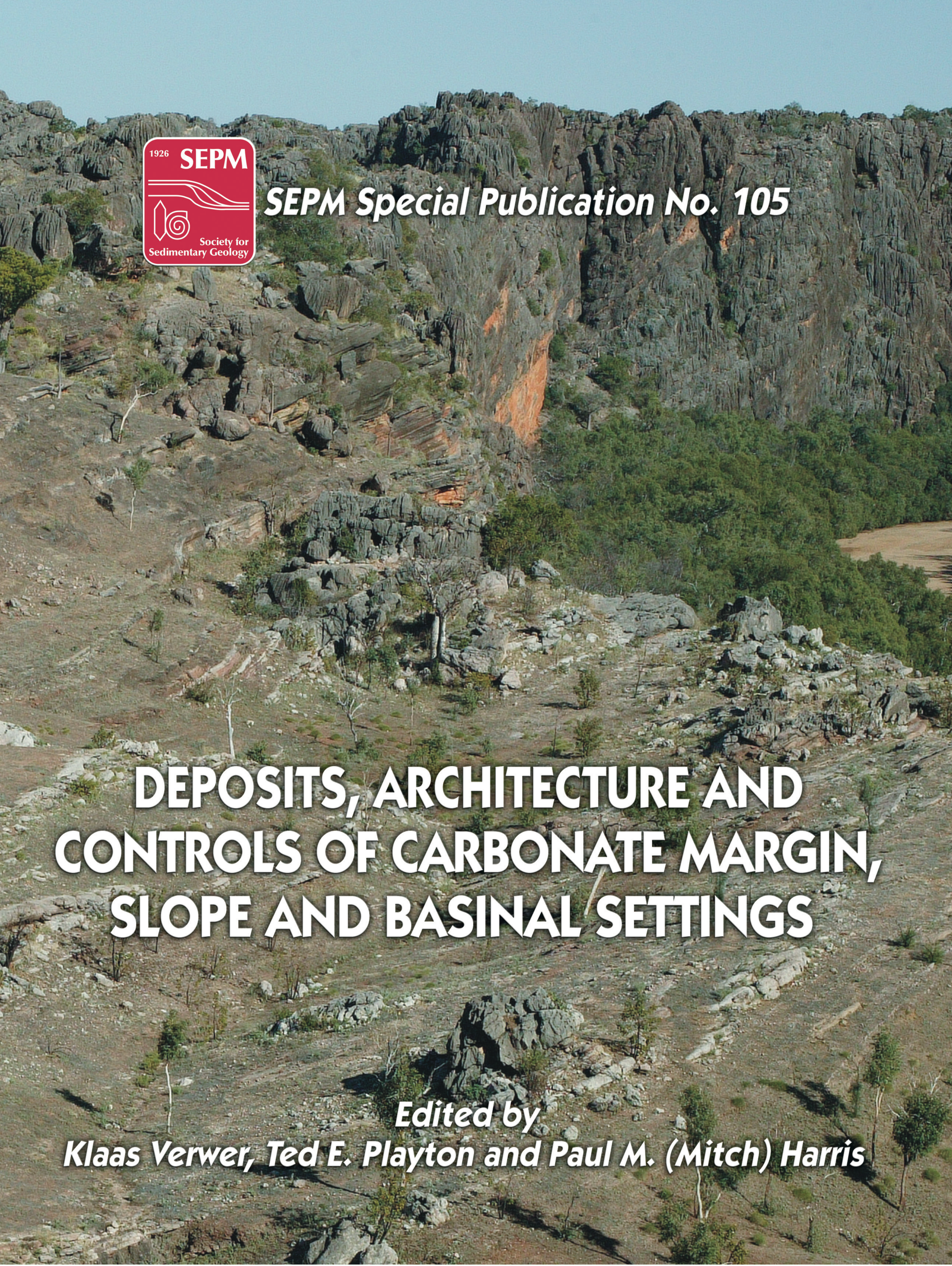

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DEPOSITS, ARCHITECTURE AND CONTROLS OF CARBONATE MARGIN, SLOPE AND BASINAL SETTINGS

Edited by
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Deposits, Architecture, and Controls of Carbonate Margin, Slope, and Basinal Settings

KLAAS VERWER, TED E. PLAYTON, AND PAUL M. (MITCH) HARRIS

CONTENTS

Introduction and Synthesis

Conceptual Works or Syntheses

Studies—Margin-to-Basin Development and Controlling Factors

Studies—Architecture and Controls of Carbonate Margins

Studies—Carbonate Distal Slope and Basin Floor Development

SO DIFFERENT, YET SO SIMILAR: COMPARING AND CONTRASTING SILICICLASTIC AND CARBONATE SLOPES

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ABSTRACT: Carbonate submarine slopes have a tendency to be steeper than their siliciclastic counterparts. Commonly the stabilization potential by binding of slope sediment and early cementation of carbonates is invoked to explain this difference. However, differences and similarities between siliciclastic and carbonate slope systems with respect to their gross development, curvature, and angle of dip are only expressed if one evaluates slope settings that are affected by comparable extrinsic and intrinsic processes. Three basic types of slope profiles (planar, concave, and sigmoidal) are reviewed and their mathematical expressions (linear, exponential, and Gaussian, respectively) used to compare and contrast slope systems originating from various settings. Exponential slopes with sharp shelfbreaks develop if sedimentary base-level fluctuations are minor compared to slope progradation. Gaussian profiles develop as a result of rounding of the shelfbreak by significant base-level fluctuations, whereas linear profiles result from excess sedimentation creating an angle of repose system. Both carbonate and siliciclastic systems exhibit all three types of slope curvature and mutually comprise muddy and grainy as well as debris-dominated slopes.

Similarities between continental slopes of siliciclastic passive shelf margins flooded during the Holocene transgression and nonrimmed, cool-water carbonate platforms are evident where deep shelves, low slope angles, and usually Gaussian slope profiles are typical. Lacustrine and proximal, active marine deltas compare with tropical carbonate platforms. Both have steep, exponential, and linear slope profiles and coarse sediments originating from shallow water depths. Exponential profiles are common on rimmed platforms because reefs are resistant to erosion and the platform edge is therefore relatively stationary vertically, thus forming a distinct platform–slope break. This also accounts for ice-covered margins because the grounding level of the ice limits vertical fluctuations.

