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Abstracts of the International Conferences on Evaporite Stratigraphy, Structure and Geochemistry, and their role in Hydrocarbon Exploration and Exploitation

October 12–13, 2004 and November 7–8, 2006. Abu Dhabi, United Arab Emirates

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Research into the carbonates and evaporites of the Arabian Gulf, and particularly Abu Dhabi, United Arab Emirates (UAE), extends back to the late 1950s and early 1960s with the work of K.O. Emery (University of Southern Califronia) and J.J.H.C. Houbolt (University of Utrecht). A group of geologists from London's Imperial College became the leaders in this research subject when they carried out extensive studies along the Abu Dhabi coast between 1961 and 1970. This group's work was initiated by G. Evans and D. Shearman, and was published in numerous PhD dissertations (e.g. D. Kinsman, C. Kendall and P. Skipwith) as well as papers and books.

Shell Research, The Netherlands, followed Imperial College and carried out regional studies along the coast of the Arabian Gulf from Qatar to the UAE. B. Purser of the Shell E&P Lab, Rijswijk, directed this research and worked with many Shell geologists including E. A. Shinn, L.F. Illing, J.C.M. Taylor, M.W. Hughes-Clarke, K. Glennie, P. Kassler. G. Varney, K. DeGroot, and B. D. Evamy. Later, Purser and his team carried out fieldwork sponsored by France's National Museum of Natural History, Paris, and France's Total petroleum company. K. Hsu and his graduate students, including G. Butler and J. Mckenzie at the then Polytechnic Institute of Zurich, Switzerland (now Geological Institute, ETH-Zentrum), made significant contributions to the understanding of the recent carbonates and evaporites of Abu Dhabi in the early 1970s

In the late 1970s and 1980s, several teams studied the coastal settings of the Arabian Gulf, including S. Golubic (Boston University, USA) and colleagues R.J. Patterson (Princeton University), R.K. Park (Reading University), and D.J. Kinsman (University of London), A. Gunatilaka in Kuwait, along with D. Shearman from Imperial College, and G. Walkden and A. Williams of the University of Aberdeen, UK.

During October 12–13, 2004, the first international conference on *Evaporite Stratigraphy, Structure and Geochemistry, and their Role in Hydrocarbon Exploration and Exploitation* was held in Abu Dhabi. The conference honored Professor Douglas Shearman for his outstanding contributions to the geological understanding of sabkha evaporites in the UAE and their role as analogues to evaporites that are currently associated with worldwide hydrocarbon exploration and exploitation.

The second conference was held in Abu Dhabi during November 7–8, 2006. It honored Professor Bruce Purser for his outstanding research contributions to understanding the geology of the Holocene evaporites and carbonates of the United Arab Emirates and the adjacent regions of the Gulf.

Post-conference, one-day field trips followed both conferences and examined the recent carbonates and evaporites of western Abu Dhabi. Selected papers from these two meetings have undergone a detailed review by professionals and a special volume on this subject will be edited by Alsharhan, Kendall and Al-Suwaidi, and published by the International Association of Sedimentologists (IAS) in 2007.

The topics reflecting the theme of the conference were divided into six parts:

(1) An Abu Dhabi Retrospective on contributions from the 1960s and 1970s and their impact on the current thinking on evaporites and their association with hydrocarbon exploration and exploitation.

(2) *Evaporite Stratigraphic Signals of Base-Level Change in the Geologic Record*, with contributions relating these to hydrocarbon exploration and exploitation in the infra-Cambrian, Permian, Jurassic, and Tertiary (Cenozoic) of the Arabian Plate, the North Sea Zechstein, the Mediterranean Messinian salinity crisis, the Western Canadian Devonian, the Permian Basin of West Texas and New Mexico,

the Paradox Basin of the Four Corners area, Sverdrup Basin, and the Mesozoic evaporites of the early Atlantic break up.

(3) *Tectonic Response of Evaporites to Burial and Lateral Compression*, with contributions related to oil exploration and exploitation in the late Proterozoic of the Arabian Plate, Gulf of Suez, offshore Gabon, Equatorial Guinea, Brazil, the Gulf of Mexico, offshore Senegal through Morocco, and Pakistan.

(4) *Geochemical Controls on Evaporites and Associated Dolomitization of Carbonates* as related to their contribution to the prediction of porosity and its role in hydrocarbon exploration and exploitation.

(5) *Effect of Evaporites on Reservoir Quality and Fluid Flow* with contributions related to oil exploration and exploitation associated with salt plugs and diapir examples for the Arabian Gulf and the world.

(6) *Evaporite Controversies: Evolution of Evaporites in Time and Space* as related to their contribution to hydrocarbon exploration and exploitation.

Abstracts of the First and Second International Conference on Evaporites, 2004 and 2006, Abu Dhabi, United Arab Emirates

Effect of evaporite on hydrocarbon distribution and migration in Abu Dhabi, United Arab Emirates

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The Hith Anhydrite is the main evaporite formation in Abu Dhabi's stratigraphic sequence. It is the major seal rock for most Upper Jurassic oil fields in the central and western parts of the Arabian Peninsula. It plays an important role in the hydrocarbon migration, distribution, and accumulation within the Lower Cretaceous Thamama reservoirs and Upper Jurassic Arab and Asab reservoirs in the United Arab Emirates. The major hydrocarbon source rocks are within the Upper Jurassic Diyab/Hanifa Formation.

This case study discusses the possible reasons behind the unexpected water test results from the Thamama Zones A and B in well U-1. The test results contrast with the Habshan and Arab zones, which tested hydrocarbons in the same well and also within the surrounding structures where the Thamama Zones A and B are hydrocarbon-bearing. The "U" field is located west of the B field and between the "M" and "Q" fields, both of which are oil-bearing in the Upper Thamama zones. The entire Hith Anhydrite shows progressive thinning eastward and is absent in central Abu Dhabi and further east. The Hith Anhydrite is developed in the western half of Abu Dhabi where its thickness reaches a maximum of 600 ft.

Specifically, this study concludes with how the Hith Anhydrite exercises very strong control on the present-day distribution of hydrocarbons, mainly in the surrounding structures to the Hith zone edge. Due to the Hith sealing effect, the study model shows the hydrocarbon distributions within the main reservoirs in Abu Dhabi vary. Hydrocarbons in the western area occur in the Upper Jurassic Arab Formation, whereas in the central area it is in the Lower Cretaceous Thamama Group and the Upper Jurassic Arab Formation. In the eastern area, it occurs mainly in the Lower Cretaceous Thamama Group. Other factors also have a significant impact on hydrocarbon distribution, such as vertical migration due to vertical faults and lateral migration associated with structural tilting.

Exploration challenges of the Arab Formation in central offshore Abu Dhabi, United Arab Emirates

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The Upper Jurassic of offshore Abu Dhabi, United Arab Emirates, consists from the base up, of the Diyab, Arab, and Hith formations. The Arab Formation contains large volumes of hydrocarbons in structural traps located in the western half of offshore Abu Dhabi. However, where the Hith anhydrites are absent, as in the central and eastern parts of offshore Abu Dhabi, no hydrocarbons are present in this formation. The Diyab and the Hith formations provide good source rocks and caprocks, respectively. The Arab Formation consists predominantly of carbonate and evaporite successions that were deposited on a carbonate shelf with settings that ranged from open-marine to hypersaline. The poor occurrence and preservation of fossils in these rocks renders their ages difficult to determine; however, a Kimmeridgian-Tithonian age is assigned to the formation in the offshore Abu Dhabi.

The Arab reservoirs show lateral and vertical facies and petrophysical property variations in a west-to-east direction. These variations are pronounced

in central offshore Abu Dhabi, where the differentiation between the Arab reservoirs A, B, and C becomes difficult.

Recent studies using wells and seismic data showed that the Hith Anhydrite and the Arab A, B, and C reservoirs progressively onlap the underlying Arab D reservoir towards central offshore Abu Dhabi. The onlap limit of the various intervals occurs along a NNW-trending direction. The Arab-D oolitic grainstone facies also seem to occur along the same trend. The lateral extent of the oolite facies belt is still not very well understood and requires further well and seismic data. Good potential for oil and gas accumulations is present in the Arab reservoirs both in structural and combined structural-stratigraphic traps along the onlapping edge. Proper definition of these onlapping traps represents a future challenge and is considered vital for successful and rewarding future exploration.

Reflux dolomitization of Mississippian-age sabkha and restricted subtidal sediments resulting in a 1.6 TCF giant gas field: Geologic and geochemical evidence from the Upper Debolt Formation of West-Central Alberta, Canada

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Several large hydrocarbon accumulations in Alberta, Canada, are hosted in dolomitized successions of stacked, thin sabkha-capped cycles of Visean age. Porosity is micro-intercrystalline and occurs in dolomitized restricted subtidal and intertidal muds that have their fine primary fabric preserved. The precursor substrate was probably an aragonitic or Mg-calcite mud. The normative shallowing-upward cycles in the upper Debolt Formation of the Dunvegan field (NW Alberta), are interpreted as fourth- or fifth-order transgressive-regressive parasequences (1–3 m thick) that represent the initial flooding and subsequent progradation of a sabkha system.

The dolomitized zones in the upper Debolt Formation of the Dunvegan field consist of "microsucrosic" or planar-e fabrics with crystals in the 2–30 µm range (average 10 µm). The dolomite is non-ferroan, Ca-rich (average of 58 mole% $CaCO_3$), and poorly ordered. Its stable isotopic signatures range from –0.12 to +3.4 ‰ VPDB for $\delta^{18}O$ (mean = +1.3‰) and +0.9 to +4.3‰ VPDB for $\delta^{13}C$ (mean = +2.6 ‰). The average $^{87}Sr/^{86}Sr$ ratio for this dolomite is 0.7077. The $^{87}Sr/^{86}Sr$ ratios of co-existing displacive nodular anhydrite also coincide with Mississippian (Early Carboniferous) seawater composition. These sets of values are consistent with dolomite precipitation from Mississippian marine or modified marine (evaporated) seawater. These parameters are strongly reminiscent of Holocene protodolomites and hence suggestive of a sabkha dolomitization process (shallow seepage reflux or evaporitive pumping). This deeply buried (4 km) dolomite, with its high associated porosity (average of 15% to maximum of 38%) and relatively unaltered mineralogy and geochemistry, suggests a very unique set of relatively non-reactive physico-chemical conditions during burial (likely a closed system).

Origin and sedimentology of the organic-rich levels and associated dolomites and evaporites in the Cañete Dolomites Formation, Middle Triassic, Iberian Ranges, Spain

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The upper part of the Cañete Dolomites Formation (Ladinian, Middle Triassic) of the Iberian Ranges, Spain, is a good example of shallow-water to intertidal dolomites with minor gypsum pseudomorph levels and flat pebbles solution breccias in its uppermost part. Its age is well constrained by means of ammonites, conodonts, and foraminifera (López-Gómez and Arche, 1992, 1993; López-Gómez et al., 1998; Pérez-Arlucea and Trifonova, 1993). This formation represents a complete transgressive-regressive third-order cycle with well-developed lowstand, transgressive, and highstand system tracts (LST, TST and HST).

The upper part of the formation (i.e. the regressive or HST level) contains 6 to 13 elementary metric sequences composed by, from base to top, dark gray marls, dolomicrites with opportunistic bivalves, dolomicrites with crinkled, irregular laminations, and tepee-level oxides laminations. These sequences have been interpreted as shallowing-upwards cycles of lagoon-intertidal-supratidal characteristics.

The middle part of the sequences, with irregular laminations interpreted as microbial mats (Burke and Moore, 1987), contains 0.1–0.8% total organic carbon (TOC), which is the lower range for carbonate oil source rocks. The preservation of organic matter in a well-oxygenated intertidal environment is an apparent anomaly that can be explained by the coincidence of several factors:

(1) The bacterial mat was almost impermeable, avoiding the penetration of oxygenated water; interstitial waters became anoxic at a very early stage.

(2) The high productivity of the bacterial mat was not diminished by predation, as the mats do not show burrowing or feeding traces. The salinity was so high as to preclude any other form of life in the environment.

(3) The rapid progradation of the depositional system fossilized the mats at a very early stage.

(4) The absence of sulforeductor bacteria due to hypersalinity as described by Purser and Evans (1973) in the Abu Dhabi area.

These cycles can be compared with similar ones in a formation (Pliocene) of Abu Dhabi (Wood and Wolfe, 1969), the Smackover Formation (Jurassic) of Florida, USA (Shinn, 1983), and the San Andres Formation (Permian) of Texas, USA (Sasser et al., 1987), all of which are well-known oil source rocks.

This interesting association of evaporites and organic-rich beds has been overlooked up to now as potential source rocks in oil exploration in central-eastern Spain.

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Microbial factors in dolomite formation beneath an Abu Dhabi sabkha

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The coastal sabkhas of Abu Dhabi, United Arab Emirates, remain an important modern environment in which to study the processes controlling the formation of dolomite and gypsum/anhydrite minerals. Our research seeks to define the microbial processes occurring beneath the sabkha surface in the uppermost 40 cm of modern mineral formation using a range of new analytical and molecular biology techniques.

