the petroleum industry. However, nonlinear sweeps can seriously degrade seismic data when the amplitude and frequency controls are used incorrectly.

The amplitude controls are used to overcome decoupling, ground roll, and vibrator/ground resonance problems. By suppressing the vibrator drive at the lower frequencies, the typical decoupling effect can be eliminated and the effect of the ground roll minimized. This permits the use of shorter geophone arrays that are more suitable for high resolution recording. In addition, the use of a lower amplitude sweep at the low end of the frequency range helps suppress vibrator/ground resonance. This reduces the large amplitude of the resonance frequency and allows the recording of the weaker high frequency signal.

The ability to control the rate of frequency change during the sweep allows the user to recover an improved signal-to-noise ratio at the higher frequencies. In general, the sweep time is reduced in the lower frequencies and increased in the higher frequencies. The high percentage of sweep time at the high end of the frequency range results in an improved signal-to-noise ratio in the higher frequencies. However, the improper choice of the start and end sweep frequencies can result in recovered data that is actually poorer in signal-to-noise ratio than an equivalent linear sweep.

The nonlinear method is a powerful, but sensitive tool that can be beneficial when used properly. The tool allows the user to recover excellent data in "good" data country and fair data in "poor" data country. We use Pelton's Advance I, Model 5 vibrator electronics together with the FT-1/DFS-V seismic exploration system and test extensively in the field. Areas where we have recovered excellent data include the Williston, Powder River, Big Horn, and Wind River basins.

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Early Dolomitization: its Significance in Creating Subtle Diagenetic Hydrocarbon Traps in Williston Basin

Most of the Paleozoic section of Williston basin is a thick accumulation of numerous carbonate to evaporite, shallowing-upward, cyclic sequences. These sediments were deposited in broad epeiric seas, and the deposition of the evaporite facies marked the final stage of each cycle. Many of the sequences display a pervasive replacement dolomite in the uppermost portion of the carbonate units. This secondary dolomitization is, at least in part, an early diagenetic event, synchronous with evaporite deposition.

The inception of evaporite precipitation resulted in the seepage of a dense, magnesium-rich brine into the underlying sediment. The heavy brine moved down the gentle regional dip, displacing the more normal marine interstitial pore fluid and dolomitized the primary calcitic sediments en route. The supply of magnesium-ions decreased away from the source, and correspondingly, the degree of dolomitization decreased and larger crystals formed because of slower nucleation at fewer sites.

The seepage refluxion of dolomitizing brines gave rise to the frequently observed textural variation of cryptocrystalline, impervious dolomite grading into a finely sucrosic, permeable dolomite downdip. This diagenetic facies change provides the critical updip barrier for potential hydrocarbon reservoirs. The lateral pool boundaries are controlled by either structural relief or a similar diagenetic facies change. The reservoirs are capped by the tight evaporites.

Hydrocarbon production is attained from diagenetic traps in the Mississippian Oungre Zone and the Ordovician Red River "C" Zone. Reservoir creation and the pooling mechanism are the result of dolomitization by seepage refluxion of dense, magnesium-rich brines beneath restricted, hypersaline lagoons.

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Reconnaissance and Economic Geology of Copper Mountain Metamorphic Complex, Owl Creek Mountains, Wyoming

The Copper Mountain metamorphic complex lies within a westerly trending belt of Precambrian exposures known as the Owl Creek Mountains uplift. This mountain range lies along the southern edge of the Big Horn basin, separating that basin from the Wind River basin to the south. Rocks of the metamorphic complex are exposed at Copper Mountain, at Wind River Canyon, and apparently continue several miles to the west on the Wind River Indian Reservation.

The metamorphic complex at Copper Mountain is part of a larger complex known as the Owl Creek Mountains greenstone belt. Until more detailed mapping and petrographic studies can be completed, the Copper Mountain area is best referred to as a complex, even though it has some characteristics of a greenstone belt.

The metamorphic complex is amphibolite-grade metamorphosed supracrustal rocks that have been migmatized along the north and south margins of the complex by the intrusion of leucogranitic stocks and batholiths. The regional trend of the metamorphic complex is N50° to 80°E, and regional foliation dips steeply to the south. The dominant structure along the southeastern margin of the belt is a synform. The supracrustal rocks are quartz, hornblende, plagioclase gneisses and schists, quartzites, para-amphibolites, pelitic schists, cordierite schists, iron formation, quartz-mica schists and gneisses, and intercalated orthoamphibolites.

At least three episodes of Precambrian deformation have affected the supracrustals, and two have disturbed the granites. Prior to the intrusion of granite, the metamorphic complex experienced coaxial folding of the metasediments. Following the initial folding of the supracrustals, the Copper Mountain belt was intruded by leucogranite about 2.7 b.y. ago. This intrusive event is believed to be responsible for prograde metamorphism, as well as a second phase of deformation. Portions of the supracrustal belt were mineralized during the waning stages of the intrusive event. Some tungsten-bearing veins and calc-silicates were produced. Auriferous and cupriferous fracture-fill veins were formed, followed by emplacement of simple pegmatites.