A special case for carbonates is the in situ accretionary slope factory dominated by microbial boundstone-dominated deep oligophotic “reefs” and linear slopes of rubble, boulders, and sand. However, in situ slope accretion and stabilization by itself does not necessarily explain the first-order linear profile. Because the slope factory is insensitive to light accretion by slope shedding occurs during both lowstands and highstands. In other words, when shallow-water carbonate production ceases, in situ carbonate production continues in the slope region, and the combined effort of sediment production and the resultant surplus allows the system to build up to the angle of shear and constantly prograde. Since the dominant sediment texture delivered by the slope factory is coarse rubble and boulders that yield high angles of repose, often the flanks are steep. A direct comparison are coarse-grained deltas, especially those that develop in fjords and Alpine lakes, where—because of its proximity to the sediment source—the inherent fast prograding system, which is dominated by a mixture of coarse sand and rubble, obtains steep, linear slopes.

Clearly, while sediment properties may vary greatly, stark similarities in gross development, curvature, and angle are observed in comparable settings. As a consequence, morphometric attributes captured from seismic data have to be put in the context of the entire depositional system and basin setting to fully comprehend and predict sediment properties and depositional processes.

KEY WORDS: slope environment, submarine, carbonate, siliciclastic, geometry, angle of dip

RAMP TO RIMMED SHELF TRANSITION IN THE GUADALUPIAN (PERMIAN) OF THE GUADALUPE MOUNTAINS, WEST TEXAS AND NEW MEXICO

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ABSTRACT: The carbonate ramp to rimmed shelf transition is a well-known depositional pattern in carbonate platforms, but the nature of the stepwise evolution, the evolution of facies and facies tract patterns from sequence to sequence, and the intrinsic and extrinsic controls that drive the transition are less well known. The Guadalupian carbonate platform system in the southwestern US provides an example of a ramp-to-rim transition in a carbonate to mixed siliciclastic–carbonate succession during a second-order progradational supersequence. The sequence framework of the Guadalupian section includes 30 high-frequency sequences deposited over an 11 Myr time span. Compositing data from exposures across a 50 km strike width and 30 km dip width area provides the control needed to document this transition.

Early Guadalupian San Andres sequences exemplify low-angle (<28) foreshore–shoreface–offshore profiles (ramps) with 60 to 80 m of topset to toeset relief and as much as 10 km of slopewidth (distance from shelf inflection to slope inflection point). Extensive lower slope–basin hemipelagic mudstones of the Cutoff Formation were shed from this active mud factory, and this balance of accumulation rates in the platform and slope maintained a low-angle profile. A distinct lack of sediment gravity-flow features is noted from this profile. After the protracted Brushy Canyon lowstand event, upper San Andres shelf carbonates show cessation of low-angle 2 to 4° ramplike profiles, where active carbonate factories on the shelf produced thick margins that tapered downdip into less-developed lower-slope hemipelagic mudstone aprons. Dilute toe-of-slope turbidites and upper-slope fusulinid banks add heterogeneity to this slope profile.

Uppermost San Andres and Grayburg sequences mark the beginning of a forced regressive mixed siliciclastic–carbonate pattern in which siliciclastics constitute 30 to 50% of the platform and slope. Uppermost San Andres clinoforms prograded between 5 and 10 km, range in slope angle from 4 to 15°, and have 100 m of topset to toeset relief. Acombination of siliciclastic and mixed carbonate–siliciclastic turbidites accumulated on the lower slope, and the upper slope consists of fusulinid-rich packstones with dips up to 20°.No debris deposits developed in the uppermost SanAndres sequence. Rare patch reefs occupied shelf-margin promontories between reentrants that were dominated by siliciclastic bypass. The reduced (<5 km) carbonate factory width of the uppermost San Andres results in absence of a hemipelagic mudstone lower-slope apron, which accentuates oversteepening of the slope. The lower Grayburg–upper Cherry Canyon sequence can be considered a lowstand wedge complex within the longer-term succession. This Grayburg–Cherry Canyon interval prograded 5 km and is characterized by 5- to 25°-dipping mixed siliciclastic–carbonate clinoforms, 65m of topset to toeset relief, and minor debris flows. As for the G9 high-frequency sequence, there is a narrow shelf carbonate factory (<5 km) and absence of a hemipelagic mudstone lower-slope apron.

Progradational and aggradational stacking of the middle Grayburg through lower Queen Formations most likely contains the record of the first reef-rimmed platforms with massive bedding developed near the shelf-slope break.A180-m-relief collapse scar at the margin as exposed at Bush Mountain on the Western Escarpment removed critical evidence of potential reef-margin development for the middle Grayburg–lower Queen sequences. Following this major collapse, the upper Queen (shelf)–Goat Seep (reef)–South Wells (basin) section represents the first preserved reef-rimmed platform margin. Clinoform heights of 200 m, a massive reefal margin–upper slope, and a debris-dominated foreslope with dips at angle of repose signal the final transitional stage into a Capitan-like system. Remaining Seven Rivers–Yates–Tansill–Capitan–Bell Canyon sequences continued to build relief to 500 to 600 m as they prograded an additional 5 km basinward. Slope complexes within the Capitan-equivalent section consist of compensationally stacked ponded and backfilling geometries separated by through-going collapse events.

Three primary but interrelated drivers are visualized for the ramp–rim transition recorded in Guadalupian strata of the Guadalupe Mountains outcrops. First, initial siliciclastic influx and concomitant reduced export of fine-grained carbonates to the slope during uppermost San Andres deposition led to basin starvation, margin steepening, and an increase in sediment bypass and early stage margin colonization. Second, middle Guadalupian Grayburg aggradational stacking of shelf margins drove progressive oversteepening and ultimately led to large-scale collapse of the margin, at least locally. This headwall became the site of the first preserved reefal margin in the Guadalupes. Finally, a marked increase in shelf accommodation space was created by flexural subsidence of Leonardian shelf strata over the buried Late Leonardian shelf margin. In other parts of the Delaware Basin, the steep Leonardian margin break was the single dominant control on the development of Guadalupian margins.

