Future exploration for geothermal resources must depend on effective use of geology and geophysics to discover geothermal fields with no surface expression. An effective program must begin with an understanding of the geologic and geophysical processes that interact to create regions of high potential. Further exploration in these high-potential regions must then confirm that specific geologic and geophysical factors associated with good geothermal fields are present or indicated.

The present stage of geothermal exploration is a return to basic geology and geophysics to guide future programs to discover geothermal fields with no surface expression.

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Depositional Environments in Upper Cambrian Jordan Sandstone in Wisconsin

The Upper Cambrian sandstone formations of the Upper Midwest are superficially uniform over broad areas. Individual formations are homogeneous in texture and mineralogy, and several of the sandstone units in the sequence are nearly identical in terms of these parameters. However, texture and composition have been shown to be environmentally ambiguous, whereas sedimentary structures and trace fossils provide definite criteria for interpreting depositional settings and for distinguishing between apparently similar quartzarenites. Major differences exist among the formations in mode of deposition (subtidal marine, eolian, tidal flat, and possibly fluvial environments have been recognized). One formation, the Jordan Sandstone, is an example of marine depth zonation. The Jordan contains two major facies, based primarily on bedding style: (1) high-angle, trough cross-stratification; and (2) low-angle cross-stratification (hummocky cross-stratification). The high-angle facies is interpreted as shallow subtidal (shoreface depth) in origin, produced by constantly moving dune bed forms in a current-dominated regime. The following criteria suggest this interpretation: festoon bedding, well-defined trough axis modes, and presence of *Skolithos* without strong bioturbation. The low-angle facies is interpreted as a shoreface to offshore deposit, representing episodic deposition by storm surges—on the basis of dominant hummocky cross-stratification, wide dispersion of trough axis orientations, presence of laterally extensive bedding planes and shale seams, dominance of *Planolites*-type burrows, and localization of intense bioturbation on tops of cross-sets. Generally, the high-angle facies overlies the low-angle facies, indicating shallowing upward (progradation). However, the facies are intertongued and even lenticular in places; this stratigraphic variability and the lack of beach or nonmarine deposits suggest that no shoreline was present.

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Bioturbation as Factor in Hydrocarbon Generation—Example from Mowry Shale

The Lower Cretaceous Mowry Shale of the Western Interior has long been recognized as an oil source rock. Previous workers have shown that the Mowry displays distinct lateral changes in organic carbon content. Such variations have been ascribed to a dilution effect—siliciclastic swamping of the planktonic component in areas of rapid deposition. Examination of Mowry Shale fabric shows that sediment bioturbation was negligible in eastern Wyoming (central part of Albian seaway), but that the muds in western Wyoming (margin of seaway) were thoroughly bioturbated. Bioturbation was produced by deposit-feeding infauna; thus organic carbon was actively consumed and depleted in bioturbated muds. True source rock lithologies in the Mowry, as determined geochemically by Nixon, are localized in areas where bioturbation of the sediment was minimal or absent.

Bioturbation in the Mowry appears to reflect the degree of oxygenation, and hence the water depth, in the Albian seaway. Systematic decrease in bioturbation indicates the direction of the paleoslope. In initial basin reconnaissance, it should be possible to anticipate where the largest concentrations of organic carbon accumulated—downslope in deeper-water, less oxygenated, less bioturbated sediments.

The undisturbed shale fabric characteristic of anaerobic environments may also influence the primary migration of oil. Fine-silt laminations, common in the Mowry Shale and other black shales, could serve as preferential avenues for migration; bioturbation obliterates these laminae and could inhibit migration. The distribution of oil fields in eastern Wyoming and southeastern Montana, within the laminated Mowry facies, supports this hypothesis.

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Microbial and Invertebrate Endolithic Assemblages from Late Cretaceous Belemnite Rostra

Thick-shelled oysters, belemnoids, and terebratuloids from the Upper Cretaceous Navesink and Mt. Laurel Formations of the New Jersey Coastal Plain show an abundant, diverse, and well-preserved assemblage of microbial and invertebrate borings. Macroscopic examination of invertebrate skeletons reveals large sponge, bivalve, gastropod, and annelid worm borings. Smaller borings in *Belemnitella americana* were resin-embedded and studied by SEM after acid dissolution of the rostrum skeleton.

On the basis of morphology, size, and distribution patterns of the resin casts, at least a dozen borehole types can be recognized. The largest borings revealed by SEM (small microborings $>$ 1 mm) include acrothoracian barnacles, clionid sponges, and phoronids(?). Mesoborings (100 to 1,000 μ) include byrozoans, clionid sponges, and some large unidentified branched algal(?) tubes. Most microborings cover the range of 1 to 100 μ and include branched tubes and bags of algal and fungal origin. The microborings are the most common and uniformly distributed members of the assemblage.