In particular, within the intertidal facies of the sedimentary sequence, we have observed a unique formation of dolomite spheres enveloped in a biofilm. The spheres, with a size up to 0.8 mm, grow *in situ* and accumulate between 10 and 40 cm depth below the sabkha surface in an organic carbon-rich sediment, which represents a buried laminated mi-

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crobial mat deposited approximately 800 to 1,600 years before present, depending on the site location in the supratidal zone (Strohmenger, 2004). These spherical aggregates, observed in extracellular polymeric secretion substances (EPS), are progressively encrusted and mineralized. The production of EPS is directly linked to microbial activity, but the role of organic polymers in the nucleation and production of dolomite is only partially understood. Our measurements indicate that during the earliest stage of EPS mineralization, Mg ions are preferentially bound to the EPS structure over Ca ions, which may provide an ideal template for dolomite formation.

Although the association of dolomite spheres with EPS supports the hypothesis of microbial dolomite formation, the types of microbial metabolism occurring in the buried microbial mat remain, as yet, undefined. Preliminary cultural experiments conducted using samples collected from the buried microbial mat indicate that sulfate-reducing bacteria are present even though H_2S was not detected in the sabkha pore waters. The apparent evidence for the presence of microbes and EPS production in the buried microbial mat indicates a distinct microbiological influence in the precipitation of dolomite within the sabkha evaporite sequence.

Significance of dolomite in a large evaporite-carbonate cycle: Arab-D Reservoir, Saudi Arabia

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The Arab-D Reservoir is the most prolific reservoir in the world and produces, from the carbonate portion, the oldest and thickest of four upward-shoaling carbonate and anhydrite cycles or "couplets" in the Arab Formation. While evaporites cap and form the top-seal for each carbonate cycle, and locally occur as nodules or cements within the reservoir, the most significant evaporite-associated effect is dolomitization.

Dolomite comprises both the very best and the very worst reservoir rock, with five distinct types of dolomite identified in the Arab-D Reservoir of the Ghawar field. While a variety of mechanisms are believed to be responsible for these different types of dolomite, two types are believed to have formed from hypersaline brines related to deposition of the overlying evaporites. These dolomite types are distinct petrographically, geochemically, and stratigraphically as seen by:

(1) A finely-crystalline fabric-preserving (FP) dolomite in the uppermost Arab-D (Zone 1) that contains high oxygen isotope values and has generally fair to poor reservoir quality; and

(2) A medium-crystalline non-fabric-preserving (NFP) dolomite with high oxygen isotope values and very poor reservoir quality in the upper Arab-D (Zone 2).

Strontium isotopic ratios suggest that both these dolomite types formed very early, at or shortly after deposition of the original sediment. FP dolomite is always intimately associated with the overlying anhydrite and is interpreted to have formed very early in the diagenetic history of the sediment, by dense and highly evaporated magnesium-rich brines associated with the overlying anhydrite. On the basis of its general geochemical similarity to FP dolomite, NFP dolomite in Zone 2 is interpreted to have also formed primarily from hypersaline fluids.

These evaporite-derived dolomites have a dramatic impact on fluid flow in the reservoir, and typically occur as stratiform or sheet-like bodies. Whereas other dolomite types in the Arab-D Reservoir can have very good reservoir quality, the reservoir quality of these hypersaline-brine-derived dolomites is typically very low. This is because their stratiform geometry causes them to act as baffles that cause "stratified" flow in the horizontal direction. Due to their limited lateral continuity and their commonly fractured appearance in core, these dolomites are not believed to represent complete vertical flow barriers.

Coupled passive extension and compression on salt-based passive margins analyzed by physical models

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This study analyzes the kinematics of thin-skinned, gravitational extension and coupled passive contraction affecting the salt cover on passive margins. Analog models were designed to simulate the sliding and/or spreading of low-viscosity horizons lying beneath frictional covers. No syn-kinematic sedimentation was reproduced within the scope of analyzing the factors controlling the geometry and kinematics of active faulting. Our models, after deformation, are partitioned into domains whose cross-sectional lengths are independent of the areal extent of the basal viscous layer. However, the cross-sectional length, its geometry, and the distribution of deformed domains, as well as the total length and the rate of extension, are directly controlled by the margin's slope, the thickness of viscous décollement layers, and its overlying frictional cover as well as the relative ratio of their respective thicknesses. This ratio also controls the fault throw and the grounding of the cover, forming welding surfaces. Grounding

tends to stop extension and limit the cross length of the deformed domains. Due to the lack of syn-kinematic sediment supply, upslope extension results mainly in the form of symmetrical grabens that are concave basinward. When rafts form, their cross-sectional length commonly increases downslope.

Compression downslope takes place at the frontal termination of the viscous décollement due to the increased basal friction. Compression is expressed by allochthonous tongues in the central part of the model, whereas folds and thrusts form at the lateral termination, enhanced by lateral friction. These structures evolve as a break-back propagation sequence. Although analogue models are simplified replicas of natural systems, the results obtained by our models provide valuable insights concerning the evolution of these geodynamic systems.

The Miocene evaporite system of the Euphrates Graben in eastern Syria: Implications for an unconventional exploration play

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The Miocene of the Euphrates Graben in eastern Syria contains an extensive system of evaporite deposits; playa and sabkha anhydrites as well as salt deposits occur throughout the Miocene sequence and cover large areas along the Euphrates River and towards the northeast of Syria. These evaporite deposits form seals to the Miocene carbonate reservoirs of the Jeribe, Dhiban, Euphrates, and Chilou formations. Understanding the distribution and genetic sequence of the evaporite deposits within the overall Miocene carbonate sequence has been fundamental in the revival of these Miocene carbonate reservoirs, with the drive to increase recovery factors in two existing fields. In addition, the search for new reserves has triggered a renewed exploration campaign in this unconventional play.

This paper will discuss the evaporite stratigraphy, sedimentary architecture, and impact on the exploration play. The Miocene carbonates are a truly unconventional exploration play in that: (1) source rocks are abundant with clear migration pathways, (2) reservoirs are high quality and extensive in thickness and lateral distribution, and (3) seals (the evaporite units) are present throughout the Miocene, forming a multitude of reservoir-seal pairs. The main risk is structural because the structural traps, although present, are very subtle and are difficult to image on seismic data.

By integrating a great volume of seismic, core, log, and production data from Al Furat's acreage (two existing Miocene fields on production, some 600 production wells and 100 exploration wells penetrating the shallow Miocene sequence), the regional geology and evaporite system has been analyzed, resulting in the definition of a portfolio of new exploration prospects. This paper will show how integrating this large amount of existing data, combined with a thorough understanding of the evaporite system of the Euphrates Graben, has led to a revival of the Miocene carbonates as an exploration play.

Some engineering properties of the carbonate sediments of Abu Dhabi, United Arab Emirates

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The sedimentology of the lagoons and island of Abu Dhabi was studied in detail by Douglas Shearman and his colleagues during the 1960s. Since that time, the island has undergone extensive development and a considerable data bank on ground conditions in the area exists from site investigations. Despite this, there is little published data on the engineering characteristics of these sediments. The paper presents a brief description of the environments of deposition and the sediments of the foreshore, tidal delta, and the lagoons. The effect of both the origin and diagenesis of the sediments on their engineering properties is examined. Data from a selection of site investigations are summarized to present characteristic values for the various sediments. The ground conditions are then reviewed to identify significant issues that need to be addressed for the design and construction of engineering projects in Abu Dhabi.

Arabian Tales: A historical review of the Quaternary sedimentology of the Arabian Gulf and its geological significance

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This foreland basin between the Arabian Shield and the Zagros fold belt is today being infilled by the Tigris-Euphrates-Karun delta at its head and elsewhere is the site of carbonate and evaporitic sedimentation. Previously, other than a few preliminary surveys by officers of the Indian Geological Survey and other minor geological studies associated with archaeological excavations on the Mesopotamian Plains, its Quaternary deposits received little attention. However, since the late 1950s, following the pioneering studies by Emery, Houbolt, and Sugden, these have attracted considerable interest.

Today, the Arabian Gulf is quoted as a model for foreland basin sedimentation, carbonate evaporite-dune-fan associations, and carbonate ramps. Also, it has become the type area for open water spontaneous precipitation of calcium carbonate (whitings), production of hardgrounds (diastems), oolitic production, dolomitization, and most famously for the development of shallow-water carbonate-evaporite associations. The surprise discovery of anhydrite forming in the supratidal coastal plain sediments, and not in the subaqueous environment, has had a profound effect on the interpretation of ancient evaporites; if not always overturning earlier interpretations, it has caused considerable reexamination and reconsideration of these deposits.

Forty years on: Holocene evolution of Arabian coastal sabkhas with an overview of coeval historical developments in the region

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The stable-isotopes composition (especially that of hydrogen, sulfur, and oxygen) of diagenetic evaporite minerals and coexisting sabkha groundwaters, in relation to coastal geomorphological controls, gives perhaps the best description of the hydrological framework and evolution of sabkhas with time. The hydrological framework of marine sabkhas in the southern Arabian Gulf (United Arab Emirates) is controlled mainly by marine flood-recharge and reflux with a dominant marine isotopic signature in the sulfate evaporites, while in the northern Arabian Gulf (Kuwait), the marine sabkha sulfates show a dominant continental water-derived isotopic signature. In the latter region, the continental waters have virtually reached the coast, displacing the marine waters in the sabkhas. As the coastline progrades, a given marine sabkha can have sulfate minerals with both isotopic signatures, but formed at different times. The current (late Quaternary) 100,000-year orbitally driven climatic cycle with its glacial-interglacial contrasts and resulting sea/base level changes, along with accompanying groundwater table fluctuations in the sabkhas, indicate that their preservation potential is extremely poor. The Arabian Gulf and Peninsula region, which earlier was under the influence of the Indian Ocean Monsoon rainfall belt, went into a climatically hyperarid phase just over 6,000 years ago, more than a thousand years before sabkhas started forming (c. 4,800 years BP), thus priming the sabkhas for diagenetic evaporite mineral precipitation, which requires high groundwater salinities. Climate and hydrology have important implications when discussing ancient sabkha analogues, which were of a different order of magnitude compared to those of today (e.g. the giant sabkhas of the Arabian Jurassic).

The period from about 7,000 to 4,000 years BP also coincided with significant advances in human cultural history and the rise and fall of great civilizations and empires in the Arabian-Mesopotamian region (the cradle of modern civilization). It is shown that these are, to a great extent, related to the abrupt climatic deterioration (from humid to arid) that occurred since about 7,000 to 6,000 years ago. The opportunity to relate cultural history to well-constrained geological (eustatic) and climatic events is not to be missed.

Salt tectonics and structural evolution of the onshore/offshore Moroccan Atlantic basins between El Jadida and Agadir

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Structural analysis based on regional reflection seismic transects constructed across several salt basins of Morocco, especially the Atlantic coastal and offshore basins (El Jadida-Agadir segment), allowed us to define the various structural styles that characterize these areas. These styles were then linked to the main stages of the geodynamic evolution of the Atlas and Atlantic systems. The Triassic-early Liassic time is characterized by NE-trending half-grabens linked by EW-striking transfer faults and overlaid by a wide, considerably less-faulted, salt-rich sag basin with extensive basalt flows. Salt started to move in the most subsiding areas by the end of the rifting phase. Well-formed diapirs started to rise by Late Jurassic times (e.g. the Tidsi diapir), thus strongly controlling lateral facies and thickness variations. Salt also played a major role in the genesis of most of the other structures encountered in this area.

From the late Cretaceous onwards, the Safi-Agadir segment of the Atlantic margin underwent a NNE-SSW compression resulting from the Atlas Orogeny and leading to: (1) the inversion of Triassic faults, (2) the formation of salt anticlines in the onshore basins, and (3) the formation of a flexural basin in the offshore. This flexural basin is characterized by a thick northward-wedging Cretaceous series and NE- striking décollement folds. These folds, which correspond to the Cap Tafelney fold belt, constitute a system of lateral ramps which terminate the Atlas System at its intersection with the Atlantic margin. The fold belt marks the transition from an onshore thick-skin deformation style to an offshore thin-skin deformation style. Triassic-Liassic salt played an important role in the genesis of these structures. It was injected upward into the anticlines along a strike from a basal décollement, and eventually encountered the slope and initiated basinward raft-sliding systems. Large allochthonous salt bodies thus developed.

We propose a model in which the North Jebilet Fault, the North Atlas Fault, the shelf margin flexure fault, the basal décollement underlying the Cap Tafelney fold belt, and the south Atlas Fault merge together into a mid-crustal decoupling-level revealed by other geophysical studies.

A great variety of salt-related halokinetic and halotectonic structures were thus identified, including gentle salt-cored folds and pillows, compressional diapirs, salt withdrawal synclines, and completely allochthonous pluri-kilometric salt sheets and canopies in the deep offshore basin. This offers a great variety of favorable settings for possible hydrocarbon traps.

