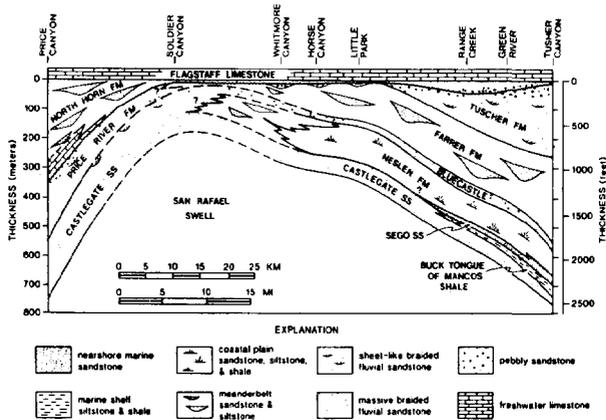


transition from thin-skinned deformation in the thrust belt to basement-cored uplift in the foreland region. Thick sections of the Mesaverde Group in the Wasatch Plateau on the west and the Book Cliffs on the east are separated by the San Rafael swell, a basement uplift across which the group is erosionally thinned. Strata in the west (Castlegate Sandstone and Price River Formation) were deposited by east to northeast-flowing braided rivers. Time-equivalent eastern sections comprise a lower sequence of mixed braided fluvial deposits (Castlegate Sandstone and Bluecastle Tongue of Castlegate), coastal swamp and meander-belt deposits (Neslen Formation), and nearshore marine deposits (Buck Tongue of Mancos Shale and Segó Sandstone), and an upper sequence that coarsens upward from meander-belt deposits (Farrer Formation) into pebbly braided river deposits (Tuscher Formation). Paleocurrent data indicate that rivers of the lower sequence flowed east, while those of the upper sequence flowed northeast.



Sandstones within the section consist of two distinct compositional suites, a lower quartzose petrofacies and an upper lithic petrofacies. The compositional boundary occurs at the top of the Bluecastle Tongue and can be correlated across the San Rafael swell. The quartzose suite contains mostly compositional quartzarenites and sublitharenites; the lithic suite is composed of litharenites and feldspathic litharenites. Lithic grain populations of the upper petrofacies are dominated by sedimentary fragments in sections of the Wasatch Plateau and volcanic fragments in sections near the Green River. The sedimentary lithic grains were transported generally eastward from miogeoclinal strata uplifted within the thrust belt. The volcanic lithic grains of the Farrer and Tuscher Formations were derived from more distal arc sources to the southwest, and transported through the thrust belt somewhere west of the Kaiparowits region, where time-equivalent sedimentary rocks are also rich in volcanic lithic fragments. Disappearance of volcanic lithics and appearance of pebbles at the top of the Tuscher Formation is interpreted to reflect a latest Campanian reorganization of drainage patterns that marked initial growth of the San Rafael swell and similar basement uplifts to the south of the swell. Contemporaneous fluvial systems that deposited the uppermost part of the Price River Formation in the Wasatch Plateau were apparently unaffected by the uplift and continued to flow northeast. Depositional patterns thus indicate that initial growth of the San Rafael swell was probably concurrent with late deformation in the thrust belt. Depositional onlap across the Mesaverde Group by a largely post-tectonic assemblage of fluvial and lacustrine strata (North Horn Formation) indicates a minimum late Paleocene age for growth of the San Rafael swell and deformation within the thrust belt.

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“Spearfish Water Sand”: An Overlooked Play?

The Waskada-Pierson plays in the Amaranth Formation in southern Manitoba have prompted a study of similar units in Bottineau County, north-central North Dakota. The pay zone in the Waskada field is a

sequence of sandstones and siltstones trapping oil which has migrated from the underlying Mississippian strata. The Triassic Spearfish Formation of North Dakota, correlative with the Amaranth Formation of Manitoba, consists of a similar sequence of interbedded sandstones and siltstones which unconformably overlie carbonate and anhydrite rocks of the Madison Group. Log characteristics show the sandstones and siltstones of this sequence to be laterally continuous over the study area.

Except for one well, production in the Bottineau area of North Dakota has been confined to either a portion of the Madison Group or a basal Spearfish sand. This basal sand is overlain by a 20 to 25-ft (6 to 7-m) thick impermeable siltstone which acts as a vertical seal for the Newburg/South Westhope pay. Above this siltstone is a unit locally known as the Spearfish “water sand,” a water-bearing sandstone in the Newburg/South Westhope fields.

The one exception to basal Spearfish production is located in Sec. 6, T163N, R78W, where the Cardinal Petroleum 1 Oscar Aftem well has been producing from the Spearfish water sand since December 1961, indicating that the water sand may have potential for more production in the area.

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Bivalve Associations of Cannonball Formation (Paleocene, Danian) of North Dakota

The Paleocene Cannonball Formation, cropping out primarily in southwest-central North Dakota, is a marine deposit with variable lithologic characteristics ranging from medium to dark-gray-weathering mudstone to fine-grained, well-sorted, brownish-yellow-weathering sandstone. Also, two distinct tongues of the formation, exposed in southwestern North Dakota, are comprised of organic-rich siltstones and claystones.

There are 30 known species of bivalves in the Cannonball. Because bivalves are abundant and well known, and because their morphology and life habits are highly reflective of environmental demands, they are used to more accurately define depositional environments of the Cannonball sea. Based on Q-mode and R-mode cluster analysis, five bivalve associations are defined: *Ostrea-Corbicula*, *Crassostrea-Corbula*, *Isognomon*, *Crassatella-Nucula*, and *Glycymeris-Arctica* associations.

The *Ostrea-Corbicula* association, in the lower Cannonball tongue, and the *Crassostrea-Corbula* association, in the upper tongue, suggest that the Cannonball sediments in southwestern North Dakota were deposited in lagoonal or estuarine environments.

Where present, *Isognomon* occurs in abundance. However, it is found at only a few known localities in southwest-central North Dakota, and it has not been found in association with any other macrofossils. *Isognomon*, found in organic-rich sands, appears to have lived attached to vegetation in shallow-water environments.

The *Crassatella-Nucula* and *Glycymeris-Arctica* associations, common throughout southwest-central North Dakota, are most characteristic of the Cannonball. The *Crassatella-Nucula* association occurs in silty, clayey sand with moderately high organic content. It is dominated by both deposit and suspension-feeding bivalves, and has a high species diversity. It appears to have been deposited in a low energy environment with moderately high turbidity. In contrast, the *Glycymeris-Arctica* association is found in fine-grained, well-sorted sandstone with low organic content. It is dominated by infaunal suspension-feeding bivalves that indicate both a higher energy environment and low turbidity. Crabs and *Ophiomorpha* commonly occur stratigraphically above this association. These two associations most likely represent foreshore, shoreface, and/or shelflike environments.

The distribution of these bivalve associations, along with lithologic characteristics, suggest that the Cannonball Formation was primarily deposited in a barrier island complex and included lagoonal, beach, and offshore environments.

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Exploration Significance of a Possible Subsurface Meteorite Impact Feature in Garfield County, Montana

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.

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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 outside clasts are interpreted as streamflow and sheetflow deposits.

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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.

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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