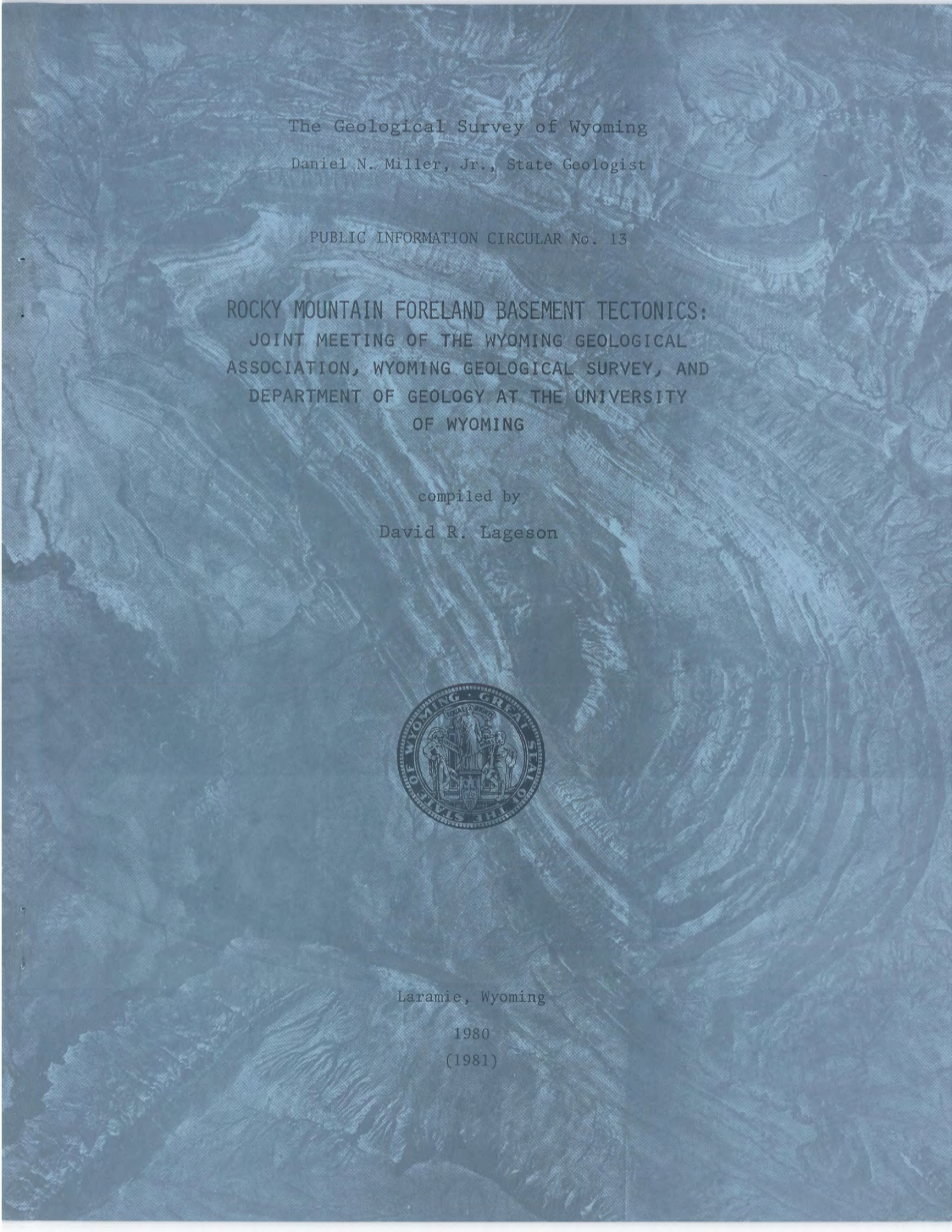


The Geological Survey of Wyoming

Daniel N. Miller, Jr., State Geologist

PUBLIC INFORMATION CIRCULAR No. 13

ROCKY MOUNTAIN FORELAND BASEMENT TECTONICS:
JOINT MEETING OF THE WYOMING GEOLOGICAL ASSOCIATION, WYOMING GEOLOGICAL SURVEY, AND DEPARTMENT OF GEOLOGY AT THE UNIVERSITY OF WYOMING

compiled by

David R. Lageson

Laramie, Wyoming

1980
(1981)

