Evolution of Shallow Marine Sedimentary Bodies: A Perspective

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One conceptual consideration which is lacking in current sedimentary research is the recognition that many shallow marine sand bodies are of composite origin, having evolved from an initial state to their final depositional form prior to preservation and burial. Because the associated sedimentary clues (physical, biogenic, textural) give mixed signals and do not entirely reflect either state, there is room for considerable interpretational variation. This explains much of the debate surrounding enigmatic sand bodies like the Shannon of Wyoming, Tocito of New Mexico, and Cardium of Canada. The variability in the evidence exceeds that expected from simple passive reworking.

We advocate that many shallow marine sand bodies (deltas, shelf ridges, shorelines, etc.) "evolve" in an active, even predictable fashion, as a function of the need to adjust to changing boundary conditions, as supply, accommodation, coastal morphology and dominant process changes. There is mounting evidence from modern sediments and ancient strata that sand body evolution is as important as the processes which initiate deposition of a sand body. To some extent this is reflected in a recent acceptance that base level as well as process molds facies models and changes in coastline type. Sand body evolution is accompanied by significant changes in sedimentary characteristics like shape, orientation, internal stratification, dimensions, micro-and macrofauna, biogenic structures, and texture.

Such evolution can occur within a single progradational episode, for example, as a function of changing hydrodynamics, or during a complete base-level cycle as a transition from lowstand to transgression, highstand to transgression, or transgressive episodes within an overall regression. This evolution, not simply a reworking, involves dynamic changes in sand body type and 3-D variability. Examples from the modern and ancient are reviewed, with a proposed classification scheme, and discussion of methods to decipher the precursor sand body from the final depositional form.

Moreton Bay, Southeast Queensland, a Modern Analogue for Clastic Reservoirs Deposited in Wave-Tide Dominated, Coastal and Shallow Marine and Shelf Depositional Systems

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Moreton Bay and the adjacent coastline in SE Queensland provide a natural laboratory in which to study the sedimentology, coastal evolution and sequence stratigraphy of a wave dominated, mesotidal sandy clastic depositional system. The area is ~130km long and ~50km wide, a broadly elongate, marine-estuarine embayment, partially protected by dune-island barriers that grade through the shoreface across a ~50km wide continental shelf.

A wide range of depositional environments exist in close proximity, ranging from bayhead deltas, sandy and mixed sandy-muddy tidal-flats, tidal channels and bars, flood- and ebb-tidal deltas and associated tidal inlet channels, barrier shorelines and strandplains, back-barrier lagoons and open marine embayments including local carbonate reefs, and coastal salt marshes and floodplain, muddy estuaries, and aeolian dune complexes on the main dune-island barriers (South and North Stradbroke, Moreton and Bribie islands). Offshore are high-energy shorefaces, mid-shelf sand ridges, and outer shelf mixed terrigenous and relict cool-water carbonate sand sheets.

These depositional environments make excellent analogues for clastic reservoirs currently being explored or producing from basins around Australia, SE Asia, and elsewhere. Based on an extensive program of boomer and sparker seismic profiling, coastal geomorphic and sediment mapping, drilling, and age-dating, a comprehensive dataset has been collated that underpins not only basic statistics for reservoir distribution, geometry and primary textural/compositional characteristics, but also a high-resolution sequence stratigraphic framework linking changes in climate, sea-level and sediment supply from lowstand, transgressive and highstand systems tracts developed during the late Pleistocene. These provide useful reality-checks for interpreting reservoir stratigraphy and associated connectivity.

Hyperpycnal Versus Hypopycnal River Plumes and the Origin of Shelf Mud

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Many sedimentological textbooks assume that most marine “shelf” mud is deposited by fallout from suspension in quiet water. Work on modern active muddy shelves, such as Papua New Guinea and the Amazon Shelf, show that sediment is mostly supplied from rivers plumes that may be hyperpycnal or hypopycnal. These concepts have not been widely applied to the interpretation of ancient sedimentary systems, such as the Cretaceous Western Interior Seaway of North America.

