uplifts indicate that the forces that caused Laramide deformation may have changed through time. Compression was primarily east-west in latest Cretaceous and formed folds parallel to the Cordilleran thrust belt and probably formed wrench fault zones perpendicular to them. Later (Eocene) compression was more north-south and formed the east-west-trending uplifts and thrusts. South-southeast-trending wrench faults were activated in the foreland at this time, and eastward thrusting ceased in the Cordilleran thrust belt.

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## Depositional Processes in Beaverhead Formation, Southwestern Montana and Northeastern Idaho, and their Tectonic Significance

The Upper Cretaceous to Paleocene(?) Beaverhead Formation is a thick sequence of interbedded and intertonguing synorogenic conglomerates, sandstones, and limestones located at the juncture of a northeast-southwest-trending foreland uplift and the northwest-southeast-trending thrust belt in Beaverhead County, Montana, and Clark County, Idaho. In the vicinity of Lima, Montana, the conglomerates carry two distinct clast assemblages, one dominated by well-rounded quartzite clasts derived from Precambrian and early Paleozoic rocks to the west, and the second by locally derived, angular to rounded limestone clasts of Mississippian to Jurassic age. Based on clast imbrication data by Ryder and Scholten in 1972, the latter assemblage has long been thought to represent a deposit shed radially from the southwest end of the foreland uplift. Recent observations on the details of depositional facies, clast composition, fining-away sequences, and the structure of deformed strata beneath the Beaverhead unconformity, however, suggest that the limestone conglomerates represent a complex of deposits with sources both in the thrust belt and the foreland terrane. Where deposits from these two uplifts can be distinguished, they display markedly different sequences of sedimentary structures and fabrics attributed to significantly different modes of deposition.

In the Antone Peak area the limestone conglomerate of the Beaverhead lies unconformably on rocks deformed solely by foreland deformation. The sequence is characterized by cycles up to 10 m (30 ft) thick beginning with laterally extensive lenses of sandy, clast supported, well stratified but poorly sorted cobble and boulder conglomerate grading upward into cross-bedded pebble conglomerate, pebbly sand, and flat laminated and rippled sandstone. Such sequences are characteristic of perennial braided stream deposits. Clast composition, distance from the thrust belt, coarse clast size, and the nature of the unconformity dictate a foreland source for these conglomerates.

In contrast, the limestone-rich conglomerates near Dell display a dominance of matrix-supported conglomerate and pebbly mudstones incised by steep walled channels filled with well-stratified, better sorted, clast-supported conglomerate lenses interbedded with thin discontinuous lenses of flat laminated coarse sandstone. These features are consistent with those observed on modern debris-flow-dominated alluvial fans in the Basin and Range province of the Western United States. Ubiquitous recycled sheared quartzite clasts strongly suggest a thrust belt origin for these conglomerates.

Recognition of the link between depositional style and source terrane in the Lima area may provide a powerful tool for distinguishing different deposits of compositionally similar conglomerate. With careful mapping of these deposits and precise dating by pollen and fossils, the chronologic relationships of the various deposits may be established, enabling us to better understand the timing of the two uplifts. In addition this relationship suggests a general model that can and should be tested in other parts of the Cordillera where synorogenic deposits are found in both foreland uplift and thrust belt settings.

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## Tectonic Setting and Depositional Environments of Hanna Formation, South-Central Wyoming

The Paleocene Hanna Formation was deposited during tectonic events that led ultimately to the development of the Hanna and Carbon structural basins of south-central Wyoming. Early Paleocene uplift prior to deposition of the Hanna Formation resulted in a regional unconformity as observed in the Carbon basin, on the east side of the Hanna basin, and in the area south of these two basins. Subsequent movement of the thrust-fault system on the north side of the present Hanna basin resulted in southward filling of this asymmetrical foreland basin by clastic wedges, which make up facies associations. The Hanna Formation deposited in the Carbon basin has the same facies associations that occur in the southern part of the Hanna basin.

Facies associations in the Hanna Formation of the Hanna basin suggest deposition in alluvial-fan and alluvial-plain environments. The alluvial-fan facies can be subdivided into proximal, medial, and distal subfacies. The proximal and upper-medial subfacies, which have been eroded away on the north side of the Hanna basin, probably consisted of medium to coarse gravels and muds deposited by debris flow and sheet floods. The lower-medial subfacies consists of tongues of conglomerate interbedded with mudstones and was probably deposited by sheet floods. This subfacies grades laterally southward into the distal conglomeratic sandstones and gray mudstones that were deposited by braided streams and sheet floods. In the Hanna basin, these distal-fan subfacies grade southward into an alluvial-plain facies. In the area of the Carbon basin, all the fan facies are isolated in the Medicine Bow Mountains and associated mountain front, and only the alluvial-plain facies occur in the basin.

The alluvial-plain facies in the Hanna Formation can be divided into two subfacies on the basis of thickness and the occurrence of coal and carbonaceous shale. One subfacies consists of overbank and backwater-deposited gray shale and claystone and splay sandstone and siltstone interbedded with backswamp deposits of thin carbonaceous shales and thin coals. These deposits lie laterally from sandstone-filled channel systems. In the Hanna basin this subfacies is thickest near the base of the Hanna Formation. The other subfacies is similar in lithology but contains more backswamp deposits of carbonaceous shale and coal beds. Stacked channel sandstones are also more common in this subfacies. This subfacies is thickest in the central part of the Hanna basin, and makes up most of the alluvial-plain strata in the Carbon basin.

Analysis of the alluvial-plain sequences in Hanna basin is hampered by poor outcrops and a lack of subsurface correlation. Complete analysis of the coal-bearing subfacies has been possible in the Carbon basin where a stratigraphic framework has been established. From this stratigraphic framework, a sequential strata model has been constructed. Analysis of several coal-bed-bounded sequences in the Carbon basin confirms the sandstone domination of the sequences as shown by the sequential strata model. Also, mapped southeasterly trends of the sandstone bodies indicate the fluvial channel systems of the Hanna basin were continuous into the Carbon basin.

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## Channeling in Paleocene Coals, Northern Powder River Basin, Montana

Interpretation of 1,200 geophysical logs in the northern Powder River basin, Montana, reveals the paleodrainages influencing coal deposition during the deposition of the Tongue River member (Paleocene, Fort Union Formation). Four channels with associated crevasse splay deposits are recognized: (1) an east-west "Rosebud" drainage near Colstrip, (2) a north-south "Wall" channel near Birney, (3) a north-south "Dietz" drainage near Tongue River Reservoir, and (4) a north-south "Anderson" channel in the vicinity of Moorhead. These channels support the concept of a major northeast-flowing drainage system during deposition of the Tongue River Member. Identification of these channels serves as a guide to future coal exploration.

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## The Use and Misuse of the Nonlinear Vibroseis Method for the Acquisition of High Resolution Seismic Data

The recent use of nonlinear Vibroseis® (trademark of Continental Oil Co.) sweeps became possible with development of an electronics system to drive the vibrators in a nonlinear mode. This new electronics system allows the user to adjust both the vibrator amplitude and the rate of frequency change during the sweep. Nonlinear Vibroseis® sweeps are now becoming popular for the acquisition of high resolution seismic data in 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-*