attained a critical sand content, large-scale linear sand bodies were triggered, which were dynamically analogous to the sand ridges of modern storm-dominated shelves. These features tended to migrate southward across the aggrading shelf surface by means of the accumulation of successive facies packages on their down-current slopes.

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Imaging Beneath Complex Structure: A Case History

Migration is recognized as the essential step in converting seismic data into a representation of the earth's subsurface structure. Ironically, conventional migration often fails where migration is needed most—when the data are recorded over complex structures. Processing field data shot in Central America and synthetic data derived for that section, demonstrates that time migration actually degrades the image of the deep structure that lies below a complicated overburden.

In the Central American example, velocities increase nearly two-fold across an arched and thrust-faulted interface. Wave-front distortion introduced by this feature gives rise to distorted reflections from depth. Even with interval velocity known perfectly, no velocity is proper for time migrating the data here; time migration is the wrong process because it does not honor Snell's law. Depth migration of the stacked data, on the other hand, produces a reasonable image of the deeper section. The depth migration, however, leaves artifacts that could be attributed to problems that are common in structurally complicated areas: (1) departures of the stacked section from the ideal, a zero-offset section, (2) incorrect specification of velocities, and (3) loss of energy transmitted through the complex zone.

For such an inhomogeneous velocity structure, shortcomings in CDP stacking are related directly to highly nonhyperbolic moveout. As with migration velocity, no proper stacking velocity can be developed for these data, even from the known interval-velocity model. Proper treatment of nonzero-offset reflection data could be accomplished by depth migration before stacking. Simple ray-theoretical correction of the complex moveouts, however, can produce a stack that is similar to the desired zero-offset section.

Overall, the choice of velocity model most strongly influences the results of depth migration. Processing the data with a range of plausible velocity models, however, leads to an important conclusion: although the velocities can never be known exactly, depth migration is essential for clarifying structure beneath complex overburden.

GOODRUM, CHRIS, Tenneco Oil Exploration and Production, Englewood, CO

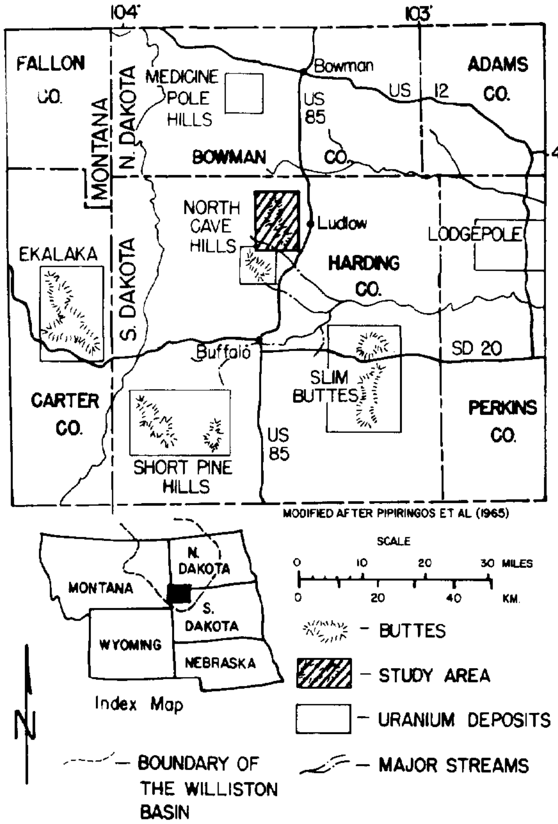
Paleoenvironment of Fort Union Formation, South Dakota

Rocks of Paleocene age are represented in the Cave Hills of northwestern South Dakota by the Ludlow, Cannonball, and Tongue River members of the Fort Union Formation. The Cave Hills are situated within the southern margin of the Williston basin, 80 mi (130 km) north of the Black Hills, South Dakota.

Numerous fine-grained, fining-upward sedimentary sequences comprise the Ludlow Member and are attributed to meandering streams occupying a low-gradient lower alluvial to upper deltaic plain. Major channel sandstones measuring up to 40 ft (12 m) in thickness, crop out and trend markedly to the northeast. Thinner sandstones adjacent to the large channel sandstones vary considerably in geometry and paleocurrent direction and are commonly associated with alternating siltstone, mudstone, claystone, and lignite deposits of levee, overbank, swamp, and possibly lacustrine origin.

The Cannonball Member is 130 ft (40 m) thick in the North Cave Hills and is represented by two fine-grained, coarsening-upward sandstone-mudstone sequences. A distinct vertical succession of sedimentary facies occur within each sequence representing offshore/lower shoreface through upper shoreface/foreshore depositional environments. A north to northeast depositional strike for the Cannonball shoreline is inferred from ripple crest and cross-bed orientations.

Numerous tree stumps in growth position are preserved along the upper surface of the Cannonball Member in the North and South Riley Pass mining districts. These stumps probably represent remnants of a cypress (*Metasequoia*) forest or swamp that stabilized the uppermost sands of the Cannonball shoreline.



The basal part of the Tongue River consists of approximately 40 to 50 ft (12 to 15 m) of lenticular sandstone, siltstone, mudstone, thin-bedded lignite, and kaolinite beds representing thin broad channels, point-bar, levee, overbank, and nearshore swamp depositional environments. Massive fluvial channel sandstones measuring several tens of ft in thickness overlie the fine-grained basal Tongue River lithologies. These channel sandstones represent the continued progradation of continental/fluvial/coastal plain depositional environments eastward over the marine sandstones of the Cannonball Member.

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Petroleum Exploration Contributes to Structural Knowledge of Rocky Mountain Foreland Deformation

The structural configuration and causal interpretation of foreland uplifts in the Rocky Mountain region have gained some clarity through recent petroleum exploration efforts. The most enlightening procedures have continued to be drilling, seismic recording, and surface mapping.

Drilling has confirmed the presence of an overturned limb of Paleozoic rocks beneath many foreland thrusts and a 20° to 30° angle of dip on most fault planes, two characteristics predicted by Berg in 1961 in his fold-thrust theory. Drilling has also revealed that some foreland thrusts do not have an overturned limb of Paleozoic rocks, and instead Precambrian rocks have been thrust directly over Eocene or Cretaceous rocks.

Seismic records have shown a relatively planar fault zone that does not appear to steepen at depth, and, in fact, frequently appears more horizontal, even with velocity corrections to depth. These records have also demonstrated thrust traces at angles ranging from 20° to 35°. Synthetic seismograms made from sonic logs recorded in wells that penetrated Precambrian rocks show zones of intense fracturing in both crystalline and metasedimentary rocks.

Surface mapping and biostratigraphic work on and adjacent to these 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