Comparison of the paleohydraulics of Cretaceous trunk river systems suggest that these systems frequently went hyperpycnal. Associated flood deposits show extremely high sedimentation rates of up to 1 m per year. High sedimentation rates are indicated by an abundance of normally graded siltstone beds, climbing ripples, and soft-sediment deformation. Associated high stresses result in a lack of infaunal burrowing, a lack of suspension feeders, and an abundance of fugichnia. Associated sandstones show well-developed Bouma sequences, suggesting hyperpycnal sandy-river-flood deposits, or over-thick HCS beds, caused by storm-wave reworking of flood deposits.

Mudstones associated with hypopycnal conditions show far higher abundance and diversity of ichnofauna. Where the shelf experiences neither hypopycnal nor hyperpycnal processes, carbonate productivity tends to increase, resulting in increased carbonate content forming units like the Austin Chalk. In contrast, shale-dominated “shelf” mudstones have a strong pro-deltaic overprint.

Carbonate Sedimentation and Reefs on Australia's Western Margin

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The continental shelves of Australia's western margin are narrow and wave-dominated in the south, and are wide ramps influenced by tides and cyclonic storms in the north. Though less continuously developed than in eastern Australia, coral reefs are present in fringing to deep ramp settings from latitudes 12 to 30 degrees S, providing a spectrum of responses to sea-level and subsidence changes. A biotic transition zone, characterised by overlap of temperate and tropical assemblages, occurs between the latitudes of 26 and 30 degrees S. The margin is strongly influenced by the poleward-flowing, warm nutrient-poor Leeuwin Current , which promotes overall downwelling, and strong summer equatorward-blowing winds, which generate local seasonal upwelling.
Whilst the more southerly shelves are dominated by bryozoans and coralline red algae, similar to the vast cool water southern margin, the warm water ramp which comprises the Northwest Shelf is tropical in character, with a mixture of sediments of relict, stranded and Holocene origins. Ooids and peloids are conspicuous but stranded particles which formed during initial stages of post-Last Glacial maximum sea-level rise, but were terminated by less saline Leeuwin Current flow, so that subsequent Holocene sedimentation is biofragmental to planktic.
As the physical, oceanographic and sea-level processes generating these modern shelf systems are evaluated more fully they are likely to assist further in the evaluation of similar ancient facies on carbonate platforms with reservoir potential.

High-Resolution Quaternary Reservoir Analogues from the Northern New South Wales Shelf

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The Pleistocene paleogeography to present day geomorphology of the Northern New South Wales Shelf has been constructed using an integrated sequence stratigraphic analysis. The data set comprises 34 000 bathymetric soundings, 320 surface samples and 450 km of closely spaced side scan sonar data. Subsurface data includes 46 vibracores, 349 km of closely spaced (250-500 m) seismic profiles and 450 line km of regional seismic. Absolute age control is provided by 37 radiocarbon samples and an optically-stimulated thermoluminescence (OSL).
Pleistocene (30 to 130 ka BP) progradational shoreface-barrier complexes, marine sands, bayhead delta, estuarine channels and flood-tide deltas occupy a 14 km wide by 15 m thick zone beneath the inner shelf. These paleo-environments are separated by strong seaward dipping reflectors that dissect Oxygen Isotope Stage 3 and 5 barrier complexes, which are interpreted as Transgressive Surfaces of Marine Erosion. Less laterally extensive, sub-horizontal reflectors are interpreted as Regressive Surfaces of Erosion that formed during low sea level times.
Latest Pleistocene-Holocene estuarine clays, muds, sands, gravels up to 8.5 m thick overlie the Pleistocene barrier complexes. These estuarine units resemble cores from the modern NNSW coastal plain. A diachronous (12-14 ka BP) transgressive wave-ravinement surface produced during the Latest Pleistocene sea level rise is correlatable across the entire shelf. Internal tidal ravinement surfaces are also preserved despite microtidal conditions, high wave energy and the low accommodation setting.
The present day Northern New South Wales Margin is a mixed siliclastic-carbonate province that experiences both year-round high-energy waves and a strong oceanic current. Quaternary studies from the NNSW margin challenge classic sequence stratigraphic models of sand-body geometries, as well as the character and distribution of major stratigraphic surfaces.