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Carbonate Mineral Reactions During Combustion Retorting of Oil Shale

Oil shale generally contains approximately 50% mineral carbonates by weight. During combustion retorting some or all of these carbonates decompose and/or react with other mineral species in the shale. Because the heat requirement for these reactions is large, they have a strong influence on the retorting process.

Data on the kinetics of decomposition of the major carbonates in oil shale have been obtained with heating rates and gas environments (N_2, CO_2 and H_2O) expected during typical combustion retorting.

Activation energies and preexponential factors characterizing the rate constants for these reactions have been expressed in a form amenable for use in mathematical models of the retorting process. X-ray data on the final-product mineral phases in fully burned oil shale indicate them to be mainly members of the akermanite-gehlenite series, merwinite, and diopside. These products are formed by reactions between carbonates in the solid state and/or their oxides and other minerals in the shale.

These results have implications for the processing and environmental aspects of oil shale retorting.

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Major Petroleum-Impregnated Rock Deposits of Western Colorado Plateau

Petroleum-impregnated rock deposits occur widely in rocks of Permian to Tertiary age in the western Colorado Plateau of Arizona and Utah. Although over 60 occurrences and deposits have been recognized to date, only six, all in Utah, are estimated to contain over one billion bbl of petroleum in place.

Two giant deposits occur in marine and marginal marine strata in the dissected plateau region of southeastern Utah. The largest of these, and the largest single known deposit in the United States, is the Tar Sand Triangle. It underlies approximately 225 sq mi (585 sq km), and is estimated to contain as much as 16 billion bbl of petroleum, principally in the White Rim Sandstone (Permian).

The Circle Cliffs deposit contains approximately 1.3 billion bbl of petroleum in siltstone and sandstone of the Moenkopi Formation (Triassic). The deposit underlies an area of approximately 28 sq mi (73 sq km) on both sides of a breached anticline. Several similar, but smaller deposits occur in the Moenkopi Formation to the north, in the Capitol Reef anticline, and in the San Rafael uplift.

The remaining giant deposits are located in the Uinta basin, and all contain petroleum which probably originated in the lacustrine Green River Formation (Eocene). These deposits include P. R. Spring, Hill Creek, Sunnyside, Asphalt Ridge, and Asphalt Ridge Northwest.

The total amount of petroleum contained in these deposits in the Tar Sand Triangle and Uinta basin approaches a resource base of 29 billion bbl. The deposits are variable, and each offers a variety of technologic and economic challenges.

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Lower Permian Depositional Systems, "Uncompahgre" Basin, Eastern Utah and Southwestern Colorado

Studies of depositional systems of the predominantly Wolfcampian Cutler Formation in the "Uncompahgre" (Paradox) basin have outlined five fluvial and two marine facies with associated eolian deposits. Outward from the source, the fluvial facies include (1) proximal braided, which consists of a fan-building sequence and a very coarse-grained fanhead sequence; (2) medial braided; (3) distal braided; and (4) 50 and (5) 100% meandering sequences. The braided facies outline three large (40 to 60-km radius) fluvial or wet fans: the Gateway fan in the northern part of the basin developed to the southwest of the Uncompahgre highland; the San Miguel fan in the central part of the basin formed to the south off the southern end of the Uncompahgre highland; and the Piedra fan in the southeastern part of the basin developed to the west off the San Luis highland.

The marine and eolian deposits occur only in the northern part of the basin around the Gateway fan. Transition of the streams from distal-braided to coarse-grained meandering occurred at the toe of the fan, which was near sea level. Westward of the toe, meandering became more common. A marine transgression occurred early during fan development, resulting in deposition of the limestones and shales of the Rico, or Elephant Canyon Formation of Baars. In a later marine invasion from the southwest, limestones, sandstones, and shales were deposited that are lateral equivalents of Cedar Mesa Member of the Cutler Formation. The eolian facies are closely related stratigraphically and geographically to the marine facies and are thus considered deposits of a coastal dune field.

The San Miguel and Piedra fluvial systems coalesced approximately along the present course of the Animas River. Transition of both systems from distal braided to coarse-grained meandering occurred along their southwest flanks and may also occur along their northeast flanks where reliable information is lacking.

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Trapping and Accretion of Aeolian Sediment by Cyanophytes

The accretion of sediment by cyanophytes is usually associated with sediment trapping and precipitation of minerals by stromatolites in the marine intertidal and subtidal zones. Stromatolitic structures are also known to form in freshwater streams, lakes, and hot springs. All of these structures originate in aquatic environments. Current work suggests similar biogenic structures can form on dry land. Aeolian quartz sands as well as silt- and clay-size particles are trapped and held by filamentous cyanophytes which intertwine to form networks around the sand grains, and to whose sheaths the smaller particles adhere. Trapping and accretion occur whenever enough moisture is present to rehydrate dormant organisms and allow them to migrate by gliding motility to the surface of the mat. Such movements are accompanied by renewed production of polysaccharide sheath. The organo-sedimentary structures