KEY WORDS: Permian, ramp, rimmed shelf, slope, carbonate

LITHOFACIES, DEPOSITIONAL ENVIRONMENTS, BURIAL DIAGENESIS, AND DYNAMIC FIELD BEHAVIOR IN A CARBONIFEROUS SLOPE RESERVOIR, TENGIZ FIELD (REPUBLIC OF KAZAKHSTAN), AND COMPARISON WITH OUTCROP ANALOGS

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ABSTRACT: Tengiz Field is a steep-sided, isolated carbonate platform in the Precaspian Basin, Kazakhstan, with hydrocarbon production from Carboniferous platform and slope facies. Systematic differences in reservoir pressure decline during production indicate that this reservoir consists of three subcompartments or material balance regions: (1) a central "platform reservoir" made up of cyclic platform-top facies that acts like a single, stratified, multistory reservoir; (2) a "wedge reservoir" formed by a prograding margin containing upper slope microbial facies; and (3) an "apron reservoir" containing allochthonous facies deposited in deep water around the base of the buildup. The facies in the apron reservoir accumulated during an early depositional stage and were subsequently partly to fully buried by prograding microbial slope facies of the wedge reservoir. The wedge and apron reservoirs together form a succession 800 to 1000 m thick within the Tengiz oil column.

The wedge reservoir shows uniform pressure decline with time and is well connected. Field data (cores and well logs) are insufficient to determine internal continuity of lithofacies and depositional environments or to quantify the pore network responsible for the high connectivity. An outcrop analog (Asturias, Spain) with facies matching those observed in Tengiz cores was used to predict that the microbial lithofacies form a distinct and continuous mechanical unit within the wedge reservoir. Tengiz microbial facies contain a high concentration of solution-enlarged, syndepositional and other early fractures oriented parallel and normal to depositional strike. Borehole image logs provide data on enlarged fracture apertures and local fracture density, but no data related to fracture height or length. An outcrop analog with early fractures in similar facies (Windjana Gorge, Australia) was used to obtain large-scale height and spacing data for solution-enlarged syndepositional fractures. Dissolution processes in the outcrop are different from those of Tengiz, but the fracture aperture and cavern sizes are comparable to their known counterparts in the Tengiz wedge reservoir, and application of the outcrop height data to geologic models of the Tengiz wedge subcompartment can account for its dynamic behavior. The apron reservoir shows a nonsystematic pressure decline with time and is less depleted than the wedge reservoir. The irregular decline indicates reduced internal connectivity within the apron reservoir, which is corroborated by core and borehole image data indicating high lithofacies heterogeneity and the absence of continuous microbial facies responsible for reservoir continuity in the wedge reservoir. A reservoir pressure increase of 1700 psi from the wedge reservoir to the apron reservoir observed in a single well penetration suggests reservoir communication between them may be reduced across a stratigraphic baffle.

The wedge and apron reservoirs both contain a late burial matrix diagenetic overprint represented mainly by co-precipitated bitumen and calcite cement and local development of matrix microporosity. Enlargement of the early fractures in the wedge reservoir also occurred during burial diagenesis based on the presence of diagenetic halos containing the burial overprint around the fractures and based on the presence of co-precipitated bitumen and calcite in the fractures. Scenarios and mechanisms for fracture enlargement are evaluated against the observations from field data and the outcrop analogs.

KEY WORDS: Carboniferous, carbonate slope, Kazakhstan, Tengiz Field, burial diagenesis

TRIASSIC TANK: PLATFORM MARGIN AND SLOPE ARCHITECTURE IN SPACE AND TIME, NANPANJIANG BASIN, SOUTH CHINA

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ABSTRACT: The Nanpanjiang Basin (NPJB) is a large, complex basin within the south China plate bordered by Precambrian uplifts on the northeast, southeast, and west and by a Triassic suture zone to the south. During the Permian and Triassic, the NPJB formed an embayment in the Yangtze Platform (YP) and contained several isolated carbonate platforms (IPs), including the Great Bank of Guizhou (GBG) and the Chongzuo–Pinnguo Platform.

The NPJB presents an exceptional natural laboratory for evaluating controls on carbonate platform margin and slope architecture. Multiple two-dimensional transects through the YP and IPs provide exposure along spatial and temporal gradients in tectonic subsidence rate, siliciclastic input, antecedent topography, and oceanography. Platform development across the end-Permian extinction and evolving seawater chemistry allow assessment of the impact of carbonate factory change from a basin-wide perspective.

The YP and IPs evolved from ramps and low-relief banks with oolite margins and mud-rich slopes early in the Early Triassic to steepening Tubiphytes reef rimmed platforms with slopes progressively enriched in clast-supported breccias in the Middle Triassic. Despite differences in the slope angle and windward–leeward differences in grain size at the bank margin, the Early Triassic margin-slope systems have very similar characteristics throughout the basin. During the Middle Triassic, the YP and IPs developed extreme lateral variability in margin architecture due to differences in tectonic subsidence and siliciclastic basin fill at the toe-of-slope.

The southwestern sector of the YP and the GBG drowned under pelagic carbonates followed by siliciclastic turbidites in the Late Triassic, Carnian, while the northeastern YP continued shallow-marine deposition until burial by prograding shallow-marine siliciclastics. The southerly IPs have backstepping geometries, terminal pinnacles, and earlier drowning and burial by siliciclastics.

Differences in antecedent topography affected margin width and stability, resulting in changes from broad aggrading to prograding margins vs. high-relief and collapsed margins. Timing and rates of subsidence largely controlled along-strike variability, timing of drowning, backstepping geometries, and pinnacle development. Timing of siliciclastic basin fill dictated differences in platform-margin geometries such as slope angle, relief above basin floor, and progradation at basin margins. Development of ramp profiles with oolite margins in the Early Triassic and subsequent development of steep-sided margins in the Middle Triassic reflects changes in carbonate factory type following the end-Permian extinction.

Process-based depositional models derived from the NPJB can aid in the prediction of facies distribution and architectural styles at the basin scale in other systems, particularly in areas of active tectonism and temporal variations in oceanographic conditions, such as, for example, in the prolific Tertiary carbonates reservoir province of southeast Asia.