A Holocene Example of a Forced Regression: Wave-Dominated Shoreface and Back/Barrier Sediments from Forster, Southeast Australia

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Shorefaces deposited under falling sea level conditions are distinguished by their sharp bases and abrupt vertical transition from underlying shelf mudstones. As exploration targets they have been well documented in ancient rocks, but there are few modern analogues. The shelf region offshore of Forster, NSW provides an ideal opportunity to reconstruct facies architecture and sequence stratigraphy of a Late Quaternary suite of forced-regressive shorefaces deposited in a low accommodation setting, based on an exceptional dataset of seismic, vibracore, and radiocarbon dates. The Pleistocene interstadial sandstone is 5-16 m thick and extends seaward 20-25 km. It consists of five shingled packages, each comprising a regressive shoreface/barrier wedge with an associated backbarrier estuary/lagoon that is partially eroded. Each shoreface has a clearly visible landward termination, in the form of a strong, concave reflector dipping seaward at 1° to 1.5°. More subdued internal reflectors within the rest of the shoreface indicate progradation. The basal surfaces of the five individual shorefaces coincide to form a bundle of strong, parallel, seaward-dipping reflectors (0.2°). The two most seaward shorefaces contain an internal reflector which is irregular, and slightly erosional. Chronostratigraphic analysis indicates that deposition occurred during Holocene Stage 3, a period marked by multiple sea level fluctuations with an overall falling trend. Each of the five packages is associated with a small-scale (10-20 m) eustatic cycle. The landward termination of individual shorefaces marks the limit of transgressive incision, which caused partial erosion of the back-barrier lagoons. During subsequent sea level fall the shoreface prograded over a regressive surface of erosion, producing the strong basal reflectors. A secondary regressive surface of erosion, within the shoreface unit itself, is an unusual feature and appears to have formed in the nearshore zone.

Shelf/Margin Deltas: Attributes of an Ideal Hydrocarbon Trap

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Shelf/margin deltas have four primary attributes that make them such significant reservoirs:
Shelf-edge deltas progrades into relatively deep water where wave energy is less attenuated than for similar environments inboard on the shelf. The high energy wave dominated environment facilitates mechanical weathering of the sands resulting in reservoirs that retain producible porosity and permeability to depths of 20,000 feet (6,200 meters).

Following shelf/margin delta deposition the transgression is rapid across the relatively planar coastal plain. Coarse-clastics are impounded progressive farther landward resulting in deposition of clean organic-rich and ductile clays on the outer shelf and upper slope. These clays resist fracturing and provide fault sealing gouge making ideal seal for the deltaic sands.

Shelf-edge growth-faulting is most active during differential loading when the sand-rich rivers are supplying high volumes of sediment to the shelf/margin. The sediment supply in-fills the fault generated accommodation space depositing thick multistoried sand packages in the hanging wall section. As the fault continues growing the hanging wall is folded into a roll-over anticline placing the deltaic sands into a trapping configuration.

During growth-fault movement there is relative extension of the fault zone allowing fluids to move upward along the fault plane. If the fault system taps into a hydrocarbon kitchen or pool of migrated hydrocarbons, the oil and gas can migrated up the fault into the trapping reservoirs sealed by the Transgressive claystone.

The presentation includes both subsurface and outcrop examples of shelf-margin deltaic complexes from foreland, convergent, cratonic and passive margin basins.

Predicting Coastal Depositional Style: Influence of Accommodation/Sediment Supply and Basin Morphology

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The Middle Jurassic succession in the Sunrise and Troubadour gas-condensate fields (Bonaparte Basin, Timor Sea) is represented by marginal marine strata that were deposited in either fluvial-dominated or wave-dominated, but pervasively tide-influenced coastal environments.

