Oblique-slip on this ramp probably resulted in about 20 km (12 mi) of crustal shortening perpendicular to the trend of the mountains.

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Dissolution of Permian Salt and Mesozoic Depositional Trends, Powder River Basin, Wyoming

Salt deposits in the Powder River basin of Wyoming occur in the Late Permian Ervay Member of the Goose Egg Formation which was deposited in a redbed-evaporite trend extending from the Williston basin of North Dakota to the Alliance basin of Nebraska and Wyoming. However, only remnants of the once extensive Ervay salt remain in the Powder River basin, with major salt dissolution events occurring during Late Jurassic and Early Cretaceous. Subsidence and deposition at the surface were contemporaneous with subsurface salt dissolution except in areas where uplift and erosion were occurring. The presence or absence of Ervay salt and the relationship to overlying syndepositional strata can be seen readily and mapped using borehole logs or seismic data.

Earliest dissolution of the Ervay salt occurred in the Jurassic, during regional uplift and erosion of the overlying Triassic Chugwater Formation in the present Hartville uplift and southeastern Powder River basin areas. Thickness variations of the Canyon Springs and Stockade Beaver members of the early Late Jurassic Sundance Formation, which unconformably overlie the deeply eroded Chugwater Formation, may be related in part to dissolution of the Ervay salt. Extensive salt dissolution, synsubsidence, and syndeposition occurred throughout most of the Powder River basin during latest Jurassic and Early Cretaceous. Evidence of this is seen in thick trends of the Morrison, Lakota, Dakota, or Muddy formations overlying areas of Ervay salt collapse. One area escaping extensive dissolution in the Early Cretaceous was the eastern Belle Fourche arch, which trends northeast across the middle of the Power River basin. Here the Lakota, Dakota, and Muddy formations are thin over areas with underlying Ervay salt, but thicken rapidly in areas of salt collapse.

Many producing fields from the Mowry, Muddy, and Dakota formations exhibit either rapid stratigraphic changes syndepositional to salt collapse or fracture-enhanced reservoir quality due to postdepositional salt collapse. Major Muddy accumulations occurring in areas of local Ervay salt collapse include Kitty, Hilight, Fiddler Creek, and Clareton which have produced jointly over 172 million bbl of oil. The relationship of Ervay salt dissolution to Lower Cretaceous deposition can be exploited as an effective exploration tool.

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Structural and Depositional History, Jefferson and Madison Basins, Southwestern Montana

Recent seismic and gravity data from the Cenozoic Jefferson and Madison basins provide new information concerning their structural and depositional histories. Both basins are north-south elongated structural basins formed as a result of horizontal extension after Laramide horizontal thrusting. Each basin is bounded on the east side by a sinuous faulted steep mountain front, and large west-sloping alluvial fans extend almost completely across both basins.

Gravity data show that each basin in the subsurface is asymmetric with a large steep west-dipping fault on the east flank, and one or more east-dipping fault(s) of smaller magnitude on the west flank. The deep axis of each basin runs parallel to the east mountain front and lies east of the surface geographic central axis. Jefferson basin has two deep, closed, structural lows (one east of Silver Star and one east of Twin Bridges), which are separated by a structural arch. Sediment depth on the arch exceeds 3,000 m (10,000 ft). Madison basin is shallow on its north end (approximately 2,100 m, 7,100 ft) where it is terminated by the prominent northwest-southeast Spanish Peaks structural trend, and progressively becomes deeper (4,500 m, 5,000 ft or more) south of Ennis, Montana.

Seismic data confirm or support the gravity data. Seismic also shows the folded and thrusted rocks of the east mountain footwall block dipping steeply westward to where they gradually disappear beneath the thick Tertiary sediments. Tertiary strata lying directly against the large west-dipping basin fault show dip reversal caused by drag-folding during basin subsidence. Downthrown "rollover" type anticlines are thus present on the east side of the basins. Numerous small faults, many antithetic, cut the deeper strata and diminish in throw upward.

Strata seen in the seismic sections can be subdivided into a lower set which forms the bulk of the basin fill (possibly equivalent to the Renova Formation, late Eocene to early Miocene); a thinner middle set unconformably overlying the lower set (equivalent to the Sixmile Creek Formation, Miocene and Pliocene); and an upper set composed of west-dipping Quaternary alluvial fan deposits. Each set thickens toward the east basin-bounding fault. In the lower "Renova" set, lacustrine intervals are indicated by their consistent lateral seismic character, whereas fluvial intervals appear to terminate abruptly.

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Example of Inner-Shelf Sand Ridges from Upper Cretaceous Eagle Sandstone, Central Montana Uplift

The Upper Cretaceous Eagle Sandstone of central Montana was deposited during a general eastward progradation of the western shoreline of the narrow, north-south-trending Western Interior epicontinental seaway. Cordilleran highlands to the west were episodically uplifted, and provided the main source for sediments deposited in the seaway.

