Geophysical information gathered near the western edge of the Williston basin by ARCO Exploration Co. indicates the presence of a structural anomaly resembling a meteorite impact feature. Many anomalous features believed to be subsurface astroblemes are documented in the literature. Controversy exists concerning these astroblemes, not only as to their existence but also to their potential as hydrocarbon reservoirs. There have been many hypotheses generated concerning the origins of such structural anomalies. Upon examination of the seismic data, surrounding well control, and literature, the most reasonable interpretation remains that of an astrobleme.

ARCO's Chimney Prospect, located in Garfield County, Montana, has seismic features similar to those seen at Red Wing Creek field, a well-documented probable astrobleme in North Dakota. These similarities formed the basis for the interpretation of Chimney Prospect as an astrobleme feature. Both impacts occurred in the Jurassic, and seismic evidence indicates that neither feature resulted from basement tectonic movement. Seismic data also indicate that Chimney Prospect has a central uplift with approximately 250 ft (76 m) of structural closure. It is surrounded by an identifiable rim syncline and a much less developed outer rim. Chimney Prospect encompasses approximately 2,000 acres (800 ha.). The time of impact has been determined to be Jurassic, with deformation found in pre-impact sediments as old as the Mississippian Kibbey Formation. The deposition of post-impact sediments has been affected by the rebound of the central uplift. The ARCO Coastal/BNRR 1-9 Skeleton Creek, located 3 mi (5 km) southeast of the prospect, has been used as a control well representing normal nonimpact sedimentation in the region of the anomaly.

Chimney Prospect has been tested by the ARCO-1-1 BNRR/Coastal well. No significant hydrocarbons were encountered. Geologic evidence indicates that a small meteorite landed in a shallow Jurassic sea impacting soft, plastic sediments which dispelled much of the impact force. The underlying sediments at the time of impact were elastic enough to brecciate. Subsequent to impact, the open fractures were either healed or filled with calcite, thereby destroying the porosity and permeability in the potential reservoir prior to oil migration. By contrast, the fracturing at Red Wing Creek field was more extensive because the meteorite body was larger; and it impacted more brittle, lithified carbonates.

Using Donofrio's classification system, Chimney Prospect must be considered to be a possible rather than a probable meteorite impact crater. Borehole samples did not confirm the presence of any shock metamorphic features.

The occurrence of astroblemes in the subsurface is rare. When detected, five main criteria must be met to enhance the possibilities of an economic reservoir: (1) a meteorite body of sufficient size and velocity to produce a brecciated reservoir, (2) preservation of open fractures and pore space through time, (3) effective seals for trapping hydrocarbons, (4) oil migration after impact and deposition of the seal, and (5) open-minded management aggressive enough to drill such features. One obviously does not actively explore for these features; however, once stumbled upon, they should be considered as an unusual opportunity to explore and test for hydrocarbons.

LINDSEY, DAVID A., REINO F. CLARK, SANDRA J. ASHE, and RICHARD J. FLORES, U.S. Geol. Survey, Denver, CO

Minturn and Sangre de Cristo Formations of Southern Colorado—A Prograding Fan-Delta to Alluvial-Fan Sequence Shed from Ancestral Rocky Mountains

The Pennsylvanian Minturn and Pennsylvanian-Permian Sangre de Cristo Formations of the northern Sangre de Cristo Mountains comprise a 3,800-m (12,500-ft) thick progradational sequence of coarse clastic sediments shed into a basin on the northeastern side of the late Paleozoic San Luis–Uncompahgre highland. From bottom to top, the mostly marine Minturn Formation contains probable deltaic (700 m, 2,300 ft), mixed fan-delta and prodelta (800 m, 2,600 ft), and fan-delta (600 m, 2,000 ft) deposits; the mostly continental Sangre de Cristo Formation contains distal alluvial fan (600 m, 2,000 ft) and proximal alluvial fan (1,100 m, 3,600 ft) deposits. This sequence of deposits coarsens and passes upward from mostly gray (reduced) nearshore marine strata in the Minturn to mostly red (oxidized) continental strata in the Sangre de Cristo Formation. The sequence reflects the rise of the San Luis–Uncompahgre highland beginning in Middle Pennsylvanian and later time, as indicated by fusulinids identified in the Minturn Formation. At least three episodes of uplift are indicated by the distribution of unconformities, geometry of intertonguing facies, and abrupt vertical changes in facies.

The deltaic and mixed fan-delta and prodelta deposits of the lower and middle parts of the Minturn Formation consist of coarsening-upward cycles 30 to 300 m (100 to 1,000 ft) thick of shale, siltstone, sandstone, and conglomeratic sandstone. Some of the shales in the lower part of the Minturn are interpreted as having been deposited on the delta plain because they contain land plants in growth position. The mixed deposits in the middle part of the Minturn contain cycles of shale, proximal-turbidite sandstones, and conglomeratic sandstone; such cycles are interpreted as deposits of submarine fans overridden by fan deltas. Fan-delta deposits in the upper part of the Minturn consist of conglomeratic sandstone and thin limestone beds containing fossils of shallow-water marine invertebrates; fan-delta sandstones locally contain large-scale cross-bedding interpreted as deltaic sedimentation units.

