Integrated Model for Vadose Diagenesis of Carbonate Rocks

The composition, morphology, and distribution of vadose diagenetic features are related to extrinsic and intrinsic factors. Extrinsic factors include the total yearly precipitation, and its seasonal distribution, evapotranspiration, and temperature. These influence the total carbon dioxide supplied, and the relative time during which input (by vadose percolation) and loss (by degassing and evapotranspiration) occur. Intrinsic factors include rock type and composition, porosity and permeability, soil cover, and topography. These influence the rate of water infiltration, and the resulting rate at which descending waters become saturated. The interaction of the two factor groups determines the final character of the zones of vadose diagenesis. There results a land surface-, joint-, or fracture-related zone beneath which descending waters are generally saturated and little solution occurs. Also a zone exists beneath which pore fluids and gasses are unaffected by degassing or evapotranspiration, and within which vadose precipitational fabrics are confined.

As such, the zone of active vadose diagenesis may constitute only a small part of the total zone of percolation, much of the zone being characterized by fluids which pass through without altering their composition (i.e., causing no diagenetic alteration of rock fabric or mineralogy). Furthermore, because of the high wettability of most carbonate grains (in the absence of adsorbed organics), pores in the zone of slow degassing and high relative humidity may not display "typical" vadose meniscus cements, but may instead display coatings and fills of euhedral crystals. Consequently, the absence of vadose diagenetic features is probably the more common case (without indicating a lack of exposure). As such, periods of exposure may only be patchily recorded by the presence of vadose diagenetic zones.

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Exploration Strategies as Integral Part of Corporate Strategic Planning

With rising exploration costs, recent stabilization of world oil prices, and local surpluses of natural gas, the "bloom is off the sage" for just finding hydrocarbons as an exploration strategy. Now the explorationist must tie his exploration strategies to his company's strategic planning or, in smaller companies, to their long-term goals and objectives. Without these considerations, the company's exploration efforts will not be successful over the long term. The explorationist must now realize that exploration is a business, not merely a function.

There are two critical areas that need to be defined to combine exploration strategy and strategic planning. The planners' strategic criteria must be consistent and reasonable. Criteria should be designed so that the explorationist can clearly understand his responsibility. The explorationist will need to define his exploration environment. Questions like the following should arise in the explorationist's mind. Should I be exploring in this basin? What field sizes are left to be found? What is a realistic chance of wildcat success for a specific prospect, play, or basin? What mix of prospects will give my program a realistic chance of success?

Recent techniques and methods are available tools for defining the exploration environment. In the mature domestic areas, historical digital data bases can be used to describe the present environment and can project future environments. From these environments, along with geologic considerations, geophysical input and physical restraints such as capital and lease position, an exploration strategy can be created that will be compatible with the company's strategic planning.

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Facies Relationships and Paleoenvironments of a Tide-Dominated Delta—An Estuarine-Barrier Complex in a Mesotidal Setting, Upper Cretaceous, Drumheller, Alberta

The transition between the Bearpaw and Horseshoe Canyon Formations (100 m thick) near Drumheller represents an upward-coarsening deltaic sequence. A detailed field sedimentologic investigation of these rocks has led to the recognition of several distinct lithofacies. In stratigraphic order, the lithofacies of the subaqueous part of the delta are: (1) an offshore bar cross- and hummocky-stratified sandstone, (2) a prodelta marine shale and siltstone, (3) a distal mouth-bar shale, (4) siltstone and sandstone with *Chondrites,* and (5) a proximal mouth-bar sandstone and minor shale with *Teichichnus, Rhizocorallium, Lockeia,* and other burrows. The subaerial part of the delta and the interdeltaic shoreline sediments consist of 15 lithofacies that can be grouped as follows: estuarine distributary channel; barrier; back-barrier; tidal inlets; tidal channels and flats; peat swamp; and middle to upper delta-plain meandering rivers and overbank complexes. Trace fossils associated with these are: *Teredolites* borings, *Ophiomorpha, Teichichnus*?, *Cylindrichnus, Palaeophycus, Asterosoma,* and *Anemonechnus*?. Vertical lithofacies transitions suggest a few transgressive episodes. This sequence was deposited in a mesotidal, embayed shoreline, where a system of meandering distributary channels formed estuarine, tidally dominated deltas flanked by mesotidal barrier-island complexes. Minor transgressions of the sea interrupted the generation of a simple prograding sequence and resulted in formation of very complex facies relations.

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Facies Control of Carbonate Reservoir Properties

The relation between the depositional and diagenetic facies within a carbonate reservoir may affect the success of a secondary-recovery project in terms of the residual oil saturation following displacement of oil by water. Recognition of facies control on the evolution of porosity and permeability aids in the prediction of reservoir performance. Displacement tests, performed on vugular carbonate cores, illustrate this point.

Strongly wetting countercurrent imbibition tests, conducted on full-diameter cores from the Meekwap field in Alberta, reveal the effects of secondary porosity on the displacement of a nonwetting oil phase. In *Amphipore* sp. wackestones, dolomitization and dissolution of *Amphipore* segments have produced a random distribution of small moldic pores that are matrix connected. During water-wet displacement tests, poor displacement efficiency is realized in the high moldic porosity wackestones. Visual observations indicate that the nonwetting oil phase is preferentially trapped in the moldic pores. Reef-core boundstones, composed of a laminar stromatoporoid and algal assemblage, have a pore structure dominated by tabular vugs linked by vertical fractures. In contrast to the moldic pore system, displacement efficiency is maximized in the high porosity intervals as buoyancy forces allow oil to migrate through the vug-fracture system. Visual differentiation of the end-member pore systems will allow the development of a reservoir model that can predict oil recovery within various depositional facies within the reservoir.

