemical parameters is preferentially achieved in shallow-marine settings and especially in those influenced by tides (Fig. 2). This explains the limited environmental and stratigraphic distribution of microbialites mainly formed by 'trapping and binding', and opens new ways to look at this process, so often cited and yet so rare.

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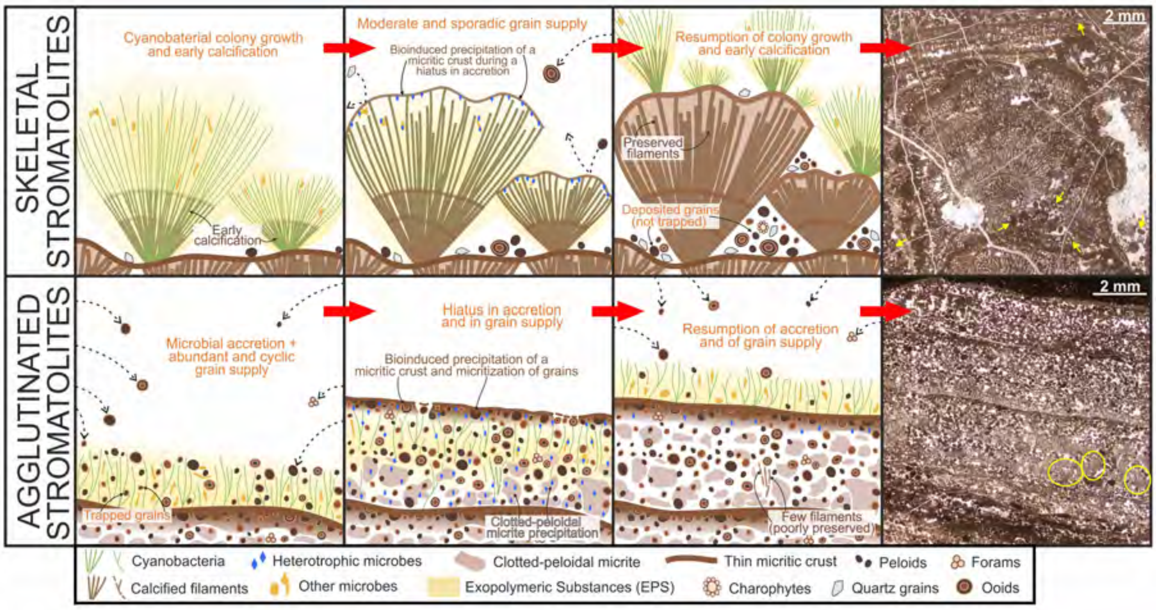

Figure 1: Contrasting microbialite accretion processes: Skeletal stromatolites formed in grainy $CaCO_3$-rich freshwater settings and accreted through early EPS mineralization of microbial filaments. Thus, the grains supplied were not trapped and bound by the EPS, but only deposited between the filament fans (yellow arrows in photomicrograph). Agglutinated stromatolites formed in grainy shallow-marine tide-influenced areas, where filamentous microbes were not early lithified (and thus only locally and poorly preserved, yellow areas in photomicrograph), indicating lower $CaCO_3$ concentration. Grains continuously mobilized by currents were profusely trapped and bound in the uncalcified EPS.

		ENVIRONMENTAL CONTROLS ON TRAPPING AND BINDING				
	Paleo-environment	Availability of grains	Common agitation by currents	Electrolytes to enhance EPS adhesiveness	$CaCO_3$ supersaturation	**Trapping and binding**
Oncoids	Small clastic-rich channels or creeks and shallow freshwater bodies	**Yes**	**Probably constant water flow within the channels**	Relatively low abundance and diversity in freshwater	Very high, due to hardwater sources, promoting early and strong precipitation	Not significant
Thrombolites	Shallow water bodies with marine influence and dasyclad meadows	No	Not significant	**Hig abundance and diversity due to marine influence**	**Relatively low in sea-water, hindering early and strong precipitation**	Not significant
Skeletal stromatolites	Shallow freshwater bodies with common clastic input from alluvial fans	**Yes**	Only sporadic, associated with discharges from fans	Relatively low abundance and diversity in freshwater	Very high, due to hardwater sources, promoting early and strong precipitation	Not significant
Agglutinated stromatolites	Marginal-marine tide-influenced water bodies	**Yes**	**Continuous and cyclic tidal currents in addition to waves and storms**	**High abundance and diversity due to marine influence**	**Relatively low in sea-water, hindering early and strong precipitation**	**Major accretion process**
Micritic-evap. stromatolites	Very shallow and restricted marginal-marine areas with sulfate precipitation	No	Not significant	**High abundance and diversity due to marine influence**	**Relatively low in sea-water, hindering early and strong precipitation**	Not significant
Fenestral laminites	Very shallow marine-influenced water bodies rich in ostracods and forams	Only locally	Probably waves and storms	**High abundance and diversity due to marine influence**	**Relatively low in sea-water, hindering early and strong precipitation**	Only partially in some specimens