Continental and coastal sabkhas of Bar Al Hikman, Eastern Coast, Sultanate of Oman

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The Bar Al Hikman sabkhas develop on the landward portions of a shallow-water, high-energy carbonate system, under arid southwest Monsoon climate conditions. Strong winds, together with extremely limited rainfall, lead to a net evaporation of 1,000 mm/year. The continental aquifer is driven by rainfall on the Oman Mountains. NNE-trending faults feed freshwater springs nearby. Free-water levels in saline ponds near the southern tip of the peninsula have risen slowly over the 2001-2006 period, after little to no rain in the mountains from 1995 to 2000.

High-resolution satellite images clearly show the patterns of Holocene geomorphic features upon which the sabkhas are forming. On the periphery of the peninsular, beach ridges, lagoons, and littoral bars have accreted seawards. Inland on the peninsular, sabkhas overlie stranded or upraised lagoonal deposits, with shelly beach ridges and bars, tidal channels, and sand flats. Preliminary dating of corals from the peripheral carbonate system suggests that the lagoon records the 6,000-year BP sea-level maximum. Continental sabkhas, driven by the regional aquifer, are dominated by gypsum precipitation, whereas coastal sabkhas fed by seawater form thicker inland halite accumulations.

The present-day superposition of younger sabkhas, developing below a surface cut into older sabkhas, is clear from the erosion and surface exposure of corroded gypcretes. Ongoing studies should help to establish whether or not there are two distinct phases of sabkha formation. The evaporite system may be under continuous development, with local superposition of sabkha profiles resulting from fluctuations in aquifer depth and wind-driven erosion patterns.

The upper Arab Formation: Is the present really the key to the past?

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The upper part of the Arab Formation is one of the most prolific reservoirs in the Middle East Gulf Region and in the world. The complex, fine-scale intercalation of dolomitic and anhydritic units poses a number of operational challenges at both the exploration and production scales. These are linked to two fundamental issues: (1) the sedimentological and sequence stratigraphic interpretation of evaporites and their relation to the carbonates, and (2) the diagenesis and remobilization of anhydrites. In order to address these issues, a core thin-section and geochemical synthesis of a number of cored upper Arab wells was studied.

The 3-D facies mosaics are extremely complex, especially for the evaporites where complete gradations between facies types are present. A simple supratidal sabkha versus deep subtidal salina model is too simplistic – there are numerous types of evaporitic facies, complete gradations between evaporite types, and they can occur across the whole depositional profile. Moreover, late-stage anhydritization and the development of "later" replacive nodules can also cause problems as not all nodular anhydrite-rich units are syn-sedimentary or early diagenetic in origin. The majority of the evaporites in the study window are various types of sabkharized shallow salina and sabkha deposits. Also important are zones of later replacive nodules. The sabkha and salinas deposits of the study window appear to be significantly different from the sabkha deposits of the present-day Gulf in terms of facies characteristics and facies cycles.

The principal conclusions are: (1) understand the anhydrite facies and diagenesis are key in mixed dolomite-anhydrite reservoirs, (2) do not over-rely on uniformitarianism (actualism) for understanding the evaporites deposits and anhydrites (not all evaporites are sabkha, not all anhydrites are syn-

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sedimentary/early diagenetic), and (3) there can be significant amounts of anhydrite mobilization and post-depositional changes. These issues will have an impact at the regional-scale by providing a predictive stratigraphic model in terms of facies organization and reservoir quality, and at the reservoir-scale by refining reservoir layering schemes and petrophysical groupings.

Geological evolution of Qatar sabkhas during the Holocene: An alternative to the facies model of the United Arab Emirates

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Holocene sabkhas of Qatar are undergoing a revival as an alternative to better-known sabkha models of the United Arab Emirates. Although Qatar's sabkhas were well documented in the 1960s and 1970s, differences in facies patterns and diagenesis are not widely appreciated. The observations made nearly forty years ago were extremely perceptive and have stood the test of time. This paper draws attention to some of the major features of the Qatari sabkhas as an alternative to the better-known models from Abu Dhabi.

Most of the Qatar Peninsula consists of Tertiary dolomite bedrock overlain by a few meters of Pleistocene limestones in coastal areas. The Holocene (typically 2 m thick) infills topographic lows inland, and thickens seaward to a maximum of approximately 10 m. Qatar's sabkha facies vary considerably, depending on the frequency of marine flooding. Inland continental areas are characterized by a high rates of evaporation and precipitation of halite, gypsum, and pedogenic micrite. Surface features include pustulose gypsum crusts, salt flats, a scattered plant cover of bryophytes, and sand dunes. Continental sabkhas infill structural lows and shallow valleys incised during sea level low stands.

In coastal areas, large sabkhas are found in the lee of bedrock promontories and along protected shorelines. Strong longshore drift creates prominent beach ridges that build southward and refract into bays, similar to chenier coastal ridges of the US Gulf Coast. Landward of the beach ridges are typical sabkha facies: algal flats, gypsum flats, salt flats, soil crusts, tidal channel complexes, and mangrove swamps. Gypsum is the major authigenic mineral, occurring as a subaqueous precipitate in low-lying areas as disseminated laths and nodules just above the water table. During the Holocene sea-level rise, as many as five to six major cycles of beach ridge accretion and sabkha infilling occurred. Over time, this mechanism of punctuated spit accretion and infilling juxtaposes reservoir-prone, shoreline grainstones with more mud-prone, evaporitic sabkha facies.

Gypsum-anhydrite genetic relations in the Badenian Evaporite Basin of the Carpathian Foredeep, Southern Poland

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The Badenian (middle Miocene) sulfate deposits in the Polish Carpathian Foredeep basin have undergone varying degrees of diagenetic changes. They are preserved mainly as primary gypsum in the peripheral part of the basin, whereas toward the center of the basin they have been totally transformed into anhydrite. The facies variation and fabrics' succession reflect different genetic patterns of anhydrite, depending on both paleogeographic (linked to different parts of the basin) and burial controls.

In the peripheral part of the basin (the gypsum-to-anhydrite transition zone), abundant primary gypsum is still preserved. The irregular (patchy) distribution of anhydrite within the primary gypsum, sharp oblique boundaries between the two components, and the presence of large anhydrite pseudomorphs after gypsum in the lower section suggest that anhydrite was formed by replacement of the former gypsum deposits (Kasprzyk, 1995, 2003; Kasprzyk and Ort', 1998). Some nodular lithofacies show sedimentological and petrographic features distinctive of syndepositional anhydrite in modern settings (Shearman, 1985; Rouchy et al., 1994), which strongly suggest a sabkha environment and/or phreatic anhydritization processes. The formation of nodular lithofacies by early-diagenetic modification of former gypsum deposits at the surface (a process termed 'sabkhatization' or 'nodulization') was documented from the Salt Flat playa, West Texas (Hussain and Warren, 1989) and the Holocene evaporites in the Gulf of Suez, Egypt (Aref et al., 1997).

In the more deeply buried (> 500 m) part of the basin (gypsum totally replaced by anhydrite), anhydrite lithofacies (mosaic, nodular-mosaic, massive) display common pseudomorphic structures of selenitic gypsum, some of them resembling crusts of vertically oriented gypsum crystals in modern salinas (e.g. Warren, 1992; Ortí Cabo et al., 1984) Thus, the nodular lithofacies of the Badenian sulfate deposits could be interpreted by two different hypotheses: (1) early-diagenetic evaporites formed in subaerial settings, or (2) mostly subaqueous deposits of hypersaline coastal lagoons or sub-basins subsequently subjected to early-diagenetic modifications (anhydritization) in surficial to shallow-burial environments.

Laminated anhydrites and breccias of the upper section are interpreted as originally gypsum-dominated clastic deposits derived from the reworking and redeposition of the former deposits. Evidence for this comes from the abundance of pseudomorphs after gypsum, the presence of intraclasts, common intraformational redeposition features, and the incorporation of terrigenous material within the anhydrite. In the distal parts of the basin, this association, which displays features characteristic of slope-basinal deposits and extensive pseudomorphic fabrics after sandy gypsum laminae, originally also comprised gypsum resedimented facies. Frequent compaction effects affecting the anhydrite fabrics suggest that anhydritization of the gypsum could have started during early diagenesis and continued during burial (Kasprzyk and Ort', 1998).

Micronodular laminites are one of the most representative lithofacies of the basinal anhydrite (the anhydrite-halite transition zone). In some respects, this lithofacies resembles micronodules described from other evaporitic formations, whose origin may have various explanations (e.g. Richter-Bernburg, 1985; Rosen and Warren, 1990; El Tabakh et al., 1998). The petrographic observations of the Badenian micronodular laminites suggest syndepositional formation of micronodules by displacive, interstitial anhydrite growth within laminated bottom sediments. In addition to this *de novo* anhydrite growth, the gypsum of the bottom sediments was transformed into anhydrite by circulating pore fluids of high salinity and ionic strength.

The sedimentary and petrographic observations indicate that anhydritization of gypsum deposits in the Badenian basin was a complex and long-lasting process starting under synsedimentary conditions and continued in burial (during early to late diagenesis). Different genetic patterns of anhydrite involve both synsedimentary anhydritization of gypsum and successive phases (syndepositional *de novo* growth, early to late diagenetic replacement of gypsum) of anhydrite formation with progressive burial.

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First view of the cyanobacterial mats and strandline evaporite/ carbonate deposits of Abu Dhabi: A personal retrospective

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The late 1950s and early 1960s ushered in a period of intense study of Holocene sedimentary systems and their comparison to the ancient geologic section. The geological community at large had little information on the character of the southern shore of the Arabian Gulf. Initially in 1962, Imperial College of London fielded a series of expeditions to study the coastal lagoons of Abu Dhabi. This paper recalls the events through 1963 to 1965 that befell Patrick Skipwith and myself as we first mapped the largest algal flat that parallels the coast of the Khor Al Bazam for 42 km, and a smaller one that parallels the coast for some 9 km in the vicinity of Khusaifa. The presentation traces our arrival from Iran to Dubai, our trip across the desert to Abu Dhabi, and how we eventually reached and studied in the Khor al Bazam, particularly the wide, long, algal tidal flat and flanking coastal evaporites or sabkhas. These field studies were conducted from a small 20-ft open diesel-powered dingy and locally hired Land Rovers at a time when Abu Dhabi was without roads and most people lived in houses woven from the date palm fronds.

These studies established that these mats have an average width of about 2 km and are underlain by some 5–30 cm of compacted peat-like remains of living algae and bacteria lying on the seaward edge of the prograding coastal plain. We were able to investigate the hypothesis that the modern algal sediments that occur in these settings may also have been present in similar ancient sequences, and consequently could account for the occurrence of petroleum in these sequences. We now believe that the association of concentrations of organic matter interbedded with carbonates and evaporites of the Holocene were common in the geological past, and may represent a potential source-rock. A number of major oil fields in the Arabian Gulf, the USA, and in other parts of the world occur in ancient carbonate/evaporite sequences similar to those of the study and could also have contained similar algal deposits.

Holocene geomorphology and recent carbonate-evaporite sedimentation within the coastal region of Abu Dhabi, United Arab Emirates

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Seaward reefs, barrier islands, and tidal flats characterize the Holocene shallow-water carbonate and supratidal evaporite tract that lines the UAE coastal embayment of the southern Arabian Gulf coast. The entire province has undergone constant change. An offshore bank is accreting seaward through the agency of coral growth and tidal delta formation. South of these banks, supratidal flats are encroaching on the lagoons with the development of beach ridges and algal flats. The sediments of this coastal region mark the transition between landward continental facies and seaward basinal facies. Traced from the east, the Holocene coast of Abu Dhabi trends northeast-southwest and is composed of a macrotidal barrier/lagoon complex that narrows northward. To the west, in central Abu Dhabi, the protecting barrier islands are more widely spaced than those to the east. They are sited on extensive carbonate shoals and coral banks cut by tidal channels. South of the barrier is a continuous open body of water, the Khor Al Bazam lagoon. Its circulation is less restricted than the lagoons to the northeast and its western end is connected to the Arabian Gulf.

The character of the Holocene sediments of central Abu Dhabi matches the physiography of this coast. Coral reefs grow along most of the offshore banks; in contrast, ooids collect in the east on the inter-island tidal deltas and coral reefs are restricted to small patches. In the central area to the west of the Al Dhabaiyah Peninsula, carbonate muds accumulate as a narrow belt south of the offshore bank. Grapestones and skeletal debris are the dominant components of the inner western coastal terraces. Eastwards, extensive barrier islands protect the lagoon so that instead of a coastal terrace, a widespread intertidal cyano-bacterial mat occurs seaward of supratidal flats that are the site of evaporite accumulation. In eastern Abu Dhabi, protected lagoons occur to the leaside of the barrier islands and are the site in which carbonate mud and pellet accumulate.