KEY WORDS: platform margin and slope architecture, south China, comparative analysis, Nanpanjiang Basin, Triassic carbonates

WARM- VS. COOL-WATER CARBONATE FACTORIES ANDADJACENT SLOPES: PENNSYLVANIAN–EARLY PERMIAN SVERDRUP BASIN, ARCTIC CANADA

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ABSTRACT: Pennsylvanian–Early Permian carbonate factories of the Sverdrup Basin, Arctic Canada, and their adjoining slopes were under warm-tropical conditions in the Bashkirian–Asselian and cool-water warm-temperate conditions in the Artinskian–Kungurian. All other factors being the same, the Sverdrup Basin is a unique laboratory where these two types of slope development can be compared and contrasted. Key differences include high carbonate production, widespread boundstone margin development, shelf-margin storm protection, and early lithification for warm margins, and the lack thereof for cool margins. In addition, slope sedimentation below a shallow lysocline during the cool interval led to extensive carbonate dissolution. As a result, Artinskian–Kungurian middle and lower slopes are dominated by spiculitic chert. The Pennsylvanian–Early Permian succession consists of four third-order unconformity-bounded transgressive–regressive (T–R) sequences driven by episodic tectonics. The regressive systems tracts of each sequence recorded progradation of an accretionary margin at a time of tectonic quiescence. The warm-water accretionary margins had slopes that were either planar or exponential. Steep upper slopes formed the downward extension of a lithified boundstone margin. Strike-discontinuous erosion of that margin led to the shedding of channelized debris in the proximal middle slopes. Grainflows and proximal turbidites accumulated between areas of debris deposition. Distal turbidites forming large strike-continuous aprons were deposited in the distal part of the middle slope. This part of the slope also contains high-amplitude truncation surfaces and slump folds. The lower slope was composed of distal turbidites interstratified with hemipelagic material. The cool-water accretionary margins had sigmoidal slopes. Upper slopes formed the downward extension of a high-energy open shelf. Gravity-aided grain-dominated tempestites were deposited in the upper slope, locally associated with mud mounds. The steeper part of the sigmoidal slope was the middle slope, where key processes included slope failure and extensive sponge spicule production. Grainflow and proximal turbidites accumulated in the proximal portion of the middle slope. Mud-dominated siliceous distal turbidites associated with large-scale truncation surfaces accumulated in the distal part of the middle slope. Distal turbidites interfinger with hemipelagic siliceous shale and fine siltstone in the lower slope.

KEY WORDS: carbonate, slope, heterozoan, photozoan, Arctic

MAGNETIC SUSCEPTIBILITY (χ) STRATIGRAPHY AND CHEMOSTRATIGRAPHY APPLIED TO AN ISOLATED CARBONATE PLATFORM REEF COMPLEX; LLUCMAJOR PLATFORM, MALLORCA

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ABSTRACT: Inorganic whole rock geochemical and magnetic susceptibility (χ) data have been gathered from seven sections through the Upper Miocene reef complexes of the Llucmajor Platform, Mallorca. The aim of acquiring these data is to determine what chronostratigraphic information a combination of magnetic susceptibility stratigraphy (MSS) and chemostratigraphy can provide in reef complexes of a carbonate platform with no nearby source of terrigenous material.

Chi values display short-term cyclical fluctuations, maximum values commonly being associated with the upper bounding surfaces of sigmoids and sigmoid sets, the building blocks of the Llucmajor reef complexes. Values of χ are low at the bases of the sigmoids; they reach a maximum at the top of the sigmoids, and then fall rapidly to the base of the next sigmoid, indicating a base-level control on χ values. No longer term variation in the χ values have been identified that would enable differentiation of an old reef complex from one that is demonstrably younger in the cliff sections, and there is no apparent facies control on χ values. While the elemental data do not vary in response to base-level fluctuations and therefore do not define stratigraphic surfaces, they do show long-term variations, enabling reef complexes of differing ages to be geochemically characterized: the key to defining chemostratigraphic schemes. The elements used to characterize different age reef complexes are Cr, Zr, Al_2O_3, TiO_2, Ga, and Rb, which are controlled by changes in the amount and composition of wind-blown terrigenous material and tuffaceous material. As such, the changes are chronostratigraphic events on the scale of the study intervals here. Although the two datasets used are both ultimately controlled by the mineral composition of the sediments, it has proved impossible to find a direct link between the elemental data and χ values.

Despite the lack of an understanding of the relationship between whole rock geochemistry and v values for this dataset, they clearly provide a means to (1) define stratal surfaces that relate to base-level fluctuation and (2) recognize reef complexes deposited at different times. Therefore, the combined approach adopted here for the Llucmajor reef complex has the potential to provide cross-facies chronostratigraphic correlations in detached platform carbonate settings, and since both methods can be applied to core and cuttings samples, the approach could work in subsurface settings where samples would be from well bores.

KEY WORDS: stratigraphy, chemostratigraphy, magnetic susceptibility (χ), carbonate platform, Llucmajor Platform, Mallorca, Upper Miocene

ORIGIN OF MIXED CARBONATE AND SILICICLASTIC SEQUENCES AT THE MARGIN OF A "GIANT" PLATFORM DURING THE QUATERNARY (BONAPARTE BASIN, NWAUSTRALIA)

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ABSTRACT: A 630-km-wide continental shelf characterized by mixed carbonate and siliciclastic sedimentation formed during the Quaternary across the Bonaparte Basin, NWAustralia. During this time interval (~2.6 million years), shelf-margin and slope deposits were disconnected from the inner shelf and hinterland by the 200-km-wide, low-gradient Malita intrashelf basin. In this study, two-dimensional (2D) and three-dimensional (3D) seismic, well log, and core data were used to determine the relative importance of allogenic and autogenic controls on the stratigraphic architecture of shelf-edge and slope deposits at multiple timescales. This work has determined that Quaternary sea-level variations (glacio-eustasy) provided a primary control on the stratigraphic evolution of shelf-margin and slope deposits. The early Quaternary period was marked by the aggradation and progradation of a carbonate margin under global sea-level highstand conditions. The onset of high-amplitude sea-level fluctuations at the Mid-Pleistocene Transition (ca. 0.9 Ma BP) enhanced the development of a mixed clastic–carbonate margin and slope system. During the late Quaternary, long-duration sea-level falls and lowstands and high rates of terrigenous sediment supply resulted in stacked fourth- and fifth-order systems tracts in the form of prograded shelf-margin and slope wedges. Conversely, rapid, high-amplitude, fourth- and fifth-order transgressions between these time intervals enhanced the aggradation of carbonate buildups at the shelf edge. Hence, high-frequency sea-level changes resulted in reciprocal sedimentation similar to many other mixed depositional systems of the late Quaternary. However, the main locus of carbonate and mixed deposition across the Bonaparte Basin shelf margin and slope varied spatially at longer times scales. Indeed, conventional seismic data have revealed that the third-order systems tracts at two separate locations in the Bonaparte Basin (eastern and northwestern shelf-margin) show stratigraphic asymmetry (rimmed carbonate margin vs. shelf-margin and slope progradation), which reversed during the late Quaternary. Our results suggest that this reversal in the locus of carbonate vs. mixed sedimentation was related to the shift of the detrital feeder system (the Malita tidal valley) during a major sea-level fall of the late Quaternary (tentatively ascribed to the ca. 0.6 Ma BP lowstand). This study illustrates the importance of both allogenic and autogenic parameters in controlling the stratigraphic architecture of shelf-margin and slope deposits at multiple timescales, in a very wide, mixed carbonate and clastic depositional setting.