Figure 2: Factors that control 'trapping and binding' by microbialites, applied to the examples of the Leza Fm.

Interaction of constructive and destructive processes in peritidal stromatolites: build-up, tear-down, eat-up and re-build

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KEY WORDS: bioturbation, Cretaceous, evaporites, microbialites, peritidal.

Stromatolites are common constituents of carbonate sequences developed in highly-dynamic peritidal environments. The combination of the physical, chemical and biotic processes of tidal flats results in a complex interplay of constructive and destructive processes that control the development and preservation of microbialites. Here, we present exceptionally preserved and exposed Cretaceous stromatolites that allow the detailed documentation of those interactions.

In the studied area, the Oncala Group (Berriasian, Cameros Basin, Spain) includes carbonate peritidal cycles consisting of stromatolites, thinly-bedded to laminated carbonates and intraclast breccias, all of them disrupted by pseudomorphs after anhydrite nodules precipitated within the supratidal zone. In that environment, the main constructive process was microbial activity, leading to the formation of 5-120 cm-thick stromatolites, which show a great macro-, meso- and microscopic variability. Stromatolites range from subspherical-domed bioherms to tabular-domed biostromes, and they can be internally composed of flat, wavy, convex or columnar laminae. Furthermore, different microscopic textures are observed: agglutinated, dense micritic, clotted, spongiostromic, filamentous and reticulate, all of which may occur in different types of laminae and even pass laterally to each other within the same lamina. In addition, thin crystalline crusts, composed of pseudomorphs after evaporites, are often observed separating stromatolite laminae.

These stromatolites, along with the thinly-bedded to laminated carbonates, were subjected to hydrodynamic, diagenetic and biological synsedimentary destructive processes. Waves, tides, storms and repetitive desiccation in the intertidal zone, caused breaking of stromatolites and thinly-bedded to laminated carbonates into intraclasts, which were subsequently reworked into cm-thick continuous beds, into interdomal spaces, and into stromatolite agglutinated laminae. Furthermore, intraclast breccias created topographic reliefs that were subsequently colonized by microbial mats. The early-diagenetic precipitation of anhydrite nodules, although highly destructive, produced additional accretion in the tidal flats by adding new material to the sediment column. Moreover, abundant bioturbation of the stromatolites is another important destructive process. However, the filling of burrows displays textures similar to those observed in stromatolite laminae, and thus microbial activity within burrows also played a constructive role. In addition, some burrowers excreted the faecal pellets that were afterwards agglutinated within the stromatolites and accumulated in the tidal flats. Consequently, microbial mats were the most important primary sediment producers in the studied peritidal flats, but the subsequent destructive processes were also responsible for the generation of sediment that was eventually deposited in the same setting. Thus, the products of constructive and destructive processes created an indispensable feedback loop for the final sedimentary accretion.