Continental deposits of the lower member of the Sangre de Cristo Formation consist of fining-upward cycles 2 to 37 m (6.5 to 121 ft) thick of cross-bedded conglomerate, sandstone, and siltstone deposited by braided streams on the distal parts of alluvial fans. The upper part of the Sangre de Cristo Formation, known as the Crestone Conglomerate Member, consists of proximal alluvial-fan deposits of conglomerate and coarse sandstone. Abundant poorly sorted conglomerates are interpreted as debris-flow and mud-flow deposits; sandstones containing horizontal stratification, low-angle cross-bedding, paleoplacers of black sand, and outsize clasts are interpreted as streamflow and sheetflow deposits.

LORENZ, JOHN C., Sandia National Laboratories, Albuquerque, NM

Compound Structural History of Sweetgrass Arch, Northwestern Montana

The present form of the Sweetgrass arch is the cumulative product of a geologic history which began in the late Precambrian. At that time, the area of the arch formed the eastern limit for the Belt strata, which were deposited on the Precambrian continental shelf. These thick (40,000 ft, 12 km) deposits depressed the underlying lithosphere sufficiently to cause a mild upwarping at the adjacent shelf hingeline, the area of the arch. During the Paleozoic, the arch was a relative high between the Williston basin to the east and continued shelf sedimentation to the west, and the arch was mildly uplifted in Walcott's 1970 process of "amplified topography."

With the formation of the Sevier overthrust belt in Late Jurassic time, this ancestral arch provided a susceptible area at an optimum distance for the formation of a forebulge on an elastically flexed lithosphere. This forebulge (the arch) was mildly uplifted in response to the supracrustal loads created to the west by overthrusting. Although uplift events at the arch can be tentatively correlated with thrust events in the eastward-migrating overthrust belt, the arch remained stationary, and the load to forebulge distance did not remain constant as flexural theory would predict. This was probably caused by early curvature at the arch in excess of elastic limits, creating brittle and plastic components in the local lithosphere, which thus became more susceptible to flexure than the adjacent areas, localizing the arch.

With the onset of the Laramide orogeny, involving basement as well as thin-skinned tectonics, horizontal compressive forces tightened and significantly uplifted the existing arch. In addition, sinistral shear along the elements of the Lewis and Clark lineament may have enhanced the arch as a large-scale drag fold feature, as proposed by Thomas in 1974 and 1979.

LORENZ, JOHN C., Sandia National Laboratories, Albuquerque, NM

Laramide Interactions of Structural Elements in Southwestern Montana

The present geologic framework of southwestern Montana is the result of the interactions of several structural units during the Laramide orogeny. The Lewis and Clark lineament is the oldest of these, having been in existence since the Precambrian when some of its elements bounded the Belt embayment. It is composed of five or six parallel features with differing geologic histories. During the Laramide orogeny, horizontal compression initiated deep-seated wrench faulting along the Lewis and Clark lineament. This faulting allowed the transition from the continued Sevier style of thin-skinned overthrust deformation, which occurred north of the lineament, to the foreland basement-involved thrust deformation, which occurred to the south. The differential motion of the basement was absorbed by small amounts of left-lateral transform motion.

This lineament may also have created a weak zone in the crust into which the Boulder batholith intruded during the early stages of the Laramide. The voluminous volcanic material associated with the batholith created a supracrustal load which downwarped the adjacent lithosphere. If the batholith itself slid eastward, as advocated by Hyndman in 1979, the load was enhanced. Decoupling of the lithosphere along the southernmost elements of the Lewis and Clark lineament localized and accentuated the load-induced subsidence, creating the Crazy Mountains basin and localizing the accumulation of the thick volcaniclastic sediments of the Livingston Group.

LOWELL, JAMES D., Colexcon, Inc., Denver, CO

Foreland Detached Deformation

In an area having perhaps more relief on the top of the Precambrian surface than any other structural province in the world, attention understandably has been focused on the basement-cored structures of the Rocky Mountain foreland. Deep-seated compression interpreted as responsible for the shortened basement features has also created detached structures in the overlying sedimentary cover. These latter structures have never been the object of systematic study, yet they provide important additional evidence of a compressional origin for the Rocky Mountain foreland and other forelands, and are also prospective for oil and gas.

Detached structures can be attributed to at least two types and stages of deformation. First, compression operating early in the development but prior to the differentiation of the foreland created small-scale fold and thrust structures. Probable examples of early compressional structures include those formed on what are now the gentle tilted flanks of the Owl Creek Range in Wyoming and the Cara Cura Range in Argentina. Second, after differentiation of the foreland into blocks, the flexural slip mode of folding in competent sedimentary layers dictates that space problems in both anticlines and synclines be accommodated by the creation of decollement surfaces and associated detachment structures. Examples have been documented from virtually every Rocky Mountain foreland basin. Specifically cited are the North Park basin in Colorado, Elk Mountain area, northwestern Wind River basin, and Big Horn basin in Wyoming, and the Cara Cura mountains in Argentina. Prominent detachment horizons in the Rocky Mountain foreland are shales of Cambrian, Triassic (Chugwater), and Cretaceous (Mowry, Cody, and equivalent) age.