Coastal Abu Dhabi carbonates and the role of cyanobacteria in their diagenesis – significance to ancient carbonates with micritic envelopes

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The coastal sediments of the United Arab Emirates are accumulating at a low latitude, under arid conditions adjacent to the gently sloping ramp-like bathymetry of the southern Arabian Gulf. This setting has favored the extensive development of an arid coastline system with a variety of different shallow carbonate and evaporite depositional settings. Carbonate sand and mud are accumulating and prograding on the offshore bank flanking the Khor Al Bazam of the western Abu Dhabi mainland coast. North and seaward of the Khor Al Bazam lagoon, the offshore bank is progressively extending an area of shoals and channels, coral banks, tidal deltas, and nearshore coastal terraces. Where wave energy is minimal, cyano-bacterial mats colonize protected intertidal sediments, building seaward and binding any sediment washed onto them. This sediment surface is raised to the high-water mark, and the cyano-bacterial mats become incorporated beneath prograding supratidal carbonate/evaporite coastal sabkhas. Locally, mangroves flourish in tide-dominated areas that are protected from all but the smallest waves. This aids the entrapment of sediment later colonized by algal mats. Local beach ridges extend as spits that have beach faces, berms, and dunes. Where the beach line is stranded by coastal accretion, these dunes are deflated. Landward of the beach ridges, sediment accumulates, transported here by the wind and by the floodwaters of storm wash-over.

Understanding of the evolution of the Holocene sediments in this area has been established by field studies. These show that the shoal and channel area were once part of the offshore bank complex. Most of the protected coastal lagoonal areas of the United Arab Emirates are being encroached on, and are covered by shallow to intertidal carbonate sediments, algal mats, and sabkhas. These latter facies extend back to the lines of stranded beach ridges that rimmed these lagoons before they were filled. Ooids, grapestones, pellets, muds, and bioclastic grains of the region are often altered on their surface by cyanobacteria. This micritization coats and alters the grains so their origin is often only possible to discern from their external shape while their interiors are completely altered to micrite. This alteration and development of micrite envelopes on the grains matches that found coating particles associated with ancient settings and can be used as evidence for extended exposure on the sea floor.

Organic and carbon isotopic geochemistry of the lagoon-sabkha system of Abu Dhabi, United Arab Emirates

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The three main sources of the organic matter preserved in transgressive and regressive Holocene sediments of Abu Dhabi sabkha are seagrasses, *Avicennia* mangroves, and microbial mats. The hydrocarbon and isotopic compositions of these three sources are distinct. The modern microbial mats, which contain low molecular weight branched and straight-chain hydrocarbons (C_{16} – C_{20}), have an average total organic carbon isotopic composition ($\delta^{13}C_{TOC}$) value of -11.7 ±1.4‰ versus VPDB (n = 10), identical to that of Holocene microbial mats (-12.1 ±1.1‰; n = 6). *Avicennia* paleosols have a classic distribution of long-chain *n*-alkanes (C_{21} – C_{33}) derived from of higher plant epicuticular waxes and have an average $\delta^{13}C_{TOC}$ value of -25.3 ±0.4‰ (n = 2), characteristic of higher plants assimilating carbon via the C_3 pathway. Seagrass containing sediments have an average $\delta^{13}C_{TOC}$ of -12.6 ±0.6‰ (n = 2), typical of C_3 subaqueous plants, but a hydrocarbon fraction dominated by C_{21} and C_{22} highly branched isoprenoids and long-chain *n*-alkanes (C_{21} – C_{33}) with an odd-over-even carbon number predominance. Compound-specific carbon isotope analyses of the hydrocarbons derived from these sediments reflect the diversity of bulk isotopic data. The extractable hydrocarbon distribution observed for modern and Holocene microbial mats does not match that of ancient microbial sabkha deposits. However, the kerogen pyrolysate of a Holocene microbial mat and the extract of a laminated anhydrite from the Khuff Formation (Permian, Saudi Arabia) show strong convergence (similar distribution of monomethyl-alkanes; C_{15} – C_{29}), confirming the microbial nature of the organic matter preserved in ancient sabkha evaporites.

Chloride and sulphate deposits, Abu Dhabi Coastal regions

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The evaporites of the Abu Dhabi coastal areas are dominated by sodium chloride (halite) and calcium sulfates (gypsum, hemihydrate, and anhydrite), which are generally accepted as originating predominantly from marine waters that intermittently flooded the coastal sabkhat surfaces or saturated the subsurface of the seaward margins of the sabkhat throughout the last 4–6 thousand years. These evaporite distributions are discussed mainly in relation to the late Holocene coastal sabkha evolution, which was dominated by progradation under forced regression due to a relative sea level fall of about 1–2 meters, although there is some evidence to suggest that transgressive anhydrites also occur. Deformation structures and probable micro-karstification features are displayed by these evaporites and raise questions regarding the processes that have affected the coastal sabkhat environments. The halite accumulated mainly as surface precipitates constituting ephemeral salina deposits, but also occurred as more persistent deposits within the subsurface of continental sabkha. The sulfates have traditionally been interpreted entirely as pedogenic deposits formed either within the capillary zones or beneath the water tables of the coastal sabkha. However, there is increasing evidence to suggest that significant volumes of the Holocene sulfates originated as gypsum salina deposits. Example exposures of Pleistocene and Miocene gypsum salina deposits are also discussed.

Vanished evaporates, carbonate replacement, and bacterial sulfate reduction

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Vanished evaporites are well documented in the geological record, but many may go unrecognized because of a lack of obvious field or petrographic evidence, particularly in organic-rich carbonates deposited in restricted settings where bacterial sulfate reduction (BSR) was active. An early stage in evaporite replacement by carbonates may be observed in modern salterns in Eilat, where gypsum crusts are colonized by stratified, endoevaporitic microbial communities including sulfate-reducing bacteria (Sørensen et al., 2003). Here, BSR can be associated with gypsum dissolution and replacive carbonate formation. Rapid consumption of aqueous sulfate by SRB is illustrated in the ephemeral Coorong lakes of South Australia, where extremely high concentrations are completely removed by intense BSR during evaporation so that no solid sulfate precipitates. Here, carbonates form as the consequence of mediation of ambient waters by BSR, with sedimentary pyrite providing the only indication of the former presence of dissolved sulfate in the lake waters (Wright, 1999; Wright and Wacey, 2004).

Pyrite patches in the patterned dolomite facies of the largely evaporitic Jurassic Arab Formation have been interpreted as 'birds eyes' or fenestrae, but show no signs of porosity. A hostile environment mitigates against their interpretation as burrows, although some form of root pseudomorph is not ruled out. However, it is more likely that the pyrite is related to BSR operating in a hypersaline, microbially-dominated environment in which solid sulfate removal and sulfide formation is followed by dolomite formation (Kirkham, 2004).

Field and petrographic evidence from bedded strata and thin sections of the Neoarchaean Gamohaan and Kogelbeen carbonate formations of South Africa argue for the former existence of evaporites, and suggest deposition in mainly shallow subtidal and sabkha environments. On the macroscale, cross-stratified grainstones showing multiple directions of sediment transport, together with abundant microbialites and rare, well-preserved cyanobacterial fossils, indicate shallow-water deposition and microbial growth in the photic zone. Tepees and large tepee-like fold structures, intrastratal karst, pseudomorphs after evaporites, replacive calcite after selenite, solution collapse breccias, autobrecciation, corrosion surfaces, nucleation cones, irregular bedding contacts, and flowage structures are all indicative of evaporites, their dissolution, and their replacement by carbonate.

Replacement was largely fabric destructive, leaving few obvious clues at the microscale as to the former presence of vanished evaporites other than diagenetic recrystallisation, deformation, disruption, and crosscutting relationships, although length slow chalcedony in silicified stromatolite heads may suggest the former presence of sulfates (Folk and Pittman, 1971). However, fold shapes indicative of enterolithic gypsum, picked out by trails of degraded organic matter and dolomitized clusters of folded filaments preserved within replacive calcite, are evident in thin sections of contorted microbialites.

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Anhydrite, its occurrence in carbonates, and impact on reservoir quality: Case studies from the Eocene carbonate reservoirs, Kuwait

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The 2nd Eocene Dolomite Reservoir, first discovered in 1953, is a key-producing reservoir in the giant Wafra field located in the Divided Neutral Zone on the southern border of Kuwait and the northern border of Saudi Arabia. The Paleocene-age reservoir has been producing since the late 1950s, principally

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under depletion drive with partial solution gas and limited aquifer support. However, the recoveries remain low, mainly due to low-gravity viscous oil, lithology and reservoir heterogeneity, and the limited aquifer drive. A better understanding of the reservoir heterogeneity is a prerequisite for evaluating and implementing future development and EOR technologies.

The primary porosity in the subtidal dolomitized carbonates is generally high but partially or entirely modified by later dolomitization, dissolution, and cementation. Porosities are inter-crystalline; however, moldic, intra-crystalline, and fracture porosity are also observed and reported. The reservoir structure is further complicated by evaporites, mostly in the form of anhydrite. Anhydrite is found in nodular, nodular mosaic, and massive bedded forms, as well as pore-occluding cements. Discrete anhydrite nodules are observed with various sizes from very small pinpoints to boulder size exceeding the well-core diameter. The abundance of anhydrite varies significantly, both vertically and laterally, throughout the field. Its lateral variation is revealed by the many vertical wells drilled in the field and has been more recently evaluated by a number of horizontal wells. Core, high-resolution image logs, and open-hole logs together provided key data to recognize the anhydrite, its occurrence, and abundance. The regional distribution of the anhydrite significantly impacts the pressure and permeability distribution within the reservoir. Its effects on reservoir quality are assessed with integration of dynamic data, such as mobility data from wireline formation tester. This allows for definition of the better, inferior, and non-reservoirs zones in a systematic manner. Better understanding of reservoir properties and heterogeneity assists in targeting different reservoir zones for maximum oil drainage, selecting zones for acid jobs, planning for horizontal wells, as well as reserve estimation and field development plans.

Lithofacies, palynofacies, and organic facies of Triassic evaporitic-carbonate succession: Examples from Croatian offshore and Syrian onshore wells

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Evaporitic–carbonate deposits have been penetrated in the exploration wells from the Croatian offshore (e.g. Kornatimore-1, Vlatka-1, Vlasta-1) and Syrian onshore (e.g. Jihar-1, Al Mahr-1 and Mrah-2). Palynostratigraphically, the evaporitic–carbonate successions of both regions, which contain characteristic “Onslow” palynoflora, are approximately isochronous and were deposited during the latest Ladinian, Carnian, and Norian times. By means of petrographical, palynological, organic geochemical, and wire logging analyses, these successions have been studied in order to recognize their lithofacies, palynofacies, and organic facies features and to correlate the similarities and differences of their depositional environments.

The oldest sediments of the evaporitic–carbonate succession in Vlasta-1 well are assigned to the latest Ladinian and they consist of dolomitic limestone, early-diagenetic dolomite, anhydrite, and salt, which alternate with marl, siltite, and fine-grained sandstone. In Syrian wells, the corresponding deposits are represented by interbedded dolomite, limestone, anhydrite, shale, and claystone, which are regularly multiple repeated. The deposits of this section were deposited within restricted tidal flats to supratidal settings.

The “Main salt body,” the most noticeable lithofacies of the evaporitic–carbonate succession, has been identified in both regions as a Carnian event. It consists of glassy salts with frequent intercalation of dark, dolomitic claystone/shales and acicular anhydrites with relicts of argillaceous dolomites, and its total thickness is up to 650 m. The “main salt body” is the result of cyclically controlled deposition within the intertidal to supratidal saline environment. Other Carnian evaporites are composed of anhydrite with early diagenetic dolomite and salt, with intercalations of dolomitic claystone/shale being deposited in a broad area from restricted shallow marine to supratidal environment.

The succeeding evaporitic–carbonate deposits contain Norian palynoflora. The upper sections of the Norian in both regions are characterized by the termination of the “Onslow” palynoflora, which are completely replaced by the Circum-polles dominated palynoflora. In Syrian wells, the Norian deposits consist of dolomitized mudstone, mudstone/wackestone, and packstone together with medium crystalline, partly anhydritized dolomite. In places, very fine crystalline argillaceous dolomite and mainly acicular anhydrite, with relics of argillaceous dolomite laminated with dark dolomitic claystone, predominate. In Croatian wells, anhydrite and early-diagenetic dolomite predominate. The lower section of the Norian in Croatia may be regarded as supratidal, whereas the upper section indicates lagoonal intertidal settings. The Syrian section throughout the Norian revealed periodical open-sea influence within restricted tidal flat settings with low terrestrial influence. The Norian successions were deposited in a broad area from restricted shallow-marine (tidal flat) to supratidal settings. The deposition of the evaporitic–carbonate successions terminates at the end of the Norian.

The investigated organic facies is mostly amorphous with sporadical traces of liptodetrinite. Appearance in transmitted, reflected, and blue fluorescent light displays thermal alteration, i.e. catagenetic stage in thermal evolution. Gas chromatograms of saturate fractions of soluble organic matter show domination of phytane over pristine and a smooth *n*-alkane profile that reaches a maximum of about n-C_{16} to n-C_{20}. This type of distribution is characteristic for sediments containing organic matter of microbial and/or algal origin deposited under reducing conditions. However, some chromatograms display a lower degree bimodal distribution of *n*-alkanes, presenting the input of terrestrial organic matter. The palynological composition of organic matter is consistent the with the organic facies features.