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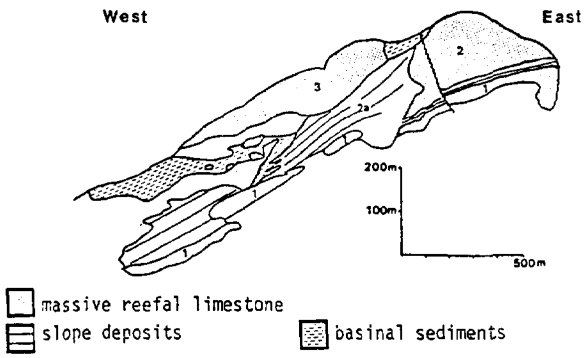
Lime Peak—An Upper Triassic Reef Complex in Yukon

Upper Triassic carbonates in the Whitehorse trough, Yukon, are lenticular bodies surrounded by Triassic graywacke and volcanic-clast conglomerate derived from an arc to the west. The carbonates at Lime Peak are unusually well exposed. They show multiple stages of reef growth and a complete facies zonation from massive reefal limestone to offlapping slope and basin.

The massive reefal limestones have variable lithology from peloidal mudstones to organic framestones containing spongiomorphs, tabulozoans, and calcareous sponges, with lesser contributions from corals, brachiopods, mollusks, algae, and echinoderms.

Cross Section, South Face of Lime Peak



Slope deposits are alternations of thick beds of reef-derived debris with thinner beds containing attached spongiomorphs, thick-shelled pelecypods, large gastropods, and corals which colonized the debris beds.

Basinal sediments include thin-bedded limestones and shales consisting of muddy layers rich in sponge spicules and organic matter and graded packstones containing thin-shelled bivalves and skeletal debris.

The stages of growth were (1) initial development of lensoid masses each about 25 m thick (1 on sketch), (2) growth of a much larger reefal mass about 150 m thick (2 on sketch) which shed an apron of debris to the west (2a on sketch), and (3) development of a second thick buildup (3 on sketch) on the underlying forereef debris (2a) as the whole system prograded to the west.

The Lime Peak reef complex is not typical of other Triassic buildups in North America which are generally low-relief, thin accumulations (less than 10 m thick) dominated by corals and spongiomorphs. The buildups at Lime Peak are much thicker, and tabuloazons and sponges are more important builders than corals.

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Sedimentologic and Stratigraphic Interpretation of Sand Bodies in a Tidal Embayment

A depositional model for intertidal sand bodies indicative of tidal embayments was developed from 20 vibracores and 25 can cores taken at St. Helena Sound, South Carolina. This V-shaped embayment located 35 km south of Charleston, South Carolina, has a tidal range of 2.0 to 2.8 m.

The intertidal shoals are formed and reworked by opposing tidal currents. Ebb currents usually exceed 100 cm/sec in the deep adjacent channels and produce the long linear features on the shoals. Flood currents rarely exceed 75 cm/sec and are dominant across the broad seaward sand flats.

The range of sedimentary features gradually changes from a dominance of physical sedimentary structures on the exposed seaward sand flats to a dominance of biogenic sedimentary structures on the protected sand flats. The distribution of each feature is controlled by their relative position on the sand flats to maximum wave energy. Where biogenic sedimentary structures are abundant, protection from wave energy is afforded by the shoal crest. Laterally the shoals grade into ebb channels or lower subtidal mixed sand and mud flats.

The shoals display a coarsening-upward sequence of wavy-bedded to flaser-bedded clays and sands overlain by clean well-sorted, cross-bedded to burrowed sands. The sands are composed of fine to very fine subangular quartz grains.

The depositional history of the intertidal sand bodies indicates a vertical buildup of sediments and subsequent lateral accretion. Subtidal sand bodies were first deposited on preexisting bay-fill muds. With a decline in sea-level rise, an increase in vertical deposition occurred, producing incipient intertidal bars. As the bars became fully emergent, increasing wave energy and tidal currents reworked the shoals into their present shape. Continued sand deposition occurred as lateral accretion and infilled adjacent channels.

The shoals are up to 10 m thick and cover an area of 1 to 4 km^2. They extend 3 to 5 km seaward and are as much as 1 to 2 km in width. Because most of the shoals are subtidal to intertidal, preservation potential is high. As the embayment fills, prograding salt marshes will eventually cap the sand bodies.

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Niobrara Formation (Upper Cretaceous), Eastern North Dakota

The Niobrara Formation (Upper Cretaceous) has recently gained attention as a shallow, low-permeability reservoir for natural gas. Understanding its distribution and the conditions under which it was deposited will contribute to its evaluation as a source of hydrocarbons in this region.

On the basis of outcrop sections and cores in northeastern North Dakota, the Niobrara Formation is approximately 64 m thick and can be divided into two subequal units. The lower 31-m unit is medium dark gray and medium olive-gray, laminated calcareous shale with "white specks" (fecal pellets), comminuted fish remains, *Lingula,* and thin fine-grained sand stringers near the base. The upper 33-m unit is light-gray to light olive-gray, shaly chalk containing abundant "white specks", with a thin (5 m) very light gray, bioturbated chalk at its base. Sediments are bioturbated at the top of the lower unit and the base of the upper unit.

The main controls of sediment character are rates of calcareous plankton productivity and aerobic versus anaerobic bottom conditions. The Niobrara represents, from bottom to top, the following sequence of environments: (1) low productivity anaerobic conditions; (2) low productivity aerobic conditions; (3) high productivity aerobic conditions; and (4) high productivity anaerobic conditions.

Over the eastern half of North Dakota, the Niobrara ranges in thickness from less than 17 m to greater than 75 m. Alternating thinning and thickening bands trend northwest-southeast and suggest structural control of deposition.

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