On the Central Montana uplift, the lower member of the Eagle consists predominantly of very fine-grained sandstone, which is exposed as a thick (average 100 ft, 30 m), continuous topographic rim. This sandstone gradationally overlies shales of the Telegraph Creek Formation. Within the rim, resistant beds and concretions of calcite-cemented sandstone define several smaller units, which can be traced laterally over distances of several miles. These units maintain fairly uniform thicknesses from north to south. However, in an east-west direction, the units thin, are imbricated, and become younger to the west. Excellent exposures of these imbricated lenses occur along a rim that extends 12 mi (19 km) southwest from the town of Winnett.

Although the sandstone of the lower member is very fine-grained throughout the rim, systematic changes occur within a single lens. These changes include: (1) thinning and grading into shale and siltstone to the southwest: (2) bioturbation decreasing upward and to the northeast; (3) oblique *Asterosoma* burrows predominating in the lower part of each lens and to the southwest, with horizontal *Ophiomorpha* burrows being more common in the middle part of each lens and to the northeast; (4) parallel bedding and hummocky cross-stratification successively occurring in the upper part of each lens and to the northeast; and (5) relatively straight-crested symmetrical ripples generally capping each lens. The sedimentary structures within each lens indicate increasing energy and shoaling upward, but do not indicate subaerial exposure.

The lenses in the lower member are interpreted as landward-prograding (westward) sand ridges that were deposited on the inner shelf at distances of tens of miles from the shoreline. Laterally equivalent coastal sandstones of the Virgelle Sandstone Member prograded seaward (eastward) at this same time. The lenses are elongated in a north-south direction, generally parallel to the coast. However, the exact geometry of individual ridges is unknown. After bypassing the shoreface zone, the sand probably was transported parallel to the shoreline by geostrophic currents driven by wind-forcing. Storm waves reworked the upper, seaward-facing slopes of the ridges, whereas landward-facing parts of the ridges were more protected and subjected to bioturbation.

Ridges that occur on the Central Montana uplift are comparable in many aspects to sand ridges on the modern Atlantic inner shelf. However, the modern sand ridges differ from those of the Eagle in two ways: (1) they occur at angles oblique to the shoreline, and (2) they resulted from "shoreface detachment" during the Holocene transgression.

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Haybarn Field, Fremont County, Wyoming, an Upper Fort Union (Paleocene) Stratigraphic Trap

In the fall of 1981, Northwest Exploration Co. drilled the discovery well for Haybarn field. The field is located in the Wind River basin of Wyoming and produces stratigraphically trapped 43° API gravity, 80°F pour point oil and associated gas from the Paleocene upper Fort Union Formation; these rocks are thought of generally as poor exploration targets and gas-prone at best. The reservoir is an arkosic sandstone deposited along the front of a lacustrine delta system. Clays in the reservoir are almost entirely secondary. Despite the precipitation of diagenetic kaolinite and chlorite, the reservoir capacity has remained high with porosities ranging from 18 to 26% and averaging about 20%. Reservoir permeabilities average about 7 md. Transmissibility has been enhanced in some zones by natural vertical fractures. The fractures also provide an avenue for water from lower water sands. The resistivities of the formation waters are variable, making electric log calculations difficult. The R_w of the productive sand tongue in the discovery well ranges from 0.35 ohm-meters at the top to 1.40 at the base, over a vertical distance of 75 ft (23 m). Oil production is limited to the upper, more saline portion. Both the petroleum source and the trapping mechanism for the field appear to be the lacustrine Waltman Shale. The depositional system responsible for Haybarn field is not unique. Similar oil fields remain to be found in other parts of the Wind River basin.

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Three-Dimensional Seismic Survey Applied to Field Development in Williston Basin

The Medicine Lake field of Sheridan County, Montana, was discovered in March 1979 by the drilling of a seismic anomaly. Production is obtained from Paleozoic carbonate reservoirs ranging in age from Ordovician to Mississippian. Cumulative production from the field, as of March 1982, is 1.2 million bbl.

A mini-3D seismic survey was acquired in October 1981 to facilitate development drilling. The survey covered 2.4 mi^2 (6.2 km^2), encompassing the field's seven producing wells and two dry holes. The purpose of this survey was to provide an accurate image of the subsurface structure and delineate the extent of the producing formations.

The areal coverage and improved subsurface imaging of the 3D survey provided a detailed view of the Medicine Lake anomaly. The seismic data reveals that the structure results from a local basement (Precambrian) high. Mapping of the Ordovician Winnipeg Formation revealed a domal structure covering approximately 0.6 mi^2 (1.5 km^2) with closure in excess of 180 ft (55 m).

