

ogy of the sand bodies under investigation, and provide insight to a major control of diagenesis.

The fluid flow rate through a sandstone controls the residence time of the various chemical components in solution. When the residence time is sufficiently long with respect to the time scale of the diagenetic reaction, the time invariant condition of a continuous system approaches chemical equilibrium. Thus it is possible to have different diagenetic reactions occurring within a sand body due to local changes in fluid flux (or flow velocity) and the resultant varying degrees of approach to equilibrium.

In systems where fluid flow is high and residence time is small with respect to diagenetic reaction rate, the fluid chemistry is largely controlled by the chemistry of external fluid source. This situation results in either introduction of new material (or minerals) into, or removal of existing material or minerals from the sandstone. If the fluid is saturated or nearly saturated with respect to some specific mineral this mineral is added. Conversely, leaching of material occurs when the fluid is undersaturated.

In systems where fluid flow is slow and residence time is large with respect to diagenetic reaction rates, the fluid chemistry is largely controlled by the chemistry of the host rock. In this case, chemical equilibrium is approximated and the material originally present in the rock is redistributed by solution/precipitation reactions. Only small amounts of materials are introduced to or removed from the host rock. Understanding this control on sandstone diagenesis is important in delineating trends in diagenetic alteration and projecting those trends into new areas, and in identifying the trends in differential cementation that produces some types of diagenetic traps.

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Role of CO₂ in Evolution of Secondary Porosity in Pennsylvanian Morrow Sandstones, Anadarko Basin, Oklahoma

The Anadarko basin is one of the most outstanding hydrocarbon producers in the North American continent. Examination of more than 50 cores from the Pennsylvanian Morrow sandstones reveals a complex diagenetic history. Although quartzarenite is the major lithology, shell fragments, glauconites, and clayey matrix occur in considerable amounts throughout the section. This diagenetic complexity is a function of depositional environment and burial and thermal history of the basin.

Most porosity in the Morrow sandstones throughout the Anadarko basin is chiefly secondary. Such porosity results from the dissolution of clayey matrix, carbonate fragments and cement, glauconite, and quartz grains and their overgrowth.

Evolution of secondary porosity is related directly to the generation of hydrocarbons. CO₂ gas, with concentrations ranging from 0.3 to 4.7% by volume, was detected in more than 150 natural gas wells examined in the basin. Based on geothermal and geopressure gradients, and on experimental investigations of the solubility-potential of CO₂ in formation fluids under elevated temperatures and pressures, a good estimate of solubility of CO₂ in the Morrow Formation water may be attained. Because the concentration of CO₂ appears to increase with depth in the basin, secondary porosity should not be restricted to a particular zone or to particular depths, but definitely would persist with depth. Organic acids at shallow depths and H₂S in deeper zones may be important in enhancement of secondary porosity.

Amounts of porosity and the geometry of pore space are directly related to the original lithology. A better understanding of lithofacies is very critical in evaluating reservoir quality.

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Dolomitization and Late Secondary Porosity Development in Nisku Reefs (Late Devonian) of Alberta

Dolomitization and associated calcite dissolution are important controls on reservoir quality in coral reefs of the Nisku Formation. Average porosities of 13 to 15% and permeabilities of 3 darcys are recorded in the fully dolomitized reefs, while lower average porosities of 3 to 5% and permeabilities of 350 millidarcys are recorded in partly dolomitized reefs. The close correlation between dolomites and high porosity and permeability is best understood by examining the paragenetic sequence and spatial distribution of the dolomites.

Dolomitization occurred over a long period of burial and resulted in the formation of two major types of dolomites that are volumetrically significant. The first is characterized by matrix-selective, gray, cloudy, 20 to 150- μ crystals that grade from scattered subhedral and euhedral rhombs to interlocking crystalline mosaics. Matrix dolomites are slightly calcitic (51 to 53 mole % Ca), have a low iron content (less than 0.04 oxide wt. %), show a pronounced fabric selectivity toward micrite, and are abundant in all of the reefs. The second major type of dolomite is characterized by pervasive, brown, cloudy, 60 to 300- μ crystals that occur in the flanks of structurally updip reefs and throughout the downdip reefs. The pervasive dolomite exhibits similar chemical characteristics to the matrix dolomite and in some places replaces it.