The evaporitic–carbonate successions of both regions contain "Onslow" palynoflora which characterizes successions of continental margins that surrounded the western and southern Tethys. Accordingly, the latest Ladinian–Norian evaporitic–carbonate successions from Croatia and Syria belonged to the same paleogeographic province. The most striking common feature of the studied successions in both regions is the cyclic sedimentation. These cycles were driven by cyclical variation in rainfall, aridity, in-flux of clay–silt fines into the shallow basin, repeated isolation of the basin, and repeated phases of evaporate precipitation. Therefore, the environmental model in which these successions were deposited corresponds to the tidal-flat environment, which many times became lacustrine through repeated interludes of evaporite precipitation and isolation from sea water. A high subsidence rate, balanced with eustatic changes and evaporation rate, enabled the accumulation of up to 1,800-m-thick evaporite–carbonate deposits during the latest Ladinian–Norian times. Some differences of lithofacies, palynofacies, and organic facies features reflect locally controlled environmental conditions (paleorelief, a source of both inorganic and organic terrestrial material, run-off episodes, nutrient availability, primary bioproduction, etc.).

Depositional environment of the Triassic carbonate-evaporitic "megacycles" in the central Palmyrides, Syria

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In the wider area of Central Palmyrides, the carbonate-evaporitic succession, because of its newly emerging exploration potential, has been studied in more detail. In Syria, deposits from Lower Triassic (Amanus Shale Formation) and Middle Triassic (Kurrachine Dolomite Formation) to Upper Triassic (Kurrachine Anhydrite, Butmah, Adayah, Allan, Mus, and Sergelu formations) comprise various carbonate types intercalated with shale, claystone, anhydrite, and salt. Thicknesses of the entire Triassic succession vary from 1,000 to 2,100 m.

At a regional scale, the Neo-Tethys Ocean was in the process of creation simultaneously with the mid-Permian break-up of the Gondwana Supercontinent. The Eastern Mediterranean Basin opened at that time, and the position of Syria changed from an east-facing to a west-facing passive margin in the Arabian Plate. Moreover, the Arabian Plate moved from high to warmer low latitudes. A widespread transgression resulted in the change from the Paleozoic and predominantly clastic section to mainly carbonates and evaporites with minor shale.

During the Triassic, following the Permian rifting along the Palmyride trough, synrift deposition was represented by sandstones and shales with an increasing proportion of carbonates in the uppermost part of the Amanus Shale Formation. At the end of the Early Triassic, rifting terminated as marked by an extensive unconformity that separates the synrift succession from the post-rift Middle Triassic deposits. Locally, in the Central Palmyrides and especially towards its northern margins, subsidence and deposition continued from Early Triassic to Mid-Triassic.

From Mid- to Late Triassic, deposition was exclusively limited to an extensive carbonate platform. The geometry and bathymetry of the depocenter were mainly controlled by paleo-relief, sea-level fluctuations, and climatic variations. In general, five Triassic, predominantly shoaling upward "megacycles" are apparent. The internal architecture of each "megacycle" is complex and they also can be divided into many "lower-category cycles".

(1) The first "megacycle" occurred during the Anisian and is represented by the lower part of the Kurrachine Dolomite Formation. The lower part of the formation consists of dark gray shale interbedded with lime mudstone. It represents a shoaling upward 300-m-thick succession that was deposited in basinal or distal-ramp, to lower-shelf/ramp and upwards to intertidal-supratidal settings. The first cycle was capped with salt and/or anhydrite layer of variable thickness.

(2) The second "megacycle" is also represented by the Anisian Kurrachine Dolomite Formation and is approximately 100 m thick. It is informally known as the "post-salt transgressive shale" and the shale beds are interbedded with dolomite and limestone. This unit was deposited on a dominantly muddy, middle/lower to inner/shallow shelf, which shoaled briefly to tidal-flat conditions. It is capped by very thin anhydrite beds.

(3) The third "megacycle" is represented by the upper Kurrachine Dolomite and Kurrachine Anhydrite Formation and occurred in the Ladinian and Carnian. This cycle is more than 1,000 m thick. It started with a regional transgressive, deepening event that marked the onset of shale-dominated sedimentation. Deposition took place on a broad (1,000s of sq km), shallow basin with negligible relief (one meter to tens of meters over distances of km). The succession is characterized by numerous rhythmically repeated cycles that begin with clay/silt shales and end with Ca sulfates. The area was restricted and repeatedly isolated from the sea. The basin appears to have been a lacrustine or inland-sea system in which marine incursions appear to have been brief. The climate was dominantly arid. The end of the third cycle climaxed with the deposition of a very thick salt body of irregular thickness (in places more than 700 m).

(4) After the Carnian salt crisis, the depositional environment once again returned to a restricted shelf with carbonate, anhydrite pulsing deposition with minor shale (Butmah Formation). Progressive subsidence resulted with the deposition of "clean" open-shelf dolomite (Norian, Allan and Muss formations). The thickness of this cycle is about 400 m.

(5) The final Rhaetian "megacycle" is represented by the shales of the Sergelu Formation. This cycle ended with the regional emergence of the entire area.

In the western part of Central Palmyrides, the fifth "megacycle" and part of the fourth "megacycle" are missing either from erosion or non-deposition. The above-described "megacycles" are part of the Tectonic Megasequence AP6 (Sharland et al., 2001).

Dolomite formation beneath the Abu Dhabi sabkhas, United Arab Emirates: Then and now

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With the development of stable isotope geochemistry in the late 1950s and early 1960s, a number of investigators proposed using oxygen isotopes to interpret the environmental conditions promoting dolomite formation. However, the results of various and numerous isotopic studies proved inconclusive because the temperature-dependent oxygen-isotope fractionation factor for dolomite was unknown for conditions at the Earth's surface. The recognition of modern dolomite forming in association with other evaporite minerals, beneath the coastal sabkhas of Abu Dhabi in the early 1960s (Curtis et al., 1963), offered the ideal setting to measure the physico-chemical conditions of dolomite formation and to calibrate the oxygen-isotopic signal. The detailed sedimentological research conducted by Douglas Shearman and his colleagues at Imperial College, London, provided the framework in which to carry out a geochemical/hydrologic study of modern dolomite formation. In the early 1970s, K.J. Hsü (ETH-Zürich) undertook a research project on the Abu Dhabi sabkhas to test his hypothesis of dolomitization via "evaporative pumping". His doctoral students, J. Schneider and J.A. McKenzie, re-occupied the grid of studied locations previously investigated by members of the Imperial College group, and attempted to define the hydrologic and geochemical conditions of dolomite formation (McKenzie et al., 1980; McKenzie, 1981). The interpretation of the oxygen-isotope results was, however, hypothetical because it remained impossible to experimentally calibrate the oxygen-isotope fractionation factor between dolomite and the solution from which it precipitated at low temperatures.

The discovery of bacteria that can mediate the precipitation of dolomite (Vasconcelos et al., 1995; Vasconcelos and McKenzie, 1997; Warthmann et al., 2000) now makes it possible to overcome kinetic barriers and precipitate dolomite under controlled laboratory conditions in culture experiments. Using this technique, we have established an experimental oxygen-isotope fractionation factor and used it to re-examine data compiled on hypersaline pore water and dolomite sampled beneath the Abu Dhabi sabkha surface during a field season in 1973 (Vasconcelos et al., 2005). Using the late summer temperature of 38°C, which was measured between 21 and 32 cm below the sabkha surface, and the $\delta^{18}O$ value of the sabkha water at each sample location, we calculated the $\delta^{18}O$ values of the associated dolomite. The calculated and measured $\delta^{18}O$ values of the sampled dolomite are the same within experimental error, indicating that the sabkha dolomite precipitated in isotopic equilibrium with the pore waters at each location. These calculations confirm that the dolomite is a primary precipitate within the sabkha sediments. Moreover, the temperature of 38°C is the optimum growth temperature for the sulfate-reducing bacteria used in our experiments. This suggests that the rate of microbial-mediated dolomite precipitation would be the highest when the optimal conditions for the activity of the mediating bacteria occur.

In conclusion, more than 40 years ago, the research of Shearman and his colleagues provided extraordinary insight into the formation of modern dolomite in association with evaporites. This led to the formulation of the Sabkha Dolomite Model, which has been widely applied to interpret numerous examples of ancient evaporative dolomite. Now,

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with the introduction of a new Microbial Dolomite Model, we propose that the time is ripe to return to the unique environment beneath the Abu Dhabi sabkhas and introduce the microbial factor and a geomicrobiologic approach to update the original studies conducted in the early 1970s.

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Late Proterozoic "Dolomite Seas": Dolomite precipitation versus dolomitization

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In recent years, considerable evidence has been compiled that points to major variations in seawater chemistry during the Phanerozoic (e.g. Hardie, 1996). Various authors have proposed that these variations may hold the key to understanding dolomite formation in the geologic past. In particular, comparison of dolomite abundance with the secular variations in seawater chemistry over the past 550 My indicates that dolomite is relatively much more abundant during periods when calcite prevailed over aragonite precipitation, in so-called "calcite seas", and that KCl rather than $MgSO_4$ evaporites predominated (Burns et al., 2000). Indeed, dolomite appears to have been more abundant during periods when the Mg:Ca ratio of seawater was considerably lower than the modern value. This correlation is intuitively inconsistent with the thermodynamic factors thought to promote dolomitization, e.g. the Mg: Ca ratio of seawater must be greater or equal to one. In contrast, at the termination of the late Proterozoic Marinoan glaciation, the rock record is dominated by the ubiquitous formation of a cap dolomite. This global event apparently occurred within a period when "aragonite seas" prevailed (<550–925 Ma; Hardie, 2003), suggesting that the Mg:Ca ratio of seawater may not be as important an influence on dolomite precipitation as other controls, such as alkalinity or the redox state of the ocean. Evidence for such chemical changes have been induced from the large negative anomaly in the post-Marinoan carbon-isotope record, which has been interpreted to result from the oxidation of a massive amount of methane released at the end of glaciation. Methane oxidation on a global scale would have led to increased seawater alkalinity conducive to dolomite precipitation. Thus, with our better understanding of the microbial-mediated conditions involved in dolomite precipitation, we now need to reexamine the rock record to distinguish between primary dolomite precipitation in "dolomite seas" and secondary replacement dolomite, an artifact of post-depositional diagenesis.

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Selenite facies in marine evaporites: a review

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The term selenite facies is used here for evaporitic, *in situ*, primary precipitates of coarse-crystalline gypsum. The crystals forming these precipitates are characterized by a number of features: (1) they are organized in beds with variable thicknesses and fabrics, (2) they commonly display some type of competitive growth pattern, (3) they crystallize in shallow- to deeper-water settings, (4) they can develop twins or intergrowths, which are distinctive for each formation, and (5) they usually exhibit zonation owing to fine inclusions of the sedimentary matrix.

The study of marine selenite facies can be undertaken in coastal evaporative salinas (salt works) and in some natural coastal lakes where gypsum is precipitating or has been precipitating in recent times. The observations derived from these modern settings indicate that: (1) selenite facies require hydrochemical stable conditions, (2) the topography of the depositional floor exerts a control on the gypsum facies, and (3) some chemical elements, in particular strontium, can be used as indicators of the precipitating conditions.

In ancient evaporitic platforms and basins, the depositional gypsum was mainly constituted by two groups of facies:

(1) *Fine grained-dominated facies*. In deep basins, gypsum was characterized by fine-grained cumulates in association with fine- to coarse-grained slope clastics. In large platforms, the autochthonous precipitates were not so finely laminated, in general, and the clastic facies were mainly gypsarenites.

(2) *Selenite facies*. This group involves autochthonous, bedded precipitates of relatively pure, coarse-crystalline gypsum. Two major types are distinguished: bedded to massive selenites, and domal selenites. Locally, these facies are associated with nodular anhydrite levels of a sabkha environment.

Miocene examples of selenite facies are found in the Messinian of the Mediterranean region and the Badenian of the Carpathian Foredeep. In older formations, the identification of these facies has been hindered by intense diagenetic transformations undergone by many evaporites. In fact, occurrences of selenite facies do not refer only to the facies preserved as primary gypsum, but also to the ancient facies currently preserved as pseudomorphic anhydrite/halite in borehole or as secondary gypsum in outcrop. Criteria for deciphering the selenitic origin of some pseudomorphic occurrences are fundamental to the interpretation of evaporitic environments of the past.

Ancient marine occurrences of selenites cover a wide range of environments. The following settings can be distinguished: (1) coastal salinas, (2) flanking selenite shelves, (3) selenite platforms covering salt-filled basins, and (4) selenitic basins. The ancient occurrences of the *coastal salinas* refer to selenite layers formed in local coastal lakes, small lagoons, and small coastal basins. In general, the deposits are not very thick, except for a high rate of subsidence. The association with microbial mats and nodular anhydrite is common in these occurrences.