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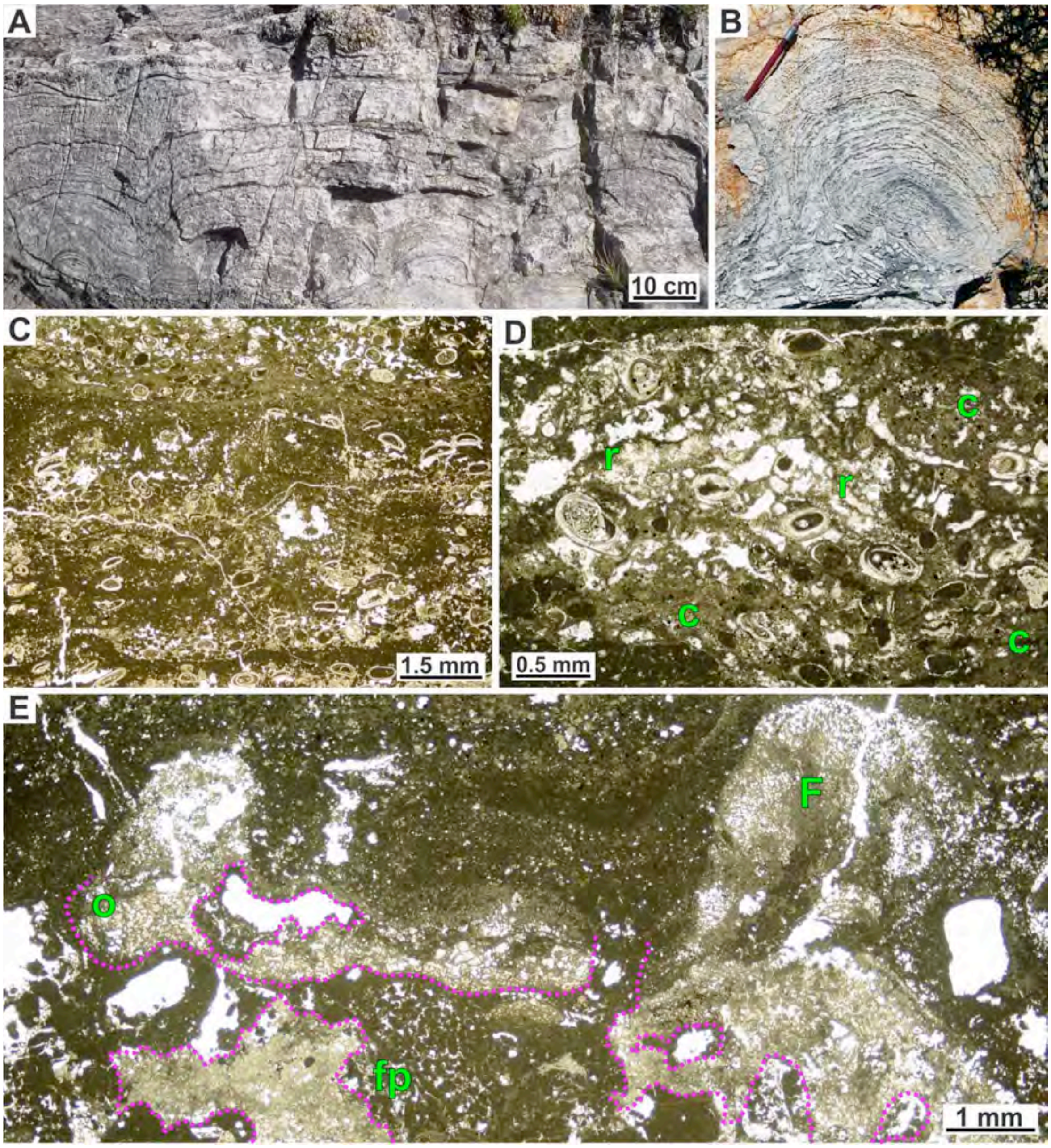

Figure 1: **A)** Domed to tabular biostrome. **B)** Subspherical bioherm developed over an intraclast breccia. **C)** Photomicrograph of stromatolite laminae with clotted and agglutinated textures. **D)** Detail of clotted (c) and reticulate (r) micritic textures with trapped grains. **E)** Photomicrograph of a columnar stromatolite lamina with filamentous (F) and open spongiostromic (o) textures, which is strongly burrowed. Burrow (pink line) is filled by clotted micrite rich in faecal pellets (fp).

Cambrian fine-grained stromatolites in oolitic shoals: how do microbial mats exclude coarse grains?

