Shale to the south. This change, together with draping of the Utica over the underlying competent Trenton, traps petroleum along the southwestern extension of the Lima-Indiana trend. (4) Fracture systems related to regional fracturing of the early Paleozoic rocks. Apparently these systems have provided fracture-enhanced reservoirs. Similar configurations are well known in the Scipio-Albion trend in southern Michigan. Secondary dolomitization and sulfide mineralization are common in association with these fractured features. (5) Possible porosity-permeability traps, probably on structure, where dolomite is replaced laterally by dense limestone. (6) Small anticlinal terraces off the main arch system, related to minor production. These terraces appear as down-to-the-basin noses on structural maps.

Considered together, the Lima-Indiana fields are a "giant" field extending 120 mi (193 km) in Ohio and another 50 mi (80 km) in Indiana. Before 1900, thousands of wells were drilled, as shallow as 1,100 ft (334 m), producing over 220 million bbl of oil at initial rock pressures between 100 and 450 psi (690 and 3,100 kPa). Exploration continues at a modest pace.

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Berea Sandstone Gas Reservoir in Portage County, Ohio

The Mississippian Berea Sandstone is a reservoir for shallow gas in Randolph and Suffield townships of Portage County, Ohio. The Berea Sandstone is well known in Ohio from its outcrops at the outskirts of Cleveland. It is among the more productive formations in Ohio where it yields gas, oil, or gas and oil at moderate to very shallow depths. The great differences in reservoir quality, sandstone distribution, and producibility in Berea oil and gas fields are partly related to the use of the term "Berea" for several sandstone bodies that produce from different structural and stratigraphic settings.

In Portage County, the Berea Sandstone is up to 60 ft (18 m) thick and has a porosity in the 15-25% range. The sand is white, medium to fine-grained quartz, poorly cemented, and without substantial shale interbeds. The reservoir lies below the "Cap Berea," a gray, cemented thin bed at the base of the Sunbury Shale (driller's Coffee shale). The sequence is similar to the outcrop found on the eastern side of Cleveland, but not like western outcrops of Berea Sandstone. In Portage County, the sand is currently interpreted as fluvial or deltaic. Within the field, thickness of the reservoir and hydrocarbon saturated zone varies little.

Natural gas is produced from the top 30 ft (9 m) of the reservoir. The reservoir energy is water drive. The gas fields lie just updip from a steep structural terrace interpreted as a fault zone. The trap for the fields is anticlinal and the Sunbury Shale is the seal. New wells drilled into the reservoir at 400-500 ft (122-152 m) in depth produce gas without water. Initial open flow tested up to 1.0 MMCFGD at an initial reservoir pressure of about 80 psig (552 kPa). This producing configuration of a nearly uniform sandstone reservoir on structure differs markedly from that found in Medina and Ashland Counties, Ohio, where the Berea Sandstone is also a producing reservoir.

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Cave Levels of Trenton–Black River in South-Central Michigan

Four generalized cave levels of the Trenton–Black River in south-central Michigan are most notable because of lost circulation zones in productive field areas. The levels are herein referred to as uppermost, upper middle, lower middle, and lowermost.

The uppermost cave level extends about 250 ft (76 m) into the Trenton. It is best developed in the widest, most productive areas of Albion-Scipio, where the drill bit dropped as much as 62 ft (19 m). About 59 productive wells in Albion-Scipio lost circulation at this level.

The upper middle level includes the lower, slightly argillaceous Trenton, and the uppermost Black River formation. This level is developed to some extent in all fields, and is a common zone of solution-collapse brecciation. Because this level is collapsed, lost circulation is less common.

The lower middle level below the "Black River shale" is not penetrated by many wells in Albion-Scipio. Where penetrated, it is developed in all fields, and is the main producer in most smaller fields. About 26 wells in Albion-Scipio lost circulation at this level, with the drill bit dropping as much as 80 ft (24 m).

The lowermost cave level extends into the Glenwood Shale. It is the most widely developed level, but is intersected by few productive holes. Only seven wells lost circulation at this level in Albion-Scipio, but the drill bit has dropped as much as 8 ft (2.4 m) in the Glenwood. This cave level effectively drained some oil from reservoirs where the oil-water contact intersects the Glenwood.

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Silurian and Lower Devonian of Southwestern Virginia

Thermal maturity of the Silurian and Lower Devonian rocks in Virginia west of New River decreases southwestward. Oil and gas shows are reported.

