uplift for the upper sequence and the Amarillo uplift for the basal Keyes member. The environment of deposition appears to have been fluvial delta plains and associated tidal channels which were alternately created and destroyed by regression and transgression of the Morrowan seas. Distribution of these elongate sandstones is generally erratic and meandering; individual sand bodies have an estimated width of up to 1 mi (1.6 km) and a maximum thickness of 42 ft (12.8 m).

The nature and distribution of these sandstones leave many areas essentially unexplored. Southeastern Colorado has had substantial Morrow discoveries which justify a closer look at the area.

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Exploration in Classic Thrust Belt and Its Foreland—Bavarian Alps, Germany

The Bavarian Alps are composed of a stack of thrust sheets, which have been transported northward onto the molasse of the Tertiary foredeep.

Exploration in the Unfolded Molasse zone and its Mesozoic substrata has resulted in the discovery of a considerable number of oil and gas fields. Most of these fields are related to monoclines, which are aligned along west-east-striking, reverse growth faults. In addition, other fields are related to facies traps which were successfully located by improved seismic methods.

The northern edge of the Alpine orogene is formed by the west-east-striking synclines of the Folded Molasse zone, which is thrust at least 20 km over the autochthonous Unfolded Molasse zone. Several wildcats reveal good porosities and oil and gas shows. Coalification studies have proved that even the deepest parts of the Molasse zones are within the oil window.

The Helveticum zone is thrust over the Folded Molasse zone, and it contains potential reservoir rocks with gas shows. The Helveticum zone is tectonically overlain by the Flysch zone, which has no reservoir properties.

The Kalkalpin zone (Cretaceous Alps) is the uppermost thrust complex. It was recently penetrated by the wildcat Vorderriss 1, which proved that the Kalkalpin consists of several nappes with a total thickness of 6,400 m. At Vorderriss the Flysch zone is not present and must have been tectonically removed; the Kalkalpin zone is thus underlain by allochthonous Helveticum zone. Minor oil and gas shows are present in the Vorderriss 1.

In the Alps, seismic data are of satisfactory to good quality and major thrust planes can be mapped. The seismic data indicate that the molasse and its substrata extend far to the south beneath the Kalkalpin zone and, furthermore, they apparently form domal structures at several locations.

At Vorderriss, seismic data indicate that the Helveticum zone, the molasse, and the Mesozoic substrata, which all underlie the Kalkalpin zone, have a total thickness of about 2,000 m. The crystalline basement is expected to be at a depth of 8,200 m. According to maturity studies this sedimentary complex is still within the oil window.

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Geophysical Exploration is Just Beginning

What fraction of the yet undiscovered hydrocarbons will ultimately be found and produced? The answer depends on our success in developing and effectively applying the seismic method. Seismic reflection technology is in its infancy, and geophysical exploration is just beginning.

We are now going after a three-dimensional quantitative subsurface image, in terms of compressional wave impedance. We are beginning to seek additional elastic properties and Q. Inference of structure from lateral variations in reflection time is being supplemented by inference of fluid content and other rock properties from "lateral" variations in impedance.

Details of seismic images should be explained in terms of subsurface geology, unless proved otherwise. If well log data disagree with seismic data, well log data are probably wrong. We have a real need for improved "ground truth" if we are to effectively evaluate and interpret the seismic image.

There are many limitations to current image quality, highly variable from one prospect to the next, and for the most part amenable to foreseeable technology improvements. In most areas, the only fundamental limitations on our ultimate seismic image quality are high frequency loss, and geologic noises—and we do not understand either one.

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Geophysical Case History of Two Hills Colony Gas Field of Alberta

Seismic waveform changes, which in their most obvious form are known as "bright spots," have been known for some years to give direct indications of hydrocarbons. An example of the successful application of waveform analysis and direct detection of gas in a shallow Lower Cretaceous formation of east-central Alberta, Canada, is detailed.

At a depth of approximately 2,000 ft (610 m), the Colony formation typically consists of only thin (10 ft; 3 m) blanket sands interbedded with shale. However, in 1976 Hudson's Bay Oil and Gas Co. investigated a 100-ft (31 m) thick occurrence of channel sand (with substantial gas pay) in this formation. After some hit and miss attempts at extending the channel trend on geologic interpretation, seismic methods were applied. A seismic line over the channel well revealed a classic "bright spot." Several other lines also showed bright spots in the Colony zone. The results of seismic modeling can be summarized as follows. The lateral consistency of the sediments above the Colony provided a stable boundary of modeling and permitted the detection of gas. The inconsistency and complexity of the sediments underlying the Colony resulted in interference patterns that prevented exact quantitative analysis of gas pays. Furthermore, other geologic phenomena provided waveform changes that were similar to that of gas sand. Through detailed examination of the geology and evaluation of alternative explanations of the waveform changes, successful interpretation was accomplished.