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Key words: microbial mat, microbialite, precipitation, stromatolite, trapping and binding

Stromatolites, laminated structures produced by trapping and binding of detrital sediment and/or precipitation of minerals on microbial mats, occur throughout Earth's sedimentary record. Present-day Bahamian stromatolites growing among ooid-sand dunes have coarse-grained agglutinated fabrics. However, such agglutinated stromatolites formed by trapping and binding of coarse sediment are geologically young and relatively uncommon. In contrast, fine-grained stromatolites are abundant in geologic history, although their mode of formation is often unclear. We studied Miaolingian (middle Cambrian) fine-grained stromatolites enclosed by oolitic packstone-grainstone at two localities in northern China to understand how they formed.

At the locality near Beijing, the stromatolites occur in a meter-scale mound consisting of centimeter-scale columns and intercolumnar oolitic and bioclastic wackestone-packstone. The mound is surrounded by oolitic grainstone. The coarse sediment does not contribute to stromatolite growth. The stromatolite columns mainly consist of poorly-defined micritic layers, with minor occurrences of calcified microbes (*Epiphyton* and *Renalcis*). At the locality near Wuhai, Inner Mongolia, small stromatolites up to 2 cm wide and high are surrounded by coarse oolite packstone-grainstone with some trilobite fragments and minor grapestone. The stromatolites consist of low-relief fine micritic layers with cross-cutting relationships, suggesting agglutinated fabric. Ooids and other grains are almost entirely absent within the stromatolite, only filling small pockets.

The microfabrics suggest that these Cambrian stromatolites formed by fine-grained trapping/binding (Wuhai) plus precipitation (Beijing). In both cases, it appears that coarse sediment was selectively excluded by the mats and only accumulated in small intra-column pockets. We infer that the coarse grains were excluded either because the mats were too firm or too thin to retain them. This is consistent with previous suggestions that coarse-agglutinated stromatolites, such as well-known examples at Shark Bay, Australia, and Lee Stocking Island in the Bahamas, trap coarse grains because the mats are – at least initially - thick and soft. In contrast, it seems likely that both the microbial composition and the initial lithification and coherence of the Cambrian examples described here hindered accretion of coarse sediment. These features are more difficult to elucidate in stromatolites surrounded by fine-grained carbonate, but they may be widespread in ancient stromatolites generally.

Deep water microbialites and associated facies of the Late Ordovician System in Thailand

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Keywords: Ordovician, stromatolite, Pa Kae Formation, Tha Manao Formation, Thailand

Late Ordovician limestones of the Pa Kae Formation and uppermost Tha Manao Formation (approximately mid-Sandbian to late Katian Stages) in western and peninsula Thailand (western Sibumasu Terrane) comprise micritic limestone with abundant bioclasts of fragile fossils, interpreted as deep water facies. Both formations have a distinctive polygonal network vein structure harder than the limestone and stands out on eroded outcrops. The Pa Kae Formation is mostly red-brown, contrasting gray-coloured Tha Manao rocks. Pa Kae limestones are previously interpreted as rich in microbialites, and our work reveals domes and columns, up to 5 cm diameter and 20 cm high, of agglutinated stromatolites made of sediment layers containing abundant bioclasts and intraclasts, but lack calcimicrobes and cements. Some domes are unlaminated and are leiolite microbial fabrics, but no other microbialite forms were found, despite reports of thrombolites and oncolites in previous work. Abundance of microbialites in Pa Kae formation is not easily determined because stromatolitic layering is rarely visible in outcrop but exists in some polished blocks and thin sections while other unlaminated samples lack microbialites. The Tha Manao Formation contains no microbialites. Both formations are affected by tectonic deformation, shown by local shear, leading to oblique preservation of some network veins, evidence that veins formed relatively early, potentially at a very early diagenetic stage.