A final Precambrian deformation event was preceded by a weak thermal event expressed by retrogressive metamorphism and restricted metasomatic alteration. During this event, a second phase of pegmatitization was accompanied by hydrothermal solutions.

During the Laramide orogeny, Copper Mountain was again modified by deformation. Laramide deformation produced complex gravity faults and keystone grabens. Uranium deposits were formed following major Laramide deformation. The genesis of these deposits is attributable to either the leaching of granites or the leaching of overlying tuffaceous sediments during the Tertiary.

Production of metals and industrial minerals has been limited, although some gold, copper, silver, tungsten, beryl, feldspar, and lithium ore have been shipped from Copper Mountain. A large amount of uranium was produced from the Copper Mountain district in the 1950s.

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Conodonts of Bakken Formation (Devonian and Mississippian), Williston Basin, North Dakota

The Bakken Formation is a thin (maximum 145 ft, 45 m), clastic unit in the subsurface of Williston basin in the United States and Canada. The formation consists of three informal members which display an onlapping relationship. A lower, radioactive, pyritiferous, noncalcareous black shale is overlain by a light to dark gray, dolomitic siltstone to calcareous sandstone and an upper black shale similar in lithology to the lower shale. The finely laminated, organic rich, black shales of the Bakken Formation were deposited in an anoxic, marine environment that was apparently offshore, sediment-starved, and below wave base. The middle member contains bedding features and fossil evidence indicative of a slightly dysaerobic, current-influenced, marine environment. The upper and lower black shales are considered important source rocks for hydrocarbons in the Williston basin.

The Bakken is similar in lithologic character and stratigraphic position to other "black shale" units deposited on the North American craton during the Late Devonian and Early Mississippian. The Bakken was initially considered entirely Mississippian in age. Paleontologic study of regional physical equivalents and analysis of the macrofauna in Saskatchewan has suggested that the Bakken is actually both Devonian and Mississippian.

Conodonts were obtained from cores of the Bakken in an effort to determine the age of the formation in North Dakota and to assess the oil generation potential. Nearly 700 conodonts have been recovered, but are unevenly distributed within the Bakken Formation. A majority was obtained from thin (approximately 0.5 cm), fossil-rich beds within the upper shale. Conodonts from the top of the upper shale reveal a Mississippian (Kinderhookian) age and are here assigned to the Lower *Siphono-*

della crenulata Zone. Only rare, fragmentary conodonts have been found in the middle member. Conodont evidence from the middle of the lower shale suggests a late Devonian (Famennian) age (Upper *Polygnathus styriacus* Zone) for this member.

Conodont color has been established as a geothermometer in carbonate rocks. Color alteration indices of conodonts from the Bakken range from 1.5 to approximately 2.5 and indicate a pattern of increasing temperature with depth. These results suggest possible hydrocarbon generation from shallower depths than has been reported previously for the Bakken. The lack of agreement in interpreted hydrocarbon generation depths may be due to, among other things, the clastic nature of the Bakken Formation.

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Geothermal Resources of Wyoming Sedimentary Basins

Geothermal resources of Wyoming sedimentary basins have been defined through analysis of over 14,000 oil well bottom-hole temperatures, thermal logging of 380 wells, measurement of rock thermal conductivities, calculation of 60 heat-flow values, drilling of 9 geothermal exploratory wells, conductive thermal modeling, and the study of existing geologic, hydrologic, and thermal spring data. All data have been integrated into interpretations of the thermal structure of the Big Horn, Wind River, Washakie, Great Divide, Green River, Laramie, Hanna, and Shirley basins of Wyoming.

Controlling factors for the formation of geothermal resources in these basins are regional heat flow, rock thermal conductivity values, depths to regional aquifers, and hydrologic flow directions. Regional basin heat-flow values range from about 40 to 80 milliwatts/m^2; measured thermal conductivities are in the general range of 1.5 to 4.0 watts/m°K; and depths to aquifers are up to 11,000 m (36,000 ft). This results in regional geothermal gradients for Wyoming basins in the range of 15° to 40°C/km (44° to 116°F/mi) with predicted maximum aquifer temperatures near 300°C (570°F).

Anomalous geothermal areas within the basins contain measured thermal gradients as high as 400°C/km (1,160°F/mi) over shallow depth intervals. These anomalous areas are the combined result of local geologic structures and hydrologic flow. A simplified model for such areas requires water movement through a syncline with subsequent heating due to regional heat flow and thermal conductivities of overlying rock units. Consequent flow of the heated water up over an anticline produces a localized area of anomalous geothermal gradients.