Total gas reserves geophysically discovered to date in the Colony formation are estimated at 110 Bcf.

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Vertical and Surface Seismic Profiles Map Aquifers in Madison Group and Red River Formation, Powder River Basin, Wyoming-Montana

Intensive energy development activity in the Powder River basin of eastern Wyoming has placed heavy demands on the water resources of the state. The U.S. Geological Survey is therefore investigating the water resource potential of the Madison Group and Red River Formation, such water to be produced from depths of 2,500 to 7,500 ft (762 to 2,286 m) to supply some of the needs. The exploration seismograph is a promising tool to aid in well-site selection; under some conditions it can be used to detect porosity development at depth.

In-situ measurements of the acoustic properties of the Madison–Red River interval have been made using vertical seismic profiles in several wells. Surface seismic profiles were then run over the wells. The combination of these results with well-log data and regional geologic subsurface studies gives considerable insight as to commercial quantities of water at depth.

The investigation also has petroleum-exploration significance. Madison porosity development often provides an excellent oil and/or gas reservoir in the adjacent Big Horn and Williston basins.

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Explorable Structures in Old Bahama Channel, North of Cuba

Approximately 3,500 km of reflection seismic profile, augmented by some gravity and magnetic data, revealed five domal structures beneath water depths of 500 m in the western reaches of Old Bahama Channel. Closure crossings span as much as 10 km. Cores of these structures are overlain by up to 400 m of semiconsolidated sediment. Cores may be salt diapirs or subducted shallow-water carbonate blocks or both. The size of these structures and their occurrence in relatively shallow water make them attractive exploration targets at the present time.

Additional seismic characteristics of the semiconsolidated sediments comprising the basin fill are (1) extensive continuity of reflections probably resulting from interbedding of shallow-water carbonate turbidites with pelagic oozes, and (2) crinkling of reflections at depths of several hundred meters which may be a compaction phenomenon. Normal faults are common in the sediments. In some places, related faulting and apparent flowage in the sediments may result from compaction and attendant water loss or from flowage of evaporites deeper in the section.

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Graded Beds as Paleogravimetric Cameras

Physicists over the past century have postulated that the universal constant of gravitation, G, is decreasing with time. Assuming an annual rate of decrease of 10^{-10} parts per year the gravitational acceleration of the earth, g, would have been 22% greater two billion years ago. Distal turbidites occur in geologic deposits as old as 2.5 billion years. Utilizing the relations developed by Scheidegger and Potter, a functional relation between g and measurable characteristics of a graded bed may be constructed. This relation, a "paleogravimeter," was tested in terms of sensitivity to changes in g as well as possible confounding effects such as sediment concentration, density, and grain packing. Only the sediment concentration in the turbidity current had a measurable effect. By utilizing Middleton's result that the transition between "distribution" grading and "coarse-tail" grading occurs at particle concentrations of 30%, a selection criteria can be established for the "paleogravimetric camera." In this respect it is meaningful to measure only beds deposited from currents of the same particle concentration. When this is done the paleogravimetric change can be measured. The paleogravimetric camera can be improved by substituting more realistic relations for Stokes' Law and allowing viscosity to vary as suggested by Roscoe. Preferably however, a purely physical model for sedimentation from a turbidite should be developed in place of the Scheidegger-Potter relation.

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Retrogradational Shelf Sedimentation: Viking Sandstone (Lower Cretaceous), Central Alberta

The Viking Sandstone in the Joffre-Joarcam area of central Alberta consists of a series of overlapping sediment sheets becoming progressively younger westward toward the paleoshoreline. During the regression at the beginning of Viking deposition, streams meandered across the former shelf surface depositing sand in deltas (today's irregular-shaped reservoirs). An ensuing transgression, punctuated by minor regressions, reworked shoreline sediment deposited during the regressions into linear shelf sand bodies (today's linear reservoirs west of the irregular-shaped reservoirs). During the transgression, the retrogradational nature of the sediment sheets, which contain the sand bodies, was formed.

Well-log cross sections show that the Viking thickens westward, pinches out eastward, and that each sediment sheet contains several northwest-trending shoestring sandstone bodies. Cores of the sandstone bodies and their underlying beds exhibit a coarsening-upward succession of: (1) silty marine shale; (2) intercalated silty shale and rippled sand (locally a structureless bioturbated clayey sand); and (3) glauconitic cross-bedded sandstone. A polymictic pebble conglomerate occurs randomly within this sequence.

Submerged deposition on a shelf tens of miles from the paleoshoreline is documented by: (1) marine shale enclosing the Viking; (2) no consistent landward-seaward facies changes; (3) abundant glauconite; (4) an