Flanking selenite shelves refer to selenite layers precipitated in inner troughs or shoals of platforms which are adjacent to evaporitic basins. In these settings, the individual selenite layers can be several meters thick, and the Ca-sulfate deposits as a whole often have thicknesses less than 100 m. In some cases, these shelves can be narrow (a few kilometers in width) and display slumping features. This type of narrow, selenite shelf represents marginal gypsum wedges, which precede sharp falls in water level leading to the basin infilling with salt.

The *selenite platforms covering salt-filled basins* refer to the occurrence of selenite facies as a significant part of the marine evaporites accumulated on a basin (and adjacent shelves) after its total infilling with chlorides. This platform has a rather flat topography, may cover large areas, and may display evaporitic cycles.

Selenite basins are depressions filled with selenite layers. These depressions are produced by the drawdown mechanism in topographically deep basins, although they never reach the stage of "desiccated basin." The progressive infilling with selenite layers results from a cyclic accumulation of shallow-water evaporites and deeper-water marls. Individual selenite layers can be 20–30 m thick and the evaporitic deposit can exceed 100 m.

All of these selenite occurrences depend on the existence of a constant outflow that prevents oxygen depletion or accumulation of chloride brines. Thus, the selenite occurrences imply specific configurations of platforms and basins, and are sensitive to changes in the sedimentological conditions. They are clearly separated from the halite deposits, which they precede, and they do not alternate with such deposits in the evaporite successions. These features also suggest a certain incompatibility between the precipitation of selenite facies and the accumulation of significant amounts of organic matter in the platforms and basins.

The impact of sea-level changes on ramp margin deposition: Lessons from the Holocene sabkhas of Abu Dhabi, United Arab Emirates

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Around the globe, the Holocene is replete with examples of the rapid accumulation and outbuilding of sediment wedges in response to, and associated with, a rise in sea level. It is particularly evident among the much-studied shallow water carbonate tidal flat associations and arguably, nowhere better displayed than by the sabkha cycle developed beneath us in Abu Dhabi. This cycle of rapid transgression and steady outward progradation throughout the last 10,000 years is but the most recent of a number of similar cycles that have been a characteristic of ramp margin sedimentation around the Arabian Gulf since the late Paleozoic and which, not incidentally, are home to huge reserves of hydrocarbons. These lie atop earlier rifted basin sequences, many salt filled.

The gently sloping ramp margin setting is one that is extremely sensitive to even minor fluctuations in sea levels. Thin high-frequency sediment cycles are their hallmark, and equally typical, they are accompanied by a similar multiplicity of diagenetic overprints that are a major factor in porosity generation within the prolific reservoirs beneath.

The sabkha cycle, as found along the Trucial Coast, is notable for: (1) extensive development of algal mats, (2) an early diagenetic cycle that sees gypsum altered to anhydrite (and back again at the slightest whiff of fresh water), (3) an almost total absence of halite, except in pockets where waters are ponded or in restricted basins that are allowed to evaporate to dryness (the thin skin of halite encrusting the surface after a storm flood is purely ephemeral), and (4) dolomite formation, which is an intimate and integral part of the sabkha depositional setting

Fluctuations in sea level, however small, bring dramatic changes to the sedimentation and groundwater chemistry of this environment, all of which can impact the rates of growth and destruction of the sequence. This may occur via increased erosion and ablation, leaching, alteration, and replacement of existing minerals and precipitation of new ones, to aerobic destruction of organic material. In this context, the preservation potential in such tidal flat facies, or lack thereof, should be recognized as an inherent feature of high frequency cyclicity.

Sedimentation of the middle Miocene Badenian Evaporites in the Carpathian foreland Basin

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The Carpathian Foreland Basin system is one of the largest sedimentary basins in Central Europe. It stretches from Austria to Romania and was formed in front of the advancing Carpathians. The Carpathian Foreland Basin hosts many methane-rich gasfields, both below thrusted Carpathian nappes and in the autochthonous zones. The basin system was generated on the interior side of a collision zone during lithospheric flexure of the East European Platform in response to a northward-stepping thrust load. The Miocene fill (locally > 5 km thick) consists of deep-water, shallow-marine, and deltaic siliciclastic sediments and evaporites. The deposition of those deposits initiated in early Miocene times and lasted at least until the end of middle Miocene. The middle Miocene Badenian evaporite deposits occur in most of the Carpathian Foredeep Basin; in addition, they occur in the foreland in Upper Silesia, Poland, and in the Opava region, Czech Republic. The age, correlation, and depositional history of the evaporites in different parts of the Carpathian Foredeep Basin are a controversial subject. Recent study of calcareous nannoplankton indicates that the Badenian sulfates of the Carpathian Foredeep represent the lower part of the NN6 zone.

Although the correlation of different Badenian evaporite facies is difficult (if at all possible), there are no such problems in the case of particular evaporite facies zones. The correlation between facies zones of the marginal sulfate platform was based on the occurrence of characteristic marker beds, as well as the observations made in areas transitional between the facies zones. The marker beds seem to reflect events that may be related to sudden and widespread changes in water chemistry, which in turn, imply major changes in basin hydrology. However, physical stratigraphic relationships between sulfates occurring in the marginal sulfate platform, sulfates from the sulfate basin, and the relationship between areas of halite and sulfate deposition remain enigmatic.

The Badenian evaporites are characterized by the occurrence of thick mappable units forming a narrow strip in the axial part of the basin (halite deposits), and are developed as a sulfate wedge at the basin peripheries. Halite deposits show the same facies successions and marker beds can be traced across and between individual basins. This lateral continuity of facies and events is best explained by an extra-basinal control such as eustatic changes. Based on the observed facies changes, it seems that the Badenian evaporite basin was located within a depression in which the brine top-level was located below the contemporaneous sea level. Accordingly, during sea-level rises, a new slush of marine water could enter this depression and bring with it a marine fauna. Basin-marginal Badenian evaporites formed in a standing body of water, as well as in desiccated environments subject to floods. The lateral persistence of thin beds over large areas (often over the distance of 500 km) with only minor changes in thickness and facies indicates that they formed on broad, very low-relief areas that were affected by rapid transgressions that led to major changes in brine chemistry. Sedimentological data (presence of gypsarenites or evaporite breccias) and geochemical data (the modeling results showing that the continental water was the main inflow) indicate “cannibalization” of the evaporites throughout most of the evaporite's depositional times. Primary shallow-water evaporites from the margin of the evaporite basin, which was adjacent to the Carpathian orogen, are absent and were deposited in deep-water settings. The orogen also controlled the sedimentary history in the basin foreland as indicated by the shoreward migration of the sabre gypsum facies in the Ukrainian part of the Carpathian Foredeep basin during the course of Badenian gypsum deposition. A general transgressive sequence of evaporites, as found in the marginal sulfate platform, results from the migration of facies zones that was induced by the nappe movement.

The scenario of events leading to the deposition of widespread evaporites, being a synchronous event in the Badenian, is not established in detail. Isotopic studies of Badenian foraminifers occurring below and above evaporites suggest that the interrupted communication of the Paratethys with the ocean was a consequence of eustatic sea-level fall, possibly related to climatic cooling. However, a tectonic closure of the connection with the Tethys could also contribute to the origin of the salinity crisis. The cannibalization at the end of gypsum deposition in the marginal sulfate platform was accompanied by block-tectonics. This resulted in the creation of a bathymetric difference of at least a few tens of meters as indicated by the occurrence of the Ratyn Limestone on stratigraphically different parts of the gypsum section. It was accompanied by a change in the hydrology of the Central Paratethys that was tectonically driven, and possibly related to the block tectonic phase manifested in the marginal part of the Carpathian Foredeep Basin. The change in hydrology implies the dilution of brines by inflowing marine water and this terminated the Badenian salinity crisis.

Fossil whale skeleton in Abu Dhabi's coastal sabkha

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The fossil skeleton of a whale was recently discovered in sabkha sediments near Abu Dhabi, United Arab Emirates. Large bones were found protruding from sabkha sediments in a small cliff face on the bank of a man-made channel, slowly eroded by tides and storms. These large bones, recently exposed in the cliff face and embedded in shallow-marine sediments that are between 4,000 and 7,000 years old, were identified as the jaw bone, the top of the humerus, and the radius of a whale beached or stranded in very shallow water several thousand years ago. The layers in which the skeleton is embedded are, for the most part, intertidal to shallow subtidal and represent tidal flats, beaches, and storm-derived beach ridges. Part of the skeleton has been excavated, and has been provisionally identified as being that of a Blue Whale, *B. musculus*. This is the first sub-fossil whale skeleton to be found in the emirates and the fact that it appears to be that of a blue whale, the largest animal on earth today, is rather surprising. Excavation and conservation of the remainder of the skeleton is planned for late 2006, with the support of the Environmental Agency – Abu Dhabi, EAD. Samples will be sent for DNA analysis in order to determine the exact genetic relationship of this individual to present-day populations of blue whale, while consideration is also being given to radiocarbon dating to try to determine its precise antiquity. It is hoped that careful excavation may yield some insight into the sequence of events that led to it beaching here.

Holocene carbonate and evaporite sedimentation in the Arabian Gulf: A critical review

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In looking at past achievements, one should be critical. Subsequent experience enables us not only to congratulate ourselves but, especially, to critically evaluate our past research. In so doing, we may contribute to future progress. Past research, both in Qatar and in Abu Dhabi, has made important discoveries, notably relating to sabkha sedimentation and diagenesis such as the discovery of Recent dolomite on Sabkha Faishakh (Qatar) and anhydrite (Abu Dhabi). However, I feel that we could have had a broader approach but *we were frightened to get our feet wet*! The Gulf is much more than a big sabkha. It has both a stable (cratonic) shoreline in Arabia, a tectonically active coast in Iran, and a major delta - the Tigris-Euphrates - located near the structural axis of the basin. Thus, there exists the unique possibility of studying carbonate-evaporite and siliciclastic transitions.

In the 1960s and 1970s, we were concerned mainly with sedimentation, neglecting the structural frame and its influence on sedimentation. This was not logical for the application of our research to petroleum exploration and development passes via structure. Structural control within the Gulf exists on all scales - the global constraints are conditioned by a distensive regime in the Red Sea whose consequences are the compressive systems, notably in Iran. On a more local scale there exist many highs in the Arabian Gulf whose bathymetric relief strongly influences modern sedimentation. Finally, sabkha sedimentation in Abu Dhabi is conditioned by the presence of a major offshore barrier whose origins, to my knowledge, have not been determined.

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The structural setting of sabkha evaporites was not sufficiently exploited. The situation was better appreciated when we shifted our research to the Red Sea where sabkhas are insignificant. Under these distensional settings, evaporites and organically rich sediments are located along the deep axis of the rift where their setting contrasts with the peripheral sabkha evaporites concentrated along the stable Arabian coasts.

Many discoveries were made concerning the sabkha environment. Initial workers such as Illing, Wells and Taylor in Qatar, and, subsequently, Imperial College (Shearman et al.) in Abu Dhabi, located modern marine dolomite and anhydrite. However, I feel that we did not fully exploit these major discoveries. The general impression (at the time) was that dolomite was forming in a zone more or less parallel to the shoreline. We failed to appreciate the fact that the sabkhas were not comprised only of parallel zones; they are drained by a complex system of tidal channels that are filled progressively with coarser sediments, possible conduits for refluxing dolomitizing fluids. Many ancient reservoirs are developed in dolomitized channel sediments.

Finally, although we did discover active dolomite formation, I doubt whether we really solved "the dolomite problem". By making the most of this modern dolomite-evaporite laboratory we could (should) have placed various, carefully calibrated samples of sediments within the zone of active dolomitization. We were over-concerned with interstitial waters and less concerned with the physical changes from aragonite to dolomite. Where does dolomite nucleate? Does organic matter play a role in this nucleation? And what happens to this "protodolomite" and anhydrite as the sabkha progrades and meteoric waters along the inner margins of the sabkha influence these presumably unstable minerals?

Geochemistry of the Pleistocene/Holocene carbonate-evaporite sediments of the Khiran Area, southern coast of Kuwait

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The coastal sabkhas in the Khiran area in south Kuwait provide insights into ancient carbonate-evaporite sequence interpretations. The Khiran area is dissected by relatively large and wide tidal creeks that cut through a sequence of five Pleistocene to Holocene oolitic beach/dune ridges, with elevations not exceeding 15 m above sea level. The generation of these ridges during high stands of sea level led to the development of a sabkha towards the land. The complex of the Pleistocene-Holocene sediments of the Khiran area represents a petroleum setting, where organic-rich source sediments of lagoons are closely associated with porous potential reservoir rocks of the oolitic ridges. Consequently, studies of the petrography, mineralogy, trace elements,and organic geochemistry for the carbonate-evaporite exposures along the southern coast of Kuwait were carried out to evaluate the physical and chemical conditions of the depositional environments of the sediments and to investigate their diagenetic history.