KEY WORDS: continental shelf, reciprocal sedimentation, intrashelf basin, Quaternary, Bonaparte Basin

SEQUENCE STRATIGRAPHIC ARCHITECTURE AND EVOLUTION OF PLATFORM MARGIN TO BASIN SEDIMENTATION: THE DEVONIAN BEAVERHILL LAKE GROUP IN ALBERTA, CANADA

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ABSTRACT: Stratal stacking patterns and platform distribution within the Devonian Beaverhill Lake Sequence of northern Alberta were influenced by several factors, those that were primarily external (e.g., climate change, trade-wind flow, terrigenous mud supply) and those that were internal (e.g., carbonate factory, water circulation, basin topography). Within the first-rank Beaverhill Lake Sequence, our study revealed two second-rank (1, 2) and 10 third-rank (A–J) transgressive–regressive (T–R) sequences within the Beaverhill Lake Sequence, many of which were progradational and basinfilling, even during a relative rise in sea level. Furthermore, our study reveals three distinct phases of sedimentation during the depositional interval.

The first phase of sedimentation occurred during T–R sequence A. During the initial sea-level rise of sequence A, the Peace River Arch fringing platform and Hay River platform initiated along the western margin of the study area. Platforms aggraded, but they did not prograde significantly, likely because detrital carbonate sediment was transported by surface currents into the inner platform and because of the proximity of the platforms to a limited but adequate supply of nutrients. The condensed limestone across the shallow Waterways Subbasin at the end of sequence A was produced by a local carbonate factory within or near the base of the photic zone, but under nutrient-starved conditions. Slope environments near the platforms contained a mixture of locally produced carbonate sediment and transported allochems. Therefore, this first phase of sedimentation during the Beaverhill Lake Sequence contains circulation- and nutrient-constrained carbonate platforms on the western side of the study area and limited carbonate accumulation within a shallow basin. Mixing of sediments between the two environments occurred only within slope deposits.

The second phase of sedimentation occurred during the clinoformal infilling of the Waterways Subbasin with the progradation of the carbonate–siliciclastic Eastern Platform, the drowning and burial of the Hay River platform, and the back stepping of the Peace River Arch fringing platform. Lithofacies and faunas found on the Eastern Platform generally grade into deeper-water components, often by the increase in argillaceous sediment in carbonate beds and the loss of shallow-water organisms. Basinal sediments are mainly argillaceous in the thin toes of the clinoforms in the Waterways Subbasin. Evidence of sediment transport by gravity flow or other mechanisms from the Eastern Platform down the slope and into the basin is rare in core and restricted to occasional tempestite-like beds and individual allochems derived from shallow-water organisms. Although the transport of micrite basinward by water currents is likely to have occurred, an in situ fauna inhabited at least the upper portion of the slope environment and produced carbonate sediment.

The third and final phase of sedimentation in the Beaverhill Lake Sequence was generally aggradational, with a much-reduced difference in topography between the Eastern Platform and the Waterways Subbasin. Lithofacies and faunas found on the Eastern Platform can be traced into the Waterways

Subbasin. Faunas change little, but lithofacies tend to become more argillaceous throughout the study area. The definition of the Eastern Platform margin can only be seen in cross section where carbonates thin abruptly westward.

KEY WORDS: sequence stratigraphy, Western Canada Sedimentary Basin, carbonate platform, climate change

CARBONATE MARGIN, SLOPE, AND BASIN FACIES OF THE LISBURNE GROUP (CARBONIFEROUS–PERMIAN) IN NORTHERN ALASKA

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ABSTRACT: The Lisburne Group (Carboniferous–Permian) consists of a carbonate platform that extends for >1000 km across northern Alaska, and diverse margin, slope, and basin facies that contain world-class deposits of Zn and Ba, notable phosphorites, and petroleum source rocks. Lithologic, paleontologic, isotopic, geochemical, and seismic data gathered from outcrop and subsurface studies during the past 20 years allow us to delineate the distribution, composition, and age of the off-platform facies, and to better understand the physical and chemical conditions under which they formed.

The southern edge of the Lisburne platform changed from a gently sloping, homoclinal ramp in the east to a tectonically complex, distally steepened margin in the west that was partly bisected by the extensional Kuna Basin (~200 by 600 km). Carbonate turbidites, black mudrocks, and radiolarian chert accumulated in this basin; turbidites were generated mainly during times of eustatic rise in the late Early and middle Late Mississippian. Interbedded black mudrocks (up to 20 wt% total organic carbon), granular and nodular phosphorite (up to 37 wt% P_2O_5), and fine-grained limestone rich in radiolarians and sponge spicules formed along basin margins during the middle Late Mississippian in response to a nutrient-rich, upwelling regime.

Detrital zircons from a turbidite sample in the western Kuna Basin have mainly Neoproterozoic through early Paleozoic U-Pb ages (~900–400 Ma), with subordinate populations of Mesoproterozoic and late Paleoproterozoic grains. This age distribution is similar to that found in slightly older rocks along the northern and western margins of the basin. It also resembles age distributions reported from Carboniferous and older strata elsewhere in northwestern Alaska and on Wrangel Island.

Geochemical and isotopic data indicate that suboxic, denitrifying conditions prevailed in the Kuna Basin and along its margins. High V/Mo, Cr/Mo, and Re/Mo ratios (all marine fractions [MF]) and low MnO contents (≤0.01 wt%) characterize Lisburne black mudrocks. Low Cr_{MF}/V_{MF} ratios (mostly 0.8–4.0) suggest moderately to strongly denitrifying conditions in suboxic bottom waters during siliciclastic and phosphorite sedimentation. Elevated to high Mo contents (31–135 ppm) in some samples are consistent with seasonal to intermittent sulfidic conditions in bottom waters, developed mainly along the basin margin. High $\delta^{15}N$ values (6–12‰) imply that the waters supplying nutrients to primary producers in the photic zone had a history of denitrification either in the water column or in underlying sediments.