The study indicates that there are direct relationships between the ratio of accommodation/sediment supply (A/S), basin morphology and the dominant character of the preserved depositional systems. When ratios of A/S were high, typical in transgressive and early highstand systems tracts (steeply rising shoreline trajectories), sedimentation rates were too low to fill all the space that was created and the underlying basin morphology became the overriding factor in determining coastline geometry and hence the dominant sedimentation style. The coastline became more embayed and protected from wave energy, such that the depositional systems that evolved were fluvial-dominated. During periods of lower A/S ratios, typical in late highstand or lowstand systems tracts (slightly rising or flat shoreline trajectories), or during periods of accommodation reduction typical in falling-stage systems tracts (falling shoreline trajectories), the sedimentation rate kept pace with or exceeded the rate of accommodation development. Hence, the underlying basin geometry became less important as it was rapidly infilled and the coastlines became less embayed and more open to the direct influence of wave energy. These shorelines were therefore wave-dominated.

A more generalised model was also developed to predict dominant and subordinate coastal depositional processes related to variability in fluvial and wave effectiveness, and a range of basin morphologies or paleogeographies in low and high A/S regimes.

Reservoir Connectivity in Fluvial/Deltaic Depositional Environments: South Timbalier 26 Field Study

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The key to successful development planning is an understanding of reservoir compartmentalization and the distribution of reservoir physical properties. The basis for this understanding is a combination of stratigraphic, structural, and attribute analysis, summarized in geologic models. In producing fields, injector and producer wells provide important information to test and refine the geologic models. We present the results of a reservoir connectivity study in fluvial/deltaic depositional environments based on the South Timbalier 26 field, Gulf of Mexico.

Analysis of the production history of the field, coupled with existing geologic model of the “O” sand was used to define depositionally-controlled reservoir compartments and connectivity. An important characteristic of the “O” sand is the presence of a sandy highstand represented mostly by deltaic sub-environments of a prograding delta. An unconformity (sequence boundary) separates these deltaic deposits from sediments related to the lowstand (fluvial channels, splays and bay muds). Differentiation of these intervals is important to predicting reservoir connectivity and performance.

Production information from wells completed in delta front facies of the HST of the “O” sand suggests that these environments have limited extent and aquifer support. On the other hand, production information from LST fluvial channels and HST distributary channels suggests that both of these sub-environments have good aquifer support and are not well connected to the delta front facies.

Sequence Stratigraphic Controls of Reservoir “Sweet Spots” in Coastal and Shelf Deposits – Cretaceous Guadalupe Formation, Colombia

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Guando oil field, Colombia Upper Magdalena Valley, has estimated OIP of 350 mmbbls, producing more than 27000 bopd from coastal and shelf sediments of the Cretaceous Guadalupe Group. The Guadalupe Group is ~1500 ft thick, with high net-to-gross sand ratio. The reservoir is a complex interfingering of transgressive and regressive shallow-marine deposits including proximal and distal shelf, tidal inlets, incised valleys, marine shale, and deltaic distributaries deposited within a shallow epeiric seaway. Reservoirs vary from very fine sand to conglomerate. Field-wide bounding surfaces include wave-ravinement surfaces, tidal-ravinement surfaces, sequence boundaries; firm grounds revealed by the Glossifungites ichnofacies, and flooding surfaces. Highstand progradational environments include proximal and distal shelf deposits as well as distal offshore marine shales. Highstand deposits are pervasively cemented with syndepositional phosphate. Transgressive environments include tidal-inlet deposits and an estuary-complex facies association; one tidal inlet complex is dominated by micritic carbonate and oyster deposits with minor siliciclastic sandstone facies association. No nonmarine strata are preserved. Optimal quality reservoirs are interspersed throughout the section and occur in tidal inlet and incised valley facies of the transgressive systems tract, with porosity exceeding 25 % and permeability up to 8 Darcies. PSDM processing of 3D seismic allowed recognition of a basal incised valley deposit.