Access to Wyoming basin geothermal resources is primarily through producing oil wells. Fifty two oil fields which account for over 90% of Wyoming's oil field water production, produce 575 million L (152 million gal) of thermal water per day. The temperature of this water ranges from 30° to 110°C (86° to 230°F) with 88% warmer than 38°C (100°F) and 60% warmer than 50°C (122°F). Over 50% of this water is disposed of, generally by discharge to the surface.

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Distribution and Age of Clinker in Northern Powder River Basin, Montana

Clinker, rock that has been baked or fused by the burning of underlying coal beds, is abundant in the Tongue River Member of the Paleocene Fort Union Formation in the northern Powder River basin. Being more resistant than unbaked rocks above and below, the clinker commonly caps ridges and plateaus, and forms topographic benches and escarpments. This clinker is primarily red and orange baked sandstone and shale, but it includes gray sintered siltstones (porcellanite) and bodies of black, fused and welded breccia. Detrital zircons in the sandstones are annealed during baking and yield fission-track ages that show the time of cooling.

An inventory of clinker areas has been completed for the Montana part of the northern Powder River basin east of the Crow Indian Reservation. The study area lies within the Powder River resource area of the U.S. Bureau of Land Management. Data were compiled from existing literature, color infrared aerial photographs, and unpublished mapping provided by R. B. Colton, W. C. Culbertson, and S. J. Luft of the U.S. Geological Survey. Clinker covers approximately 2,700 km^2 (1,050 mi^2) or 20% of the Tongue River exposures in the study area. Assuming a 15 to 25 m (50 to 80 ft) average thickness, the volume of clinker would be 40 to 70 km^3 (10 to 17 mi^3).

The most extensive clinker layers locally exceed 60 m (200 ft) in thickness. They are produced by the thickest coal beds, some of which exceed 15 m (50 ft). Two major clinker layers form extensive topographic surfaces and escarpments. (1) Near Decker, Montana, the clinker produced by the Anderson-Dietz coal zone forms benches adjacent to the Tongue River. Because of the gentle southerly regional dip of the beds, this clinker zone rises to the north, where it caps large plateaus dividing the valley of the Tongue River from the valleys of Otter Creek and Rosebud Creek. These clinker plateaus stand up to 400 m (1,300 ft) above the Tongue River. (2) Near Ashland, Montana, the clinker produced by the Knobloch-Nance coal zone, which lies about 300 m (980 ft) stratigraphically below the Anderson-Dietz zone, forms broad benches bordering the Tongue River.

The distribution of fission-track ages shows that coal has burned to form clinker in the region at least since the late Pliocene. A clinker boulder from the base of a gravel deposit 365 m (1,200 ft) above the level of the Yellowstone River west of Forsyth has been dated at 4.0 ± 0.7 m.y. This age establishes a maximum age for the gravel. The oldest in-place clinker sample dated thus far comes from the summit of the Little Wolf Mountains west of Colstrip and is dated at 2.8 ± 0.6 m.y. Clinker from the Anderson-Dietz plateau that rims the Tongue River Valley west and south of Ashland ranges in age from 1.4 ± 0.4 m.y. to 0.7 ± 0.3 m.y. Ages from clinker of the Knobloch-Nance coal zone range from 0.5 ± 0.3 m.y. to < 0.06 m.y. The older ages are from topographically higher clinker layers. Inasmuch as a coal bed cannot start burning until it is exposed by erosion, these ages indicate the Tongue River cut its present valley primarily during the Pleistocene.

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Fault Leakage Characterization by Integrative Gas Geochemistry/Mass Spectrometry/Pattern Recognition Procedures

The application of integrative gas geochemistry combined with mass spectrometry and the use of pattern recognition procedures, has enabled rapid characterization of microseepages of gases along faults and fractures. This has been accomplished by incorporating the activated carbon/Curie point wire collector in gas geochemical surveys of faulted and fractured structures which serve as conduits to the subsurface. Studies conducted in the Denver-Julesburg basin of Colorado, Green River basin of Wyoming, the hingeline of Utah, and the Las Animas arch of Colorado all produced fault-related samples where higher ($<C_7$) molecular weight components were encountered. The results of these fault-associated anomalies have been related to differing organic sources of various samples and may be correlated to areal distribution of the source leakage.

When using the analytical technique in relatively unfractured and unfaulted sedimentary rocks, the mass spectra generated typically indicates the presence of compounds containing up to seven carbon atoms. In dealing with fault samples affiliated with producing areas of petroleum, components with masses up to 150 have been analyzed. The Denver-Julesburg basin, Green River basin, and the Las Animas arch studies were all performed in relation to producing oil and gas fields. Although the results from the first three studies were not insignificant, those associated with the hingeline study have a much greater impact toward the potential of exploration application. Through this study, it was discovered that fault leakage not only changed with differing sources of the organic gases and vapors, but also appears to change with lateral proximity between the sample and the zone overlying the organic source. From these interpretations, an exploration model which utilizes fault leakage as a parameter will be discussed.

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Introduction to Stratigraphy, Structure, and Geologic Problems in Big Horn Basin, Wyoming and Montana