Concentration of dolomite crystals and dissolution of individual rhombs along stylolites indicate that the matrix dolomite initially formed at shallow depths. As dolomitization progressed, dolomite recrystallization and cementation along with extensive calcite dissolution resulted in dramatic increases in porosity and permeability. Calcite dissolution continued after dolomitization ceased, but much of the dissolution is coeval with dolomitization. Evidence for the coeval relationship includes a complete gradation from partly dolomitized corals with dissolution of parts of the calcite skeleton to totally dolomitized rock with biomoldic porosity. Dolomite overgrowths, some of which are enriched in iron (up to 1.5 oxide wt. %), formed during progressive burial. Dolomite cements commonly extend into tension fractures that displace and are displaced by stylolites, indicating formation at greater depths than the precursor crystals. Matrix and pervasive dolomites exhibit values for ¹⁸O from -2.5 to -6.0‰ PDB and ¹³C from +2.5 to +6.0‰ PDB. The negative shift of ¹⁸O values from those of modern dolomites formed at shallow depths may be the result of formation at elevated burial temperatures. Pervasive dolomites are the result of recrystallization of the matrix dolomite and possibly primary dolomitization of the reef-flank facies. Isotopic data support a strongly rock-buffered system.

Late dolomites and secondary porosity in the Nisku reef trend increase in abundance down structural dip, toward the southwest. Thus, much of the dolomite and late porosity is post-Devonian and probably formed during the late Paleozoic and early Mesozoic when the regional structure tilted to the southwest. Although all Nisku reefs form stratigraphic traps, late diagenetic overprints in some significantly enhanced their reservoir quality.

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Fine Structure of Radiolaria

Fine structure and physiological studies of major biological

processes in solitary and colonial radiolarians have begun to elucidate some of the adaptive mechanisms that may account for the remarkable success of these holoplankters in diverse oceanic environments. The diversity of algal symbionts including dinoflagellates, prasinophytes, and a brown-pigmented alga has been documented by light and electron microscopy, and the role of the symbionts in host nutrition has been determined for some solitary and colonial species using cytochemical and radioisotopic techniques. Fine structure analysis of predatory behavior and food vacuole contents shows that some larger solitary spumellarian species are omnivores consuming crustacean prey and other microzooplankton in addition to algae. This is in contrast to prior assumptions that most solitary radiolarians are microherbivores and therefore changes our conception of their niche in oceanic environments.

Fine structure examination of skeletal morphogenesis in a number of solitary and colonial species has clarified the mechanism of skeletal deposition and pattern of skeletal ontogeny. These studies contribute to our understanding of cellular specialization in radiolarians, their physiological adaptive mechanisms to a holoplanktonic existence, and the biological factors correlated with patterns of skeletal morphogenesis that may be useful in interpreting radiolarian evolution and paleoecology.

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Trace Fossils of Middle Mississippian Carbonates, South-Central Indiana

Middle Mississippian (Meramecian) predominantly carbonate units of south-central Indiana, which include the Harrodsburg, Salem, St. Louis, and Ste. Genevieve Limestones, included the following environments: (1) sabkha (supratidal flats); (2) lagoons; (3) oolitic- and calcareous-sand bars and shoals; and (4) deeper shelf impure carbonates. Probably as functions of salinity and rate of deposition, these rocks range from being intensely bioturbated to a lack of recognizable bioturbation. Although several of the trace fossils cannot be currently assigned to recognized ichnogenera, the following forms have been recorded: *Chondrites*, *Cylindrichnus*(?), *Planolites*, *Teichichnus*, and a *Rhizocorallium*-type trace.