These Late Ordovician limestones are approximately equivalent, in age and environmental setting of deep shelf, to mid-Sandbian to early Katian Stage Pagoda Formation (Yangtze Platform, south China) which also possesses a network of veins. The Thai limestone veins are composed of multiple clay-rich thin veins of largely opaque Fe-Mn mineral, intermixed with fragments of host rock micrite, altogether showing micro-scale displacement and tension fractures filled with fibrous calcite cement. However, a Pagoda Formation sample examined in comparison reveals its veins' structure to be in place and has instead undergone selective replacement of the micritic host rock by opaque matter while enclosed fossils and exotic intraclasts were unaffected. Of the six published models for the Pagoda Formation, there is evidence of only one of these models (tectonic effects) in the Thai limestones, but it is difficult to attribute widespread tectonic processes in a limited time zone across Sibumasu and Yangtze microcontinents. Some authors view the Pagoda Fm and Thai limestones as non-uniformitarian "time-specific facies". However, other time-constrained unusual facies occur in the rock record (e.g. unique microbialite facies in south China after the end-Permian extinction; Ammonitico Rosso facies of Jurassic to Early Cretaceous in Italy). Earth processes follow laws of physics, reasonably presumed to

constant through Earth history. All sedimentary facies on Earth, and indeed Mars, are controlled by associated processes, but facies of these Late Ordovician rocks are so unusual that they lie on the margins of our understanding of sedimentary facies. Nevertheless if geoscientists need a term to describe such unusual facies perhaps something like “unusual process-specific facies” would be more appropriate than non-uniformitarian “time-specific facies”, in recognition that these processes follow the laws of physics but are incompletely understood.
(494 words)

Anachronistic columnar microbialites from the Messinian of Mallorca (W Mediterranean)

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KEY WORDS: microbialites, Miocene, ooids, Precambrian, shallow-marine.

Microbialites consisting of cm-wide, often branching columns were widespread in the Precambrian, but they underwent a significant decline throughout the Neoproterozoic and early Paleozoic. Here, we present an example of Messinian (Upper Miocene) microbialites with unusual characteristics for the Cenozoic, more similar to Precambrian counterparts.

These microbialites occur in a 200 m long road cut, close to the locality of Ses Salines (Mallorca, Spain). They belong to the Santanyí Limestone, a unit with abundant microbialites deposited in a restricted back-reef position, time equivalent to the Tortonian-Messinian Mallorca Reef Complex. The studied microbialites occur as a 10-50 cm thick biostrome, laterally continuous throughout the whole outcrop, locally with flat domes ~1 m wide. It consists of calcite and Mn-oxides which cause a characteristic black colour that contrasts with the paler under- and overlying rocks, mainly composed of oolitic-peloidal packstone-grainstones with molluscs and foraminifers (Fig. 1A). Internally, the biostrome changes lateraly from columnar to non-columnar structures. The non-columnar structures consist of faint wavy-planar lamination with a slight convex curvature. Columnar structures consist of: a) a thin (<2 cm) laterally-continuous basal interval with wavy-planar lamination; and b) branching columns up to 5 cm wide and 20 cm tall (Fig. 1A). Columns are grey, lighter coloured than the dark intercolumn sediment and the boundary between them is irregular. The intercolumn sediment has faint concave-up lamination and consists of oolitic-peloidal grainstones (Fig. 1). Petrographical, elemental and SEM analyses reveal that the dark colouring is due to Mn-oxides that partially replaced ooids and peloids and precipitated after non-ferroan calcite cement in primary porosity of grainstone, and in secondary porosity, after corrosion and/or cracking of previous micrite and calcite cement. Mn-oxides are also postdated by non-ferroan calcite cement that may occlude porosity. Some light laminae within the intercolumn sediment connect the columns (Fig. 1A). Columns are poorly- or non-laminated and have clotted micritic textures with large cement-filled pores and very scarce grains (Fig. 1). Locally, thin micritic walls separate the columns from the intercolumn sediment (Fig. 1C). The columns are interpreted as the product of calcite precipitation within microbial communities that accreted vertically and simultaneously with the input of grains, which were not significantly trapped within them.

The structure of these microbialites is equivalent to that obtained from mathematical models to explain the growth of branching columnar Precambrian microbialites, which include a laterally-continuous basal interval, from which the columns start to grow when any disturbance (e.g. grain input) occurs. This Miocene example is one of the youngest analogues of Precambrian columnar microbialites and, thus, provides a unique opportunity to compare accretion processes, in order to understand why this type of microbialite structure has become so rare.