Oil and gas have been produced from detached folds. A negative aspect is that otherwise prospective beds beneath a completely detached structure do not have closure unless they are affected by deeper faults. More optimistically, closures related to local detachment are prospective.

MAUGHAN, EDWIN K., and WILLIAM J. PERRY, JR., U.S. Geol. Survey, Denver, CO

Lineaments and Their Tectonic Implications in Rocky Mountains and Adjacent Plains Region

Two orthogonal sets of lineaments in Phanerozoic rocks of the Rocky Mountains and adjacent plains region probably reflect recurrent structural movement along corresponding fractures in the underlying igneous and metamorphic rocks. The lineaments seem to have been primarily paleotopographic features that affected the depositional and erosional margins, thicknesses, and the distribution of lithofacies of Phanerozoic strata. One set is oriented near the cardinal points of the compass, approximately N5°-15°E and N75°-85°W; the other set is oriented diagonally, about N50°-60°E and N30°-40°W.

At small scales, the crosscutting lineaments of either set suggest primarily vertical movements of rectangular blocks along through-going rectilinear fractures in the basement rocks. At larger scales, the differential movement of these blocks apparently was propagated upward through the strata and formed a variety of structures, many of which are en echelon. Blocks in the region moved at different times, and they commonly rotated about horizontal axes, as indicated by lateral differences in rates of associated sedimentation and by structural features along the lineaments. Throughout most of the Phanerozoic, the movements seem to have been mainly along the diagonal set (northeast, northwest) of lineaments, but the cardinal set (north-south, east-west) also influenced the development of Laramide structures and the present landscape in the Rocky Mountain region. The structural stresses, which were released along the two sets of lineaments, may reflect plate movements, and they probably are related to orogenies caused either by plate collisions or by rifting and continental fragmentation.

MCBANE, J. DUNCAN, and ROBERT P. SWINEHART, Milestone Petroleum Inc., Billings, MT

Depositional Environment of Leo Sands, Middle Minnelusa Formation, Niobrara County, Wyoming

The Upper Pennsylvanian middle Minnelusa Formation "Leo Sands" in the north half of Niobrara County, Wyoming, and southwestern South Dakota, may have been deposited in a nearshore eolian sabkha environment. Cores reveal sedimentary features which support this hypothesis, such as deflation lags, avalanche-produced strata, probable interdune deposits, and nodular anhydrites.

The "Leo Sands" have proven to be excellent reservoir rocks. Associated anhydrites provide the seal for hydrocarbons which may have been generated from organic-rich interdunal shales.

MIKESH, DAVID L., Mallon Oil Co., Denver, CO, and RANDAL F. LAFOLLETTE, Reservoirs Inc., Denver, CO

Sedimentary Facies and Reservoir Characteristics of Cretaceous "J" Sandstone at Torrington Field (North), Goshen County, Wyoming—Exploration and Development Implications

Torrington field (North) is productive from the Lower Cretaceous "J" sandstone in the Wyoming portion of the Denver basin. The trapping mechanism is stratigraphic, with reservoir sandstones enveloped laterally and updip by shale-dominated lithofacies. The field has produced 13,000 bbl of oil from two wells since its discovery in late 1981. However, production can be increased by development based on recognition of features comprising the "J" sandstone depositional system.

Three major sedimentary environments and their associated facies, characteristic of a meandered fluvial system, occur within the "J" interval in the area: abandoned channel, point bar(s), and interfluvial plain. Production at both Torrington (North) and Torrington is from reservoir development within point bar deposits. Cores of the "J" point bar at Torrington (North) show that it is comprised primarily of very fine to fine-grained quartzarenites and sublitharenites. Dominant framework grains are quartz and lithic fragments which are cemented by quartz overgrowths and authigenic clays (primarily kaolinite). Sedimentary structures observed in the cores include burrowing and bioturbation, high-angle plane-parallel cross-bedding, discontinuous wavy shale laminae, climbing ripples, and truncated laminae. Although excellent hydrocarbon shows occur from the base to the top of the point bar, production appears to be confined to thin intervals of medium-grained quartzarenite found near the middle of the vertical sequence. This may be due to flow regime size sorting which affected differential clay diagenesis within the point bar.

Petrophysical reservoir characteristics of the "J" sandstone were established through examination of X-ray diffraction, scanning electron microscopy, thin-section petrography, and conventional core analysis data. Microporosity development and geometry also affect production.

Field extension locations and an exploratory drill site have been established as a result of this study.

MOORE, C. E., and R. J. ARCHER, ARCO Exploration Co., Denver, CO

Pennsylvanian Tyler Stratigraphic Seismic Concepts

Recent drilling in the Rattler Butte area of central Montana has renewed interest in the Pennsylvanian Tyler Formation as a drilling