Degree of weathering exerts a considerable control on field recognition of the various forms. Intense weathering obliterates the slight tonal differences that aid in identification of traces in the fine-grained carbonates. However, in some calcarenites, certain taxa are only recognizable in weathered material and are nearly impossible to discern in polished slabs.

Factors related to episodic influx of fine-grained terrigenous detritus exert a considerable control on preservation of the various forms. Field exposures of carbonates that contain shale partings commonly exhibit abundant traces that are only apparent in polished slabs of more massive carbonates. The similarity of trace-fossil assemblages from these shallow-water carbonates with traces of deeper shelf Cretaceous chalks of the U.S. Western Interior further supports the contention of a high degree of preservational control.

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Eocene-Oligocene Boundary Problems, West Coast, North America

Correlation of the international Eocene-Oligocene boundary with the provincial biostratigraphic framework of the northeast

Pacific margin has been and continues to be controversial. The controversy centers about historical nomenclature and correlations, and current correlations based on planktonic fossil group.

The Geological Society of America's C. E. Weaver Committee published the first interdisciplinary correlation chart for the Cenozoic rocks of the western United States in 1944. The committee placed the Eocene-Oligocene boundary at the base of the "Keasey" Molluscan Stage and Refugian Benthic Foraminiferal Stage. These correlations were based on faunal similarity between Pacific Coast and European assemblages.

The most useful provincial boundaries of Late Eocene to Oligocene age are the Narizian-Refugian and Refugian-Zemorrian Benthic Foraminiferal Stage boundaries. Reevaluation of the Refugian Stage has recently been completed. The stage boundaries have been correlated to the international geologic time scale using planktonic microfossils.

Rigorous stratigraphic superposition of planktonic floras and faunas from continuously deposited foraminiferal-rich rocks results in correlation of the Narizian-Refugian Benthic Foraminiferal Stage boundary with the calcareous nannofossil zonal boundary NP18/NP19, and with planktonic foraminiferal Zone P15, in California, Oregon, and Washington. Thus, the Narizian-Refugian boundary represents a provincial chronostratigraphic datum of early late Eocene age.

Planktonic assemblages are rare in samples from above and below the Refugian-Zemorrian Benthic Foraminiferal Stage boundary. In California this boundary is commonly at an unconformity or without superposition of diagnostic faunas. In south-western Washington the Refugian-Zemorrian boundary occurs in continuously deposited and foraminiferally rich sections. Nannofloras assigned to Zone NP22 and planktonic foraminifera assigned to the interval of Zones P17 to P20 occur in strata containing foraminifera assigned to the Zemorrian Benthic Foraminiferal Stage. Nannofloras assigned to the intervals of Zones NP20 and NP21, and Zones NP19 to NP21, and planktonic foraminifera assigned to the intervals of Zones P16 and P17, and Zones P15 to P17 occur in strata containing foraminifera assigned to the Refugian Benthic Foraminiferal Stage. Therefore, the Refugian-Zemorrian boundary occurs within planktonic Zones NP21 and P17, roughly correlative with the international Eocene-Oligocene boundary.

The above correlations result in the reassignment of much of the 1944 Weaver chart's Oligocene to the Eocene: the "Keasey" and "Lincoln" Molluscan Stages and the Refugian Benthic Foraminiferal Stage are now recognized as late Eocene in age.

Radiometric calibration of the provincial boundaries is not yet possible. Whole rock potassium-argon and fission track dates are available but both have very large error bars or lack adequate biostratigraphic control to be useful.

Fossiliferous stratigraphic sections have rocks with sufficient remanent magnetism for magnetostratigraphic studies but to date only reconnaissance data are available.

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Tectonic Control of Eocene Arkosic Sediment Deposition, Oregon and Washington

Chronostratigraphic and geographic studies of Eocene arkosic sandstones suggest deposition during a "volcanically quiet" interval resulting from the westward jump of the Farallon-Kula plate subduction zone in Oregon and Washington.

The Eocene arkosic sandstones were deposited as part of a broad fluvial plain-coastal plain-shelf margin basin complex extending throughout Oregon and Washington between uplands