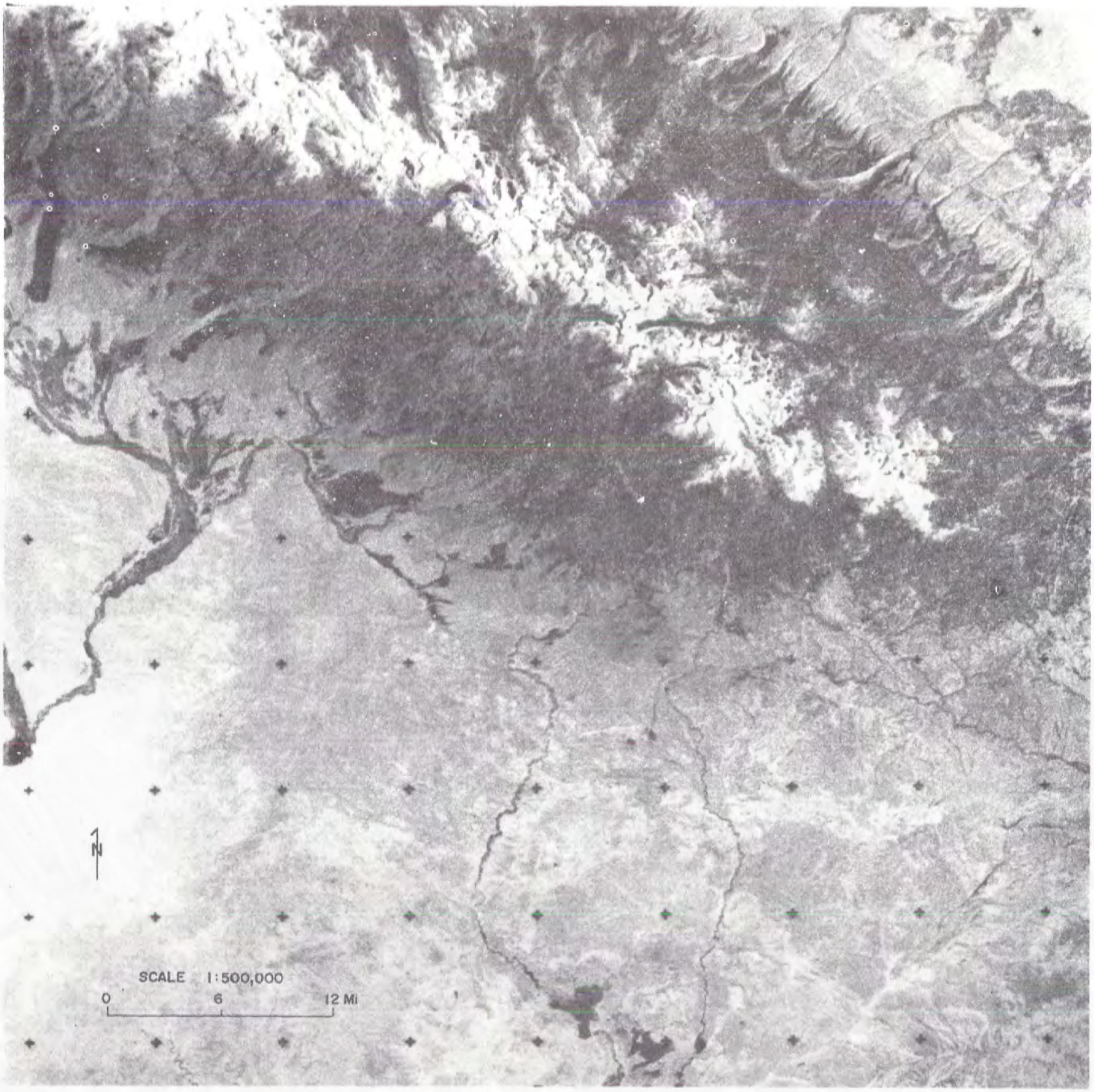
Third printing of 200 copies, March, 1981

Additional copies of this report may be obtained from

The Geological Survey of Wyoming
Box 3008, University Station
Laramie, Wyoming 82071

Cover photo. Circle Ridge anticline, northwest Wind River Basin, Fremont County, Wyoming. Permo-Triassic rocks crop out in center of structure. The Circle Ridge oil field currently has 145 producing wells that have yielded 19,985,094 