Demise of the Lisburne platform was diachronous and reflects tectonic, eustatic, and environmental drivers. Southwestern, south-central, and northwestern parts of the platform drowned during the Late Mississippian, coincident with Zn and Ba metallogenesis within the Kuna Basin and phosphogenesis along basin margins. This drowning was temporary (except in the southwest) and likely due to eutrophication associated with upwelling and sea-level rise enhanced by regional extension, which allowed suboxic, denitrifying waters to form on platform margins. Final drowning in the south-central area occurred in the Early Pennsylvanian and also may have been linked to regional extension. In the northwest, platform sedimentation persisted into the Permian; its demise there appears to have been due to increased siliciclastic input. Climatic cooling may have produced additional stress on parts of the Lisburne platform biota during Pennsylvanian and Permian times.

KEY WORDS: carbonates, black mudrocks, phosphorites, upwelling, Alaska

LOWER JURASSIC MICROBIAL AND SKELETAL CARBONATE FACTORIES AND PLATFORM GEOMETRY (DJEBEL BOU DAHAR, HIGH ATLAS, MOROCCO)

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ABSTRACT: The well-exposed Djebel Bou Dahar (DBD) carbonate platform (Lower Jurassic, High Atlas, Morocco) demonstrates the role played by different carbonate factories on the growth and architectural evolution of a high-relief, flat-topped carbonate depositional system. It also shows, in contrast with the generally accepted idea that lithiotid bivalve accumulations dominated Lower Jurassic platform margins, that microbial carbonates substantially contributed to the carbonate factory, as in Upper Jurassic reefs.

The DBD carbonate depositional system accumulated on the footwall high of an active marine rift. Its depositional architecture evolved from a low-relief ramp profile (Hettangian p.p.–Sinemurian) to a high-relief platform with slopes up to 32° and 600 m in relief (uppermost Sinemurian–Pliensbachian) as a function of changes in accommodation and carbonate factory. The Sinemurian low-relief system consisted of siliceous sponge microbial mounds associated with coated grain skeletal packstone and grainstone in middle and outer ramp facies belts. This deep-water carbonate factory did not build into wave-agitated shallow settings and lacked the capability of constructing high-relief platform margins. From the latest Sinemurian, the platform built significant relief and the slope steepened (20–32°). This switch in platform architecture coincided with the accumulation of a highly productive, coral calcareous sponge microbial boundstone at the platform margin and on the slope (from 10 to 60 m in depth). This was adjacent to deeper water siliceous sponge microbial boundstone (from 60 to 140 m below the platform break). During the late Pliensbachian increased accommodation and retrogradation, coral calcareous sponge microbial boundstone extended from the upper slope onto the outermost platform, 350 to 400 m inward of the platform break, associated with microbial microencruster boundstone and lithiotid bivalve biostromes. During this aggradational–retrogradational phase, microbialites were able to expand on the outer platform top because low-energy substrates were made available on the platform top by increased accommodation. Outer platform strata consisted of coral calcareous sponge microbial boundstone and coated grain skeletal grainstone, dipping 58 basinward, as observed in other Mesozoic and Paleozoic microbial boundstone–dominated platform margins. The platform interior was dominated by subtidal peloidal skeletal packstone with Cayeuxia-calcified cyanobacteria and intertidal fenestral packstone with laminated microbial boundstone, which contributed to the sediment budget maintaining a flat-topped platform interior geometry.

The DBD shares similarities for facies and depositional geometry with Upper Jurassic Southern Tethyan and North Atlantic carbonate systems, implying that the main components of Upper Jurassic reefs were already present in the Early Jurassic rift basin of Morocco.

KEY WORDS: Early Jurassic, carbonate platform, microbialites, coral reefs, Morocco

HOLOCENE ACCRETION RATES AND STYLES FOR CARIBBEAN CORAL REEFS: LESSONS FOR THE PAST AND FUTURE

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ABSTRACT: Early studies stressed the high accretionary potential of Caribbean coral reefs (10–15 m/kyr). Cores from St. Croix (US Virgin Islands) suggested that the earliest reefs along the shelf edge were dominated by rapidly growing *Acropora palmata*. As the bank flooded, soil mobilized by wave action moved off the bank, killed these reefs, and prevented subsequent reef development for at least 2000 years. Because the shelf east of St. Croix is similar to many Caribbean sites, it was proposed that this model was widely applicable throughout the region.

More recent data from cores and outcrops throughout the Caribbean show that reefs on St. Croix and elsewhere flourished throughout the hiatus originally proposed to have occurred between 10,000 and at least 8000 years ago. Furthermore, data compiled from all known Caribbean cores suggest that reefs built at rates averaging only 3.47 m/kyr and that reef-accretion rates above 7 m/kyr were exceedingly rare. The pattern of reef building and abandonment over the past 20,000 years is consistent with these findings. Reefs easily kept up with sea level when it was rising at rates below 3–5 m/kyr, and back-stepping consistently occurred throughout the intervening interval when sea level rose at rates up to 10 m/kyr.

While sudden shifts in sea level have been well documented in the geologic record and degraded water quality will undoubtedly compromise reef building, triggers for back-stepping need not be confined to these scenarios. The mechanisms for back-stepping are complicated and still poorly understood. In virtually every well-documented case for the Holocene, neither community structure nor water depth over the abandoned reefs and their landward replacements were significantly different. Each new reef formed as sea level rose over an antecedent feature that favored reef formation, and its success was largely determined by the rate of sea-level rise at the time accretion began. Reefs that formed when sea level was rising faster than 3–4 m/kyr were eventually abandoned.

The scale of these reefs and the magnitude of back-stepping are similar to many ancient examples. Assumptions that these reflect sudden shifts in sea level or severe environmental conditions should be reexamined in light of the realization that back-stepping can also be explained by physical and biological processes that are observable within the lifetime of a single reef scientist.