Although all producing wells are located on the Medicine Lake structure, stratigraphic variations within the reservoirs may localize production within structural closure. Porosity in several producing formations is diagenetic; prediction of reservoir trends from well data alone is difficult. Inversion and interactive modeling were used to study these stratigraphic variations. A correlation between relative acoustic impedance and porosity was established for several formations. Vertical and horizontal relative acoustic impedance sections were then employed to locate zones of possible porosity. This information, combined with the improved structural data, should aid in further development of the Medicine Lake field.

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Lemhi Arch

The Lemhi arch was a northwest-trending landmass that controlled marine depositional patterns in southwest Montana and east-central Idaho during the late Proterozoic and early Paleozoic, and provided a source for early Paleozoic clastic sediments. The arch persisted as a landmass until Late Devonian, when it was finally covered by marine sediments.

The arch first formed in the late middle Proterozoic, when middle Proterozoic miogeoclinal sedimentary rocks, the Lemhi Group and Swauger and Lawson Creek Formations were arched into an elongate dome. It was deeply eroded in late Proterozoic, and as much as 5,000 m (16,400 ft) of clastic rocks were stripped away. The eroded edges of the middle Proterozoic rocks on the west flank of the arch were partly covered in late Proterozoic(?) and Early Cambrian by the onlapping Wilbert Formation and Tyler Peak Formation of McCandless, but sedimentation apparently did not continue into the later Cambrian. On the east flank of the arch, marine sedimentation began with deposition of the Middle Cambrian Flathead Formation, and continued through the Late Cambrian, leaving a westward-thinning wedge of marine rocks against this flank.

During the Ordovician and Silurian, the east flank of the arch was emergent. The west flank was partly submerged in the Early Ordovician, and the onlapping nearshore clastic and carbonate rocks of the Summerhouse Formation were deposited. These rocks are successively overlain by the eastward-thinning marine rocks of the Kinnikinic Quartzite (Middle Ordovician) and the Saturday Mountain Formation (later Ordovician and Silurian?). The west flank of the arch was briefly exposed to erosion after deposition of the Saturday Mountain Formation, but was again partly submerged in Middle and Late Silurian, when the eastward-thinning Laketown Dolomite was deposited.

Both flanks of the arch were exposed in Early Devonian, but in Middle Devonian, deposition was renewed on the west flank as fresh- and brackish-water sandstone was deposited in channels cut deeply in the Ordovician rocks. Later Middle and Upper Devonian sandstone, algal dolomite, and sedimentary carbonate breccia indicate eastward, onlapping deposition in a nearshore environment, and these are succeeded by Upper Devonian marine dolomite and limestone; all of these rocks above the channel sandstone are included in the Jefferson Formation. The east flank of the arch was exposed through much of the Devonian, but late in the period a thin sequence of marine carbonate rocks of the Jefferson Formation was deposited across the top of the arch, and marine sedimentation in this region was continuous from the miogeocline far onto the craton for the first time since uplift of the cratonic region early in the Middle Proterozoic.

The Lemhi arch continued to influence marine deposition even after it was submerged, separating the region of shelf deposition in southwest Montana and east-central Idaho from the region of miogeoclinal deposition in central Idaho. The arch apparently was a landmass again through much of the Mesozoic; it was overridden by the Medicine Lodge thrust plate, which is composed of miogeoclinal sedimentary rocks, in late Early and Late Cretaceous.

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Seismic Interpretation of Basement Block Faults and Associated Deformation in Rocky Mountains Foreland

The reflection seismic method is the most effective technique for the interpretation of buried block fault/forced fold structures. Recent advances in seismic acquisition and processing have improved the interpreter's ability to define fold and fault geometry but limitations still exist. Two major problems involve lateral velocity changes and complicated raypath geometry. It is, therefore, desirable to study surface exposures to use as a guide for mapping buried features. The block fault/forced fold concept has been used effectively to provide models for analyzing foreland structures as demonstrated by seismic lines from several Wyoming basins.

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Foreland Deformation—A Critique of Cause

The cause of foreland deformation has been argued for nearly 100 years, and despite definitive stratigraphy, superb exposure, and extensive seismic and well data, the mechanism and geometry remain elusive. It is necessary to separate arguments for cause from arguments that only support a particular geometric interpretation.

The following statements are presented for discussion and are not advanced as "the answer."

(1) Foreland deformation is caused by end-load buckling in a plate tectonic setting driven by abnormally shallow subduction. (2) The crust is the active (competent) unit, and the plastic subcrust is a passive cushion allowing the great vertical component, though a slight slope forced on it by the subducting slab may have aided telescoping of the crust above. (3) No strictly vertical cause can allow the basins to go down as much as they did, and active (causal) intrusion under uplifts only is not likely. (4) While reverse faults and modest shortening predominate, fault attitudes can