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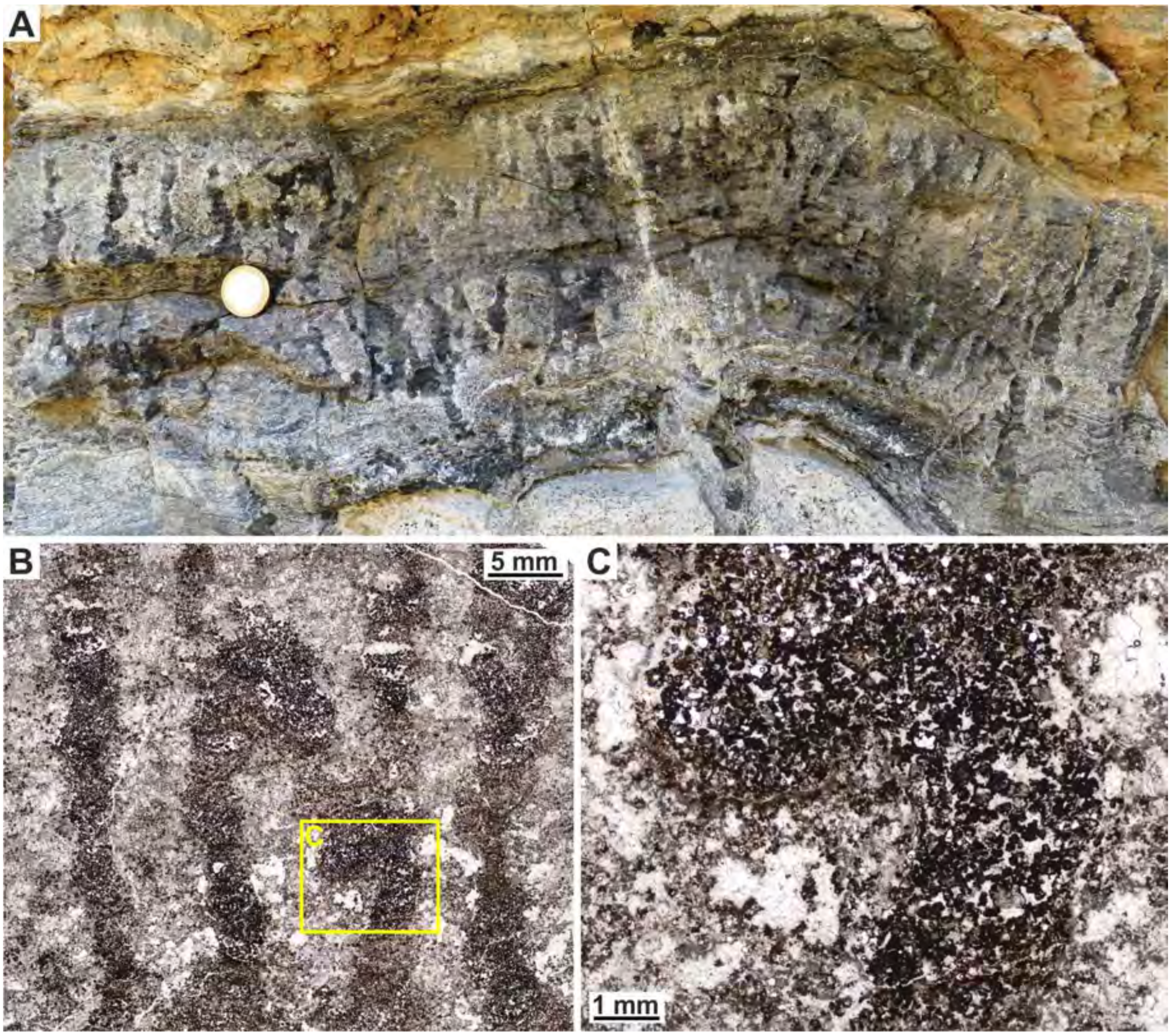

Figure 1: **A.** Studied microbialite biostrome, with a laterally-continuous basal interval and light-coloured branching columns separated by darker intercolumn sediment. **B.** Photomicrograph of the non-laminated columns (light) and the intercolumn sediment (dark) with faint concave lamination. **C.** Detail from B. Note open clotted textures of the columns, locally separated by thin micritic walls from the intercolumn grainstone.

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