The total thickness of Lower Devonian plus Silurian strata ranges from 52 to 1,000 ft (16 to 305 m), with a maximum in Buchanan County. Sandstones were derived from sources southeast of the central Appalachian basin, some from lands southeast of the outcrop belt, and some formed by reworking of sandstones within the outcrop area. Sandstones change northwestward to shales in the Clinch and Rose Hill Formations. In the Middle Silurian and Helderberg Group, sandstones grade northwestward to limestones. Limestones in the Hancock Formation change westward to dolomite. The Onesquethaw Stage is represented by sandstone, chert, and limestone assigned to the Wildcat Valley and Huntersville Formations.

In the Middle Silurian (Keefer or "Big Six" sandstone) and Early Devonian (Wildcat Valley Sandstone), longshore currents carried sand across the southwest end of the basin toward Kentucky.

Several regional unconformities are present. These unconformities are mostly related to sea level changes, but some are probably tectonic in origin. Five unconformities are significant: (1) at base of Silurian, (2) at base of upper Helderberg over much of the area, (3) at base of Oriskany Sandstone, (4) at base of Huntersville Formation, and (5) at base of Upper Devonian black shales in extreme western Virginia, where Chattanooga Shale overlies Middle Devonian to Middle Silurian strata.

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Basement and Structural Control of Ordovician Trenton Dolomite in Extreme Southeastern Michigan, with Emphasis on Hydrocarbon Accumulations in Relationship to Dolomitization

Recent exploration activities along the northerly extension of the Bowling Green fault have sparked renewed interest on the flanks of one of North America's first giant oil fields (Lima-Findlay field). Extreme southeastern Michigan lies on the northwest flank of the Cincinnati arch and the southeastern flank of the Michigan basin. Within the study area, basement and structural control dictate the occurrence of dolomite within the predominantly limestone Trenton Formation. Commercially productive hydrocarbon accumulation within this study area has been associated with dolomitization within the top 150 ft (46 m) of the Trenton Formation.

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Upper Devonian Catskill Delta of West Virginia

Oil and gas reservoir rocks of the Upper Devonian of West Virginia were deposited as shoreline sands along a coastal plain characterized by marine-dominant deltas (Catskill delta complex). These sandstones exhibit facies relationships between red beds and interbedded sandstones and shales that shift westward and eastward with offlap and onlap. Outcrop equivalents at Elkins, West Virginia, are correlated with the interval of Balltown to Fourth sands. Subsurface correlation indicates that maximum westward progradation occurred during deposition of the Gordon and Gordon Stray sands, and that transgression mainly characterized the younger Devonian sands of the Thirty-foot, Fifty-foot and Gantz.

Regional correlations suggest that the Bradford-Balltown and Speechly (B sands of Pennsylvania Geological Survey) sands are better developed in northwestern Pennsylvania, whereas the Bayard through Gantz (D sands of Pennsylvania Geological Survey) sands are better developed in northern and central West Virginia, decreasing also in buildup toward southeastern West Virginia. The oil-bearing sandstones occur in strike trend (north-south) in north-central West Virginia connected by feeder channel sandstones with dip trends (east-west). The interpreted fluvial and tidal channels combine to represent distributary channels that supplied the sands to the barrier islands and delta front. Shoreline shifts, with regression and transgression of the ancient sea, caused corresponding changes in distal-fan accumulations with time.

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Upper Devonian Deposystems of Catskill Delta, West Virginia

The oil and gas reservoir rocks of the Upper Devonian of West Virginia were deposited as shoreline sands along a coastal plain characterized by marine-dominant deltas (Catskill delta complex). The oil-bearing sandstones occur in strike trend (north-south) in north-central West Virginia connected by feeder channel sandstones with dip trends (east-west). In outcrop, the strike-trending sandstones contain occasional marine fossils, are well sorted, and exhibit sedimentary structures that suggest depositional environments ranging from shoreface to tidal delta and back barrier. Channel sandstones with herringbone bedding suggest tidal influence. These beds change to cross-bedding of unidirectional paleoflow origin in upstream fluvial counterparts of red-bed facies. The interpreted fluvial and tidal channels combine to represent distributary channels that supplied the sands to the barrier islands and delta front. Isolith maps show anastomosing belts trending east-west with both vertical and offset stacking. Stream avulsion and stream piracy probably account for lateral shifting of tidally influenced river distributaries. Gridlike patterns of sandstone belts result from the dynamic interference of tidal-fluvial channels with wave-constructed shoreline barrier islands and bars, complicated by onlap and offlap cycles. Subsurface informally named oil and gas sands generally are multiple sandstones. Detailed correlation of individual sand units is difficult, but it supports the interpretation of a combined influence of wave and tidal-fluvial processes.

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Depositional Facies and Diagenetic History of Trenton Limestone in Northern Indiana

Subsurface cores were studied petrographically to determine the facies and diagenetic history of the Trenton Limestone on a regional scale in northern Indiana.