KEY WORDS: coral reefs, Holocene, sea level, back-stepping, facies architecture

ANNEALING THE CHICXULUB IMPACT: PALEOGENE YUCATA` N CARBONATE SLOPE DEVELOPMENT IN THE CHICXULUB IMPACT BASIN, MEXICO

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ABSTRACT: Stratigraphic analysis of the Yaxcopoil-1 core (Yax-1) and seismic analysis of offshore two-dimensional (2D) seismic data provide insight into the Paleogene history of the Chicxulub impact basin and Yucatàn platform development. Ten facies were identified based on core and petrographic analysis. Slope sediments include redeposited and background facies. The former are carbonate supportstones and finer-grained facies with evidence of soft sediment deformation deposited as gravity flows. Background facies are shales and mud–wackestone interpreted as sub-storm wave base suspension deposits. Depositional setting ranged from a steep bathyal slope inside the crater rim to neritic outer carbonate platform environments of the seaward prograding Yucatàn platform.

Through sequence stratigraphic analysis of Yax-1, we documented five sequences based on identification of transgressive and maximum flooding surfaces and facies stacking patterns. Biostratigraphic ages are equivocal, but they imply that sequences 1 and 2 are Early Paleocene, sequences 3 and 4 are Early Eocene, and sequence 5 is Middle Eocene. Coarse-grained redeposited carbonates in lower sequences 1 to 4 indicate slope gravity flow processes. Upper sequence 3 records the first evidence of fine-grained turbidites, indicating progradation of the Yucatàn platform. By the top of sequence 4, facies indicate that the platform margin had prograded over the position of Yax-1.

Seismic analysis identified six units, the lower five of which appear to correlate with cored Yax-1 sequences. The geometry and distribution of seismic units A and B indicate deposition confined to the western and central parts of the basin. Unit C, with two sets of clinoforms, records a major progradational event in the eastern part of the basin likely related to Yax-1 sequence 3 turbidites. Mainly parallel reflectors in seismic units D and E indicate relatively level bottom conditions similar to the environments of facies in upper sequence 4 and 5. The tops of units D and E, in proximal settings, are erosionally truncated. This unconformity marks the base of unit F, which is characterized by discontinuous reflectors and is restricted to the northeastern portion of the basin.

Stratal patterns in seismic units C to E are more controlled by relative sea-level change, as suggested by the development of clinoforms and regional unconformities. If Chicxulub and others like the Chesapeake Bay structure are representative, large marine impacts in tectonically quiescent regions may dominate local depositional environments for millions to tens of millions of years postimpact before returning control to eustasy.

KEY WORDS: Chicxulub, Yucatàn, seismic stratigraphy, Paleogene

LOWER PERMIAN (WOLFCAMPIAN) CARBONATE SHELF-MARGIN AND SLOPE FACIES, CENTRAL BASIN PLATFORM AND HUECO MOUNTAINS, PERMIAN BASIN, WEST TEXAS, USA

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ABSTRACT: Lower Permian (Wolfcampian) carbonate platform margin depositional profiles and stratigraphic architecture were controlled primarily by the type of reef community that characterized the time, peak icehouse glacioeustatic sea-level fluctuations, and regional tectonic pulses from the paleocontinental collision along the southern margin of the basin. During transgressions, mound-shaped reef cores began growth in sub-wavebase, lowlight (oligophotic), upper slope settings. The reef mound communities quickly diversified, and the reef mounds aggraded and shallowed upward through the euphotic zone, eventually reaching wavebase during early highstand, and graded upward into progradational crestal shelf-margin shoals during late highstand. Reef mound growth seaward of and downdip from the crestal platform margin shoals resulted in distally-steepened platform margin profiles, which persisted throughout Permian time.Wolfcampian reef mound facies are composed of bafflestones–boundstones with frameworks of phylloid algae, calcisponges and heliosponges, and fenestrate and ramose bryozoans, which were encrusted by *Tubiphytes*, laminar encrusting red algae (*Archaeolithoporella*), fistuliporid bryozoans, and microbialite. Peloidal cement matrices are common. Syndepositional to early marine botryoidal radial fibrous cements are generally sparse but are more common in windward margin buildups. Reef mound cores are surrounded by shallowingupward skeletal packstone to grainstone flank beds. Crestal shelf-margin shoals are composed of medium- to coarse-grained grainstones with fusulinids, *Tubiphytes*, and robust dasycladacean algae, and contain small *Tubiphytes* patch reefs.

Early Permian icehouse glacioeustatic sea-level fluctuations and episodic tectonic pulses created erosional paleotopography on unconformities near the base of the Wolfcampian and at the mid-Wolfcampian. On the eastern margin of the Central Basin Platform, Lower Hueco Group (lower Wolfcampian) carbonate bank complexes composed of reef mounds and packstone–grainstone flank beds grew along an erosional escarpment on the underlying Bursum Formation (uppermost Pennsylvanian), as seen at South Cowden (8790 Canyon) Field, Ector County, Texas. The escarpment depositional slope was >10°. Reservoir porosity in the Lower Hueco platform margin carbonate banks was greatly enhanced by subaerial exposure and meteoric dissolution at the overlying mid-Wolfcampian unconformity. Lithoclastic–skeletal debris flows are common in Wolfcampian forebank, deeper water, slope-to-basin facies.

Outcrop analogs for the subsurface carbonate platform margin banks and forebank slope-to-basin facies are well exposed in the Hueco Group of the western outliers of the Hueco Mountains in far west Texas, which were paleogeographically located along the western (leeward) margin of the Diablo Platform and adjacent Orogrande Basin. Platform margin banks prograded over an irregular paleotopographic surface on the sub–Hueco Group erosional unconformity. The leeward upper slope to shelf-margin reef mounds have phylloid algal-dominated core facies with only sparse radial fibrous cements, which graded rapidly upward near wavebase into crestal shelf-margin grainstone shoals with *Tubiphytes* patch reefs. Proximal forereef, upper slope facies are composed of autochthonous upper slope crinoidal–fusulinid packstones, burrowed dark mudstones, and productid brachiopod wackestones and have interbedded allochthonous tongues of forereef grainflows, turbidites, and lithoclastic–skeletal packstone debris flows. More distal slope-to-basin facies are composed of autochthonous dark cherty nonburrowed mudstones–wackestones with interbedded allochthonous lithoclastic–skeletal packstone debris flow deposits and turbidites. Slope facies distributions reflect icehouse glacioeustatic sea-level fluctuations.