The study of the grain-size distribution and parameters indicates that the coastal areas, near their connection to the open Gulf, and the mouth of the tidal creeks are dominated by coarse-grained, moderately-sorted beach carbonate sands, with low amounts of organic matter (TOC = 0.3%wt). The Recent shoreline carbonate sediments consist mainly of aragonitic ooids with tangentially arranged cortices, some aggregates, and intraclasts. Large molluscan shells, calcareous algal fragments, and foraminiferas (*textularins*, *miliolids* and *rotaliids*) are the main skeletal components. Landward, at the ends of the creeks, the concentration of ooids decreases, where silt-clayey sediments composed mainly of pellets and calcareous mud interbedded with algal mats are found. This low-energy setting revealed relatively higher organic matter content (TOC = 0.9%wt.), compared to the sediments deposited at the mouth of the tidal creek.

The Pleistocene oolitic limestones are elongated, cross-bedded, thinly-laminated ridges of carbonate sands, directed parallel to the strong tidal currents. The sediments are composed entirely of well-sorted, coarse ooids (0.5 mm). The tangential arrangement of their structure indicates originally aragonitic composition and later diagenetic alteration to calcite. However, the contribution of quartz grains increases in the oldest oolitic-quartzose ridge by the effect of eolian and fluvial episode. The study of the diagenetic processes and porosity in these rocks shows that they exhibit excellent reservoir potential system as a result of prolonged exposure to the freshwater leaching.

The organic matter in the beach sediments and ridges generally has low amounts of trace metals, low organic matter content, and relatively high O/C atomic ratios. These characteristics indicate that they were laid down under highly oxygenated and bioturbated open-marine conditions, where current and wave actions led to the destruction of the organic matter. However, sediments deposited at the end of the creeks show relatively higher trace metals and higher TOC contents. These physical and chemical conditions allowed for the preservation of amorphous algal marine-type organic matter.

A retrospective on Holocene evaporites and carbonates dolomites, from evaporative pumping to hydro- and engineering geology

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In the late 1960s, "seepage reflux" and "capillary action" were the main hydrologic processes to describe the dolomitizing potential of the sabkhas in the Arabian Gulf. In the 1970s, Ken Hsu came up with the idea of "evaporative pumping" being the main process for creating a hydraulic gradient responsible for the ion exchange in the evaporitic setting of the sabkhas. Laboratory experiments and field investigations by our research group confirmed the possible existence of these processes, at least in parts of the Abu Dhabi sabkhas. The "new Abu Dhabi Sabkha model", e.g. Wood et al. (2002), is not in contradiction with the former models, but is an addition to the complex processes acting in the sabkhas.

The capillary fringe zone controls the surface and level of all sabkhas, coastal and inland. The capillary fringe of the coastal sabkhas of Abu Dhabi is in equilibrium with ground-water level, surface tension of the brine, granulometry/permeability of the soil, and flooding recharge from wind-driven floods. By evaporative pumping, the upward flux of brine in the supratidal areas is accelerated, and the concentration of the brine increases. After precipitation of gypsum/anhydrite and calcite/aragonite, the brine is enriched in magnesium and calcite can be converted to dolomite. Unfortunately, the area investigated by our former research group is inaccessible now, since Abu Dhabi International Airport was built there. Judith McKenzie continued to develop carbonate research, but the author turned his activities to applied geology. In applied hydrogeology, engineering geology and mitigation measures for geohazards, evaporites, and dolomites can play an important role. The author gives examples of the role of dolomite reservoirs for extraction of potable water in the Alps and for deep heat mining in the Vienna Basin, the role of evaporites in engineering geology, and the brittle deformation of dolomite cliffs during the October 2005 earthquake in Pakistan.

Spits, beaches, beachrock, tidal channels, evaporitic carbonates, and longshore-currents: Return to Qatar

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Carbonate sand beaches and spits nurtured by longshore currents in the Arabian Gulf often form sheltered areas favorable for evaporite and carbonate sedimentation. Promontories and embayments created by pre-Holocene topography favor such spit formation, especially in areas where contours are perpendicular to prevailing winds and longshore currents. Ras Um Sa on the northeast coast of the Qatar Peninsula provides a useful model for this style of sedimentation. Using push cores, trenching, and aerial photographs, the Ras Um Sa area was studied and mapped in detail by the author in the mid-1960s. The area was revisited in 1981, 1987, and 2005. In the original study, aerial photography revealed three 12-km-long chenier-like Holocene beaches arranged en echelon. Each chenier has several landward-projected, carbonate-sand spits that originated as terminal fish-hook-shaped spits during southward migration. The flat-lying channelized sabkha and inter-tidal areas that formed landward of and between the beaches provided low-energy areas suitable for fine-grained carbonate sedimentation and local evaporite deposition. These processes of combined cheniers and channelized sabkhas have continued to grow at a remarkable rate since the original investigation in the mid-1960s.

The original study (published in 1973) indicated that each chenier, with its recurved spits, reached a stable phase and was then protected from wave action when a new chenier formed on its seaward side. In addition, each chenier beach and recurved spit created conditions favorable for rapid beachrock formation on its low-energy landward side. The narrow beachrock became exposed as linear ridges on the seaward side of the cheniers as they eroded and migrated landward, creating a characteristic set of beach laminations. Wave erosion of these exposed rock ridges creates locally abundant lithoclasts that then become reworked and incorporated into the beach as it transgresses landward. Periodically, the entire beach/sabkha complex "jumped" and accreted seaward over offshore areas of submarine-cemented sediment. A new "jump" is beginning and growing today. The bored submarine cemented layers that become buried under the inter-tidal and sabkha sediments often constrain the depth to which tidal channels may erode. In addition to limiting channel depth, these cemented layers also serve as impermeable seals, thus preventing or retarding vertical movement of fluids. Such early formation of aquatards might explain the distribution of fluids (water or oil) in ancient analogue settings. It should be noted that under the popular sequence stratigraphy concepts, such bored surfaces could be misidentified as flooding surfaces. Creation of mainly low-angle, landward-dipping beach bedding overlying a basal, more steeply dipping set of landward-dipping beds, as described in the 1973 publication, remain indicative of this sedimentary model.

In 1987, twenty years after the initial study, four new fish-hook-shaped spits had formed at the southern end of the active outermost chenier. Beachrock had already formed on the landward sides of each new spit. In 2005, the area was again examined revealing the addition of a large new spit with beachrock forming on its landward side. Such spits will eventually seal-off the lagoon, which would then evolve into a large sabkha possibly composed of wind-blown sand. This more recent investigation also revealed a process caused by storm tides that was not identified in the earlier studies. Storm tides and currents break through the curved landward-directed spits, allowing flooding and extension of tidal channels into the sabkha and inter-tidal zones between the cheniers.

The Qatar model, in various scales, is repeated along parts of the Arabian Gulf, UAE coast, and very likely, along the southern shore of the Mediterranean Sea. Longshore drift and a steady supply of organically produced sand-sized sediment in any area where there is sedimentation similar to that at Ras Um Sa will result in net off-lap accretion. Given an additional few thousand years, and a continual supply of sediment, the sedimentary complex will increase in area and thickness. If present in ancient sabkha and evaporitic settings, this sedimentary complex could serve as a model for exploration and guide production drilling. This sedimentary model also has various societal implications. For example, at Ras Laffan, Qatar, a large one-km-long LNG and GTL tanker loading terminal and wharf has been constructed perpendicular to the shore. The wharf is up-current from the Ras Um Sa area and will potentially cut-off or retard southward movement of sediment. Chenier beach and spit formation may be terminated.

However, the positive benefit is that the reduced supply of sediment may prevent the closing-off of the Dakhirah and Khor Lagoons by growing sand spits. Continued access to these lagoons is vital to the fishing fleets and other boats at Dakhirah and Al-Khor city. Such knowledge can be applied to other future shoreline developments in the area.

Environments of evaporite deposition: Time, form, and function

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Although many laboratory studies and theoretical analyses concerning evaporites had been carried out in great detail from the 1850s onward (in review, see Borchert, 1969; Borchert and Muir, 1964; Braitsch, 1971), the first actualistic formation of evaporites in the field was studied by Douglas J. Shearman and his students along the coastal sabkhas of the Arabian Gulf in the late 1950s and continuing into the 1960s. The earlier laboratory and theoretical studies, while correct and reasonable chemically, did not seize the essence of evaporite environments, deposition, and stratigraphy, leading to many difficult and sometimes unreasonable models for the formation of evaporites. The sabkha studies were the first works that considered both chemistry and sedimentology; today, further actualistic models have been studied wherein evaporites are formed within an evaporated water body.

As early as 1953 (a, b) Richter-Bernburg speculated about rates of formation and intervals of major evaporite deposition. Reasonable actualistic models emerged by 1976–1977, based on both Messinian and modern evaporite accumulations (Schreiber and Friedman, 1976a; Schreiber et al., 1976b; Schreiber and Catalano, 1977). At about the same time, numerous geologists seized upon theoretical and laboratory experiments to create formalized depositional models (see Schmalz, 1969; Sloss, 1969). These theoretical models do not examine the sediment morphology but deal with the deposits as bodies of chemical sediments arranged in layered and/or zoned strata without actually examining their appearance or petrology. Because there is comparatively little core (or outcrop) available for many evaporites, and they are known largely from geophysical data, the theoretical models seem very reasonable but fall short of accurate representation.

Other actualistic studies were made more recently, adding new details of environmental chemistry, morphology, and styles of preservation to this emerging and exciting area of study. The picture expanded to include observations of subaqueous evaporite deposits, beginning with Shearman's observation of formation of shallow subaqueous halite (Shearman, 1970). With the discovery of thick evaporites from the Messinian deposits of the Mediterranean by the ODP drilling (Leg 13, Ryan and Hsü, 1973), actualistic evaporative depositional environments expanded even further, which illuminated the meaning of the many observed and virtually unaltered Cenozoic evaporites (in review see El Tabakh and Schreiber, 2000; Bąbel, 2004). Some of these relatively young sediments have undergone partial diagenesis, but it is largely from these very immature deposits that we also have begun to understand the many mechanisms of their alteration.

The other factor learned from these young evaporites is that their rate of deposition is much greater than that of most other sediments, such that the deposition of the full thickness of many thick evaporites (0.5-2.0 km) were formed within a period of 100,000 to 600,000 years; thus these deposits may be considered as stratigraphic marker beds (Schreiber and Hsü, 1980). Another important factor is that many evaporite cycles observed within these young rocks are formed in response to a rising sea-level, not lowering. These new views of evaporite formation aid in the creation of more realistic environmental and stratigraphic reconstructions.

Facies stacking patterns and sea-level history of the Abu Dhabi sabkha in the vicinity of Al-Qanatir Island, United Arab Emirates

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The giant coastal sabkhas of the United Arab Emirates are one of the few areas of the world where the geoscientist can observe the interplay between siliciclastic, carbonate, and evaporite sedimentation. Supratidal (sabkha) to intertidal/shallow subtidal (algal/microbial mat and peloid-skeletal tidal-flat) environments were studied along the Abu Dhabi coastline in the vicinity of Al Qanatir (Al Rufayq) Island. A transect from land to sea displays the following textbook-like examples of sub-environments (facies belts):

(1) Beach ridges: forming low-relief topographic highs paralleling the coastline that are mainly composed of *Cerithid* gastropods. (2) Upper sabkha (upper supratidal): buckled, polygonal salt crust displaying teepee structures. (3) Middle sabkha (middle supratidal): whitish anhydrite polygons on surface. (4) Lower Sabkha (lower supratidal): soft, shiny surface due to sparkling gypsum crystals (gypsum mush). (5) Upper intertidal: thin, leathery, crinkled algal mat. (6) Middle intertidal: domed, pinnacle algal mat. (7) Lower intertidal: thick, smooth polygonal algal mat and tufted algal mat. (8) Lowermost intertidal/uppermost subtidal: soft, peloid-skeletal tidal-flat displaying *Cerithid* gastropod grazing-traces, skolithos-type burrows, and eroded wave ripples.

Age-dating results from samples of four hardgrounds, two algal mats, and one anhydrite layer show a range from about 3,500 years before present (upper sabkha sub-environment) to about 900 years before present (lower intertidal sub-environment), and thus prove the seaward progradation of the facies belts since the last Flandrian sea-level highstand (formation of *Cerithid* gastropod beach ridges), about 5,000 years before present.

The state of the art: What have we learned about dolomite geochemistry in 25 years?

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It has been a quarter of a century since Lynton Land published his paper, "The isotopic and trace element geochemistry of dolomite: The state of the art," in the SEPM Special Publication No. 28. This paper remains one of the most quoted in the field and is a starting point in most geochemical studies involving dolomite. The durability of this publication raises the question as to whether there have been significant advances over the past 25 years in the study of the geochemistry of dolomite. Are the statements made by Land in 1980 still valid? In this presentation, I will examine the ideas presented by Land regarding the equilibrium oxygen isotopic fractionation and trace element partitioning in dolomite in the light of new experimental data and theories regarding dolomite formation. In particular, I will address whether the traditional geochemical parameters can be used to unequivocally assign an environment of formation or whether there are new methods that can be used to unravel one of the most enigmatic questions in sedimentary geology, the formation of dolomite.