The Trenton Limestone is a yellowish olive-gray fossiliferous limestone, which is replaced by a light-gray dolostone in northern Indiana. Facies composing the Trenton are: (1) bryozoan-echinoderm packstone, (2) bryozoan-echinoderm grainstone, (3) bryozoan packstone to wackestone, (4) lime mudstone, and (5) dolostone. The bryozoan-echinoderm packstone is the major facies. As many as three muddying-upward (packstone to mudstone) sequences occur. Whether the muddying-upward sequences represent regional or local energy conditions is not known. Coarse-grained (1-4 mm) grainstones are typically 1 ft (30 cm) thick, have abrupt bases, and become muddy upward. They are considered storm deposits. Hardgrounds occur throughout the limestone facies, but they are most numerous toward the base. These facies indicate deposition below wave base, interrupted by periods of high energy during storms. Fossiliferous white and gray chert nodules are scattered throughout the unit. Also found in the limestone facies are prevalent stylolites and microstylolites, an indication of chemical compaction.

The dolostone facies consists of coarsely crystalline (0.4 mm) idiotopic dolomite. Rhombs have cloudy centers and thin clear rims. Pyrite is associated with the dolomite. Porosity, found only in the dolostone, is discontinuous and characterized as intercrystalline, vuggy, and moldic. Porous zones are commonly oil stained or have been plugged by poikilotopic selenitic gypsum. Minor amounts of celestite are found as cavity fillings.

The upper Trenton surface has high concentrations of pyrite and phosphate minerals and is interpreted to have been a submarine corrasion surface.

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Cyclic Sedimentation Patterns in Middle Ordovician Trenton Group in Central Pennsylvania

The carbonate facies of the Middle Ordovician Trenton Group show repetitive sequences of micrite, bioclastic limestone, and siliciclastic shale. Five repetitive patterns based on sedimentologic and paleontologic data are present (in ascending order): (1) biosparite, (2) intrabiosparite, (3) pelsparite, (4) micrite, (5) alternating micrite and shale.

The biosparite is of peritidal origin and is overlain by a stromatolitic cap. The average sequence thickness is 30-40 cm (12-16 in.). The intrabiosparite is a fining-upward sequence that grades to pelsparite with a micrite cap (total thickness averages 16 cm or 6 in.). This sequence is indicative of intershoal or shoaling conditions. Overlying the intrabiosparite sequence is pelsparite grading into a micrite cap. The pelsparite averages 8 cm (3 in.) in thickness, and is of shallow sublittoral origin. Highly burrowed micrite (2-6 cm or 0.8-2.4 in. thick), with a hardground cap, indicates periodic exposure. The upper unit is a deeper, sublittoral sequence of alternating kerogenic micrite and siliciclastic shale, ranging in thickness from 20 to 90 cm (7.9 to 35.4 in.). This pattern indicates a deepening of the carbonate shelf into a deeper, anoxic basin below wave base.

These sequences are a result of storm deposition as indicated by shell and intraclast lags, by fining-upward trends, and by abrupt contacts between individual sequences. The series of sequences is a result of the decreasing effects of these storms in the deeper water facies.

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To Drill or Not to Drill: a Synthesis of Experts' Judgments

Petroleum exploration is a costly venture that always involves much uncertainty and many unknown factors. A decision to drill could result in a giant discovery, a modest discovery, or a dry hole.

Using experts' judgments and the available information on a geologic formation, we estimate the volume of recoverable oil in a given reservoir by a method called the analytic hierarchy process (AHP).

AHP is a mathematically based modeling tool that allows an analyst to derive priorities for a set of alternatives by simple pairwise comparisons. The setting of priorities involves the solution of an eigenvalue problem in the inverse matrix of pairwise comparisons. The factors are grouped on different levels, forming a chain or hierarchy, whereby the lower level elements can be compared in pairwise matrices with respect to the next level. A process of weighting yields the overall priorities for any level, but in particular for those in the lowest level.

The factors affecting the decision are assigned numerical values using judgments of geologists and petroleum engineers. The probabilities of the outcomes are determined and the "expected value" of each decision is computed. The results of the study indicate that, when good judgments are used, one can obtain an excellent estimate of the volume of recoverable oil in a reservoir in a very short time and with the least amount of physical and financial resources.

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Deposition in Anoxic Taconic Foreland Basin, Late Middle Ordovician, New York

The Taconic foreland basin resulted from a collision between the North American craton and the Ammonoosuc arc. The basin is positioned between a broad carbonate shelf on the west and the clastic arc terrane. In the downslope direction, basin deposits changed from distal shelf carbonates (Trenton Limestone), to coeval interbedded hemipelagic black shales and calcilutites on the slope (Dolgeville Formation and Utica Shale), to