KEY WORDS: shelf-margin, reefs, Lower Permian, Wolfcampian, Permian Basin

RESERVOIR-ANALOG MODELING OF FOCUSED-FLOWAND DISPERSEDFLOW DEEP-WATER CARBONATES: MIOCENE AGUA AMARGA BASIN, SOUTHEAST SPAIN

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ABSTRACT: Outcrop-based, reservoir-analog models are important tools for assessing reservoir potential and efficient schemes for exploitation in the subsurface. A new outcrop reservoir-analog model is documented herein for Upper Miocene deep-water sediment-gravity-flow and hemipelagic deposits within the Agua Amarga basin, southeast Spain. This study demonstrates that large volumes of resedimented deposits exhibiting high ratios of potential reservoir to baffle facies (net to gross) accumulate where funneling topographic features focus sediment-gravity flows from the long linear dimension of a carbonate platform into a confined channel (focused flow). Where topographic funneling features are absent, and where a short linear dimension of the carbonate platform margin is available as a source of sediment-gravity flows, deposits accumulate with lower volumes and high proportions of baffle facies (dispersed flow).

Extensive outcrops in the Agua Amarga basin allow for characterization of facies and facies architecture using measured sections, photomosaics, and core-plug petrophysical data. Petrae and Petrele were used for correlation, data integration, and static geomodeling to create a reservoir-analog model that synthesized geological observations noted in outcrop. Facies modeled as reservoir units consist of graded fine- to very coarse-grained skeletal packstones and fine- to very coarse-grained breccias. Graded skeletal packstone facies exhibit a mean porosity and corresponding permeability of 30.5% and 136 mD; breccia facies exhibit a mean porosity and corresponding permeability of 30% and 65 mD. Facies modeled as baffle units consist of foraminiferal, volcaniclastic foraminiferal, and skeletal foraminiferal wacke–packstones. These planktonic foraminifera-rich facies exhibit a mean porosity and corresponding permeability of 36% and 12 mD.

Paleotopography, in conjunction with sea-level history, largely controls the geometry, lateral continuity, and volume of a given reservoir body. Paleotopographic differences that lead to focused flow versus dispersed flow result in markedly different reservoir properties. Static model volumetric results reveal that compared to the dispersed-flow system, deposits within the focused-flow system have greater reservoir to baffle facies volume ratios (0.70 compared to 0.09), and greater reservoir facies bulk volumes (46.5 million m3 compared to 18.6 million m3). Further, the ratio of reservoir facies bulk volume to linear dimension of the shelf margin supplying both the focused-flow and dispersed-flow systems is similar, suggesting that deep-water reservoir volume may be predictable on the basis of the linear dimension of the shelf margin. Finally, interrogating modeled reservoir facies for different connected volume scenarios offers significant insight relevant to subsurface exploitation strategy and supports observations noted in the field.

KEY WORDS: carbonate stratigraphy, outcrop-analog modeling, sediment-gravity flow, deep-water, slope

RESERVOIR COMPARTMENTALIZATION OF A DEEP-WATER OOID FAN, HAPPY FIELD, PERMIAN BASIN

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ABSTRACT: The Permian (Leonardian) Upper Spraberry Formation in the Happy Field of Garza County, Texas, contains an excellent example of a reservoir composed of resedimented carbonates in a deep-water slope–basin setting. The field has one of the most complete data sets of any producing deep-water carbonate reservoir known, including 15 whole cores with matching full suites of electric logs, and high-resolution three-dimensional (3D) seismic data. Sequence stratigraphic analysis combined with detailed characterization of analogous outcrops, detailed core-based sedimentology, and well-log analysis indicate that the Happy Field ooid fans are positioned within the transgressive systems tract of the fifth composite sequence in the Leonardian. The main reservoir facies are resedimented ooid and skeletal grainstone hyperconcentrated density flows that were focused downslope through a probable reentrant in the shelf margin and deposited in a long-lived topographic depression at the toe-of-slope. Vertical heterogeneity is set up by laterally extensive shale and silt beds that punctuate the oolitic density flows. Lateral heterogeneity and compartmentalization within the reservoir are created by younger mixed carbonate–siliciclastic debris flows that are highly erosive and are characterized by relatively low permeability.

KEY WORDS: toe-of-slope, carbonate debris flow, ooid fan, reservoir, Leonardian

DISTAL FACIES VARIABILITY WITHIN THE UPPER TRIASSIC PART OF THE OTUK FORMATION IN NORTHERN ALASKA

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ABSTRACT: The Triassic–Jurassic Otuk Formation is a potentially important source rock in allochthonous structural positions in the northern foothills of the Brooks Range in the North Slope of Alaska. This study focuses on three localities of the Upper Triassic (Norian) limestone member, which form a present-day, 110-km-long, east–west transect in the central Brooks Range. All three sections are within the structurally lowest Endicott Mountain allochthon and are interpreted to have been deposited along a marine outer shelf with a ramp geometry.

The uppermost limestone member of the Otuk was chosen for this study in order to better understand lateral and vertical variability within carbonate source rocks, to aid prediction of organic richness, and ultimately, to evaluate the potential for these units to act as continuous (or unconventional) reservoirs. At each locality, 1 to 4 m sections of the limestone member were measured and sampled in detail to capture fine-scale features. Hand sample and thin section descriptions reveal four major microfacies in the study area, and one diagenetically recrystallized microfacies. Microfacies 1 and 2 are interpreted to represent redeposition of material by downslope transport, whereas microfacies 3 and 4 have high total organic carbon (TOC) values and are classified as primary depositional organofacies. Microfacies 3 is interpreted to have been deposited under primarily high productivity conditions, with high concentrations of radiolarian tests. Microfacies 4 was deposited under the lowest relative-oxygen conditions, but abundant thin bivalve shells indicate that the sediment–water interface was probably not anoxic.

The Otuk Formation is interpreted to have been deposited outboard of a southwest-facing ramp margin, with the location of the three limestone outcrops likely in relatively close proximity during deposition. All three sections have evidence of transported material, implying that the Triassic Alaskan Basin was not a low-energy, deep-water setting, but rather a dynamic system with intermittent, yet significant, downslope flow. Upwelling played an important role in the small-scale vertical variability in microfacies. The zone of upwelling and resultant oxygen-minimum zone may have migrated across the ramp during fourth- or fifth-order sea-level changes.

KEY WORDS: Otuk, Triassic, Alaska, microfacies, upwelling