Rheology and transport properties of halite: Review and synthesis

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Building on geometric and kinematic reconstructions, the study of the dynamics of salt structures and associated sediments has made rapid progress in the past two decades. However, full models that include realistic rheologies and fluids flowing through salt are still in their infancy. We present a framework for the complex microstructural evolution and rheology in halite as a function of depositional architecture and tectonic history.

In the last decades, extensive experimental work on the deformation of rock salt at a range of temperature, grain size, water content, strain rate, and porosity has provided a solid framework to extrapolate these results to natural conditions. However, a comparison of the rheological assumptions made for numerical and physical modeling of salt tectonics with structures in naturally deformed salt is still missing. By studying naturally deformed halite from a wide range of settings, we aim to provide a detailed basis for quantifying deformation mechanisms and rheology in halite in the salt tectonic cycle. We summarize microstructural studies carried out on naturally deformed salt samples, and attempt

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to define a consistent set of rheologies for rocksalt starting from the primary undeformed to the highly deformed extrusive salt. Large contrasts in rheology are common in layered salt from the onset of tectonic deformation. Early deformation of salt is accompanied by expulsion of water from a variety of sources and water-assisted deformation mechanisms are fully active. In salt diapirs, small- and large-scale folding is common, caused by the large contrasts in mechanical properties of the salt layers deforming by dislocation creep and solution-precipitation creep. In the cold stem of diapirs being extruded to the surface, differential stresses in salt are high. Grain-size reduction as a function of increasing strain is common. In surface-reaching salt structures, bedding-parallel mylonitic shear zones develop in the very fine-grained salt, and the deformation mechanism is solution-precipitation creep and grain boundary sliding. This salt is very weak and can flow downhill under very low shear stresses.

Evaporites have a strong control on fluid flow in a basin because of their very low permeabilities and ductility. Although salt is widely regarded as a perfect seal, it can become permeable for one- or two-phase fluids under certain conditions of fluid pressure, temperature, and deviatoric stress. The fluid pathways can be either along zones of diffuse grain boundary dilatancy, or along open fractures, depending on the fluid overpressure and deviatoric stress. We present a number of case studies where halite can be shown to have been permeable. The fluid can form halite veins visible in samples decorated by gamma-irradiation, or networks of brine-filled grain boundaries that conduct fluid from primary inclusions during recrystallization. In all cases, the main criterion for this to occur is the presence of near-lithostatic fluid pressures which allow dilatancy and a dramatic increase in permeability.

Formation of laminations in evaporative carbonates: Organic vs. inorganic origin?

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Sedimentary structures comprising wavy or crenulated laminations are commonly found associated with evaporative carbonates and are generally attributed to microbial mat development but may also be of inorganic origin. How exactly are these structures made and how might they be preserved in the rock record? Lagoa Vermelha, a hypersaline coastal lagoon located 100 km east of Rio de Janeiro, Brazil, provides a unique environment in which to study microbial carbonate precipitation processes. In addition, Lagoa Vermelha is an important site of modern dolomite formation under hypersaline anoxic conditions. Due to diverse factors, such as topography, geology, and climate, rapid changes in environmental conditions result in large variations of the major ion concentrations in Lagoa Vermelha, ranging from brackish to 3-times seawater concentrations. Because the annual precipitation cycle moderates the evaporative conditions, Lagoa Vermelha can serve as a complementary study area to compare with the Abu Dhabi sabkhas where the degree of aridity is more extreme.

In Lagoa Vermelha, microbial mats and stromatolites grow and accrete with the precipitation of high Mg-calcite and dolomite laminae within a gelatinous biofilm (Vasconcelos et al., 2006). Microbial processes, such as high rates of photosynthesis, aerobic respiration, sulfide oxidation, sulfate reduction, and fermentation, combine to produce microenvironments conducive to the precipitation of these exceptional Mg-carbonates. Within a sequence of multiple laminar cycles, microbial metabolism combined with carbonate precipitation leads to an amalgamation of the discrete laminae with the degradation of the biofilm, resulting in the formation of the lithified laminated structure. The specialized halophilic microbial community from Lagoa Vermelha is common in most evaporite environments, and this microbial metabolism may play an important role in controlling the availability of ions essential for evaporative mineral precipitation. In the rock record, gypsum laminae are often found interbedded with micritic dolomite- or calcite-containing microbial structures. Thus, we propose that Lagoa Vermelha model for carbonate laminae formation may be applicable to evaporite environments where gypsum saturation is exceeded.

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Are modern evaporite deposits a climatically and tectonically limited sample of a much broader depositional spectrum?

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Our largest and thickest examples of Quaternary sabkhas, saline pans and salinas, are continental. They define same-scale analogs only for ancient continental lacustrine deposition, not for ancient marine-fed salt basins, such as the Hith, Zechstein, and Messinian deposits. No widespread marine platform evaporites have accumulated since the

Eocene, and the Mediterranean Messinian (c. 5.5 Ma) is the latest basinwide evaporite event. Most ancient evaporite deposits are an order of magnitude larger than today's systems and most accumulated in large marine-seepage fed subsea-level depressions with no surface connection to the ocean. These platform and basinwide evaporites have no Quaternary counterpart in terms of scale or thickness, but can be interpreted using models that are combinations of the hydrologies of sabkhas, saline pans, and salinas. The hydrological position of the active top of the aggrading brine curtain, with respect to the evaporite depositional surface, in both platform and basinwide settings, defines the dominant textural signature of the resulting salt sequence (saline-pan, evaporitic mudflat [sabkha], saltern, deeper slope, and basin).

Once we realize that thick evaporite accumulations (continental or marine) require stable long-term brine hydrologies (c. 10^5 to 10^6 years) to accumulate to substantial thicknesses and lateral extents, we reach an understanding of why the present is not a good time to study the scale and diversity of possible marine-fed platform or basinwide evaporite systems. High amplitude, high frequency fourth-order sea-level oscillations of our current "icehouse" climate do not allow the set up of stable brine curtains behind laterally-continuous seepage shoals in present-day carbonate platforms, and so there are no Neogene examples of platform evaporites. Platform evaporites require greenhouse eustasy to form. Nor are there suitable subsea-level rift-induced intracratonic sags or soft-collision belts in arid marine-fed settings where conditions are suitable for the creation of modern basinwide marine drawdown deposits. The need for subsea-level tectonically-induced basins explains why times of worldwide "zip then split" tectonics, which define supercontinent accretion and disaggregation (e.g. Pangea or Rodinia), also encourage the accumulation of substantial volumes of salts in tectonic depressions. Throughout the Phaneozoic and Neoproterozoic, it was tectonics, not absolute sea-level change, which controlled the depositional spectra and hydrologies of the larger evaporite basins.

Evaporitic source rocks: A geological response to biological cycles of "feast or famine" in layered brines

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A source rock is generally considered to be a fine-grained rock which, during its burial and heating, generates and releases enough hydrocarbon to form a commercial accumulation of oil or gas. Back in 1981, Kirkland and Evans made the observation that some 50% of the world's oil may have been sourced in evaporitic carbonates. Heresy or not, the notion that much of the oil sealed by evaporite salts may also have been sourced in sediments deposited in earlier less saline but still related evaporitic (mesohaline) conditions is worthy of consideration. The association between saline waters, the accumulation of organic-rich sediments, and the evolution of the resulting evaporitic carbonates into source rocks has been noted by many authors.

Some guidelines are required for the usage of the terms "hypersaline" and "mesohaline" in saline brines and the associated mineral precipitates. For seawater-derived and thalassic (seawater-like) brines, the use of the term hypersaline encompasses all waters more saline than seawater (mesohaline, penesaline and supersaline). There is an associated predictable suite of evaporite minerals, starting with carbonate (usually aragonite), in modern mesohaline waters and evolving through gypsum and halite in penesaline waters into bitterns from supersaline waters. But ionic proportions in seawater have changed over time (see Warren 2006). Accordingly, some ancient evaporite primary carbonates were dolomitic, especially in the Proterozoic (although reflux dolomite has always been a widespread early-diagenetic evaporite precipitate). Bittern salts from modern seawater concentrates show a carnallite-$MgSO_4$ association and a propensity to accumulate aragaonite in the early stages of concentration, as they did also in the Permian (icehouse climate mode). Bitterns, at other times in the Phanerozoic (greenhouse climate mode), tend to lack the $MgSO_4$ minerals and have a propensity to form Mg-calcites in the mesohaline phase. Use of the term hypersaline in modern continental waters is much less well-defined and is variably applied to waters with total dissolved salt contents (TDS) that are more saline than 3 to 5‰. Many nonmarine or continental waters have ionic proportions much different than seawater (athalassic) and therefore a broader range of mineral precipitates at all stages of brine concentration.

As long ago as the middle of last century, Weeks (1961) emphasized the importance of evaporites as caprocks to major hydrocarbon accumulations. He also pointed out that many of the cycles of deposition that involve organic-rich carbonate marls or muds also end with evaporites. Many of these authors have noted the association of Type I-II hydrogen-prone kerogens in evaporitic source rocks and related their occurrence to the ability of 'halotolerant' photosynthetic algae and cyanobacteria to flourish in saline settings. Such kerogens tend to be oil-prone rather than gas-prone.

In this paper we examine what chemical pathways and species that live in these environments today and the conditions that favor them. We shall compare modern saline settings with ancient systems and attempt to define those ancient saline settings that facilitated deposition of evaporitic source rocks.

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Carbonate play prediction in subaqueous evaporite settings

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About half of the known petroleum reserves occur in carbonate reservoirs that are overlain by evaporites. One or more of the hydrocarbon-systems elements (i.e. source, reservoir, or seal) are associated with evaporites in about 75% of the world's giant carbonate fields. The relationship among evaporites, carbonates, and hydrocarbons is not coincidental. Restriction and aridity characterize evaporite basins. In these basins, carbonate source rocks are juxtaposed with carbonate reservoirs. Siliciclastic source rocks and long migration routes from basinal settings are not required for viable hydrocarbon systems. Aridity impacts carbonate reservoir quality. Shallow-water carbonate terrain that is periodically exposed is less likely to experience pervasive pore-occluding meteoric diagenesis. Better preservation of matrix porosity and permeability leads to improved storage and flow capacity of carbonate reservoirs. Carbonate reservoirs with evaporite seals commonly occur in the same supersequence. Significant hydrocarbon reserves reside in carbonate plays associated with both platform and basin-center evaporite settings. Platform evaporites can form in both transgressive and highstand systems. Carbonate play examples include the Arab D Reservoir on the eastern Arabian platform and the Osa Member in East Siberia. Basin-center evaporites are formed primarily during low stands of relative sea level. Plays include the Madison of the Williston basin and the Keg River buildups in Western Canada.

The presence of evaporites impacts seal continuity and capacity, timing of trap formation, source potential, and reservoir occurrence and quality. An understanding of carbonate-evaporite systems provides insights into the distribution of play elements and can be used to mitigate uncertainty associated with these carbonate plays.

Evolution of Holocene coastal sabkha of the United Arab Emirates

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Holocene coastal sabkha development in the United Arab Emirates results from the interplay of several critical components: (1) a porous, clastic framework, (2) a shallow water table, (3) potential evaporation greater than precipitation, (4) a source of eolian material, and (5) wind of sufficient velocity for transport. Most solutes in this system are derived from deep-basin brines that discharge to the topographically low area adjacent to the Gulf, while most of the ground water is derived from recharge of local precipitation. Ground water and solutes rise in response to water evaporation at the sabkha surface. Soluble chloride and nitrate minerals form as evaporites on the sabkha surface. Overland runoff episodically transports these ions to the adjacent Gulf, thereby preventing significant accumulation on the surface and thus within the geologic record. Within the capillary zone, retrograde minerals such as gypsum, anhydrite, calcite, and dolomite precipitate as thermalites rather than evaporites – there is no significant evaporation below the land surface. Mineral precipitation in the capillary zone reduces the effective pore diameter. This reduction results in an increased elevation of the capillary-induced head that in turn promotes the capture of additional eolian material on the surface. This increasing surface elevation causes both progradation of the sabkha and creates additional pore space for mineral precipitation. Thus, it is possible to realize both an increase in sabkha area (by progradation) and significant thicknesses of retrograde minerals without tectonic changes in sea or land level or climatic changes. Because of relatively low solubility of the retrograde minerals relative to the chloride and nitrates, and their position in the subsurface, they are preferentially preserved in the geologic record. The sulfate concentration in the input brines is exceptionally low, yet preserved authigenic sediments are dominated by sulfate minerals. Thus, one needs to exercise care in both reconstructing the past solute chemistry and environment from the accumulated mineral assemblages as well as interpretation of tectonic and climate changes associated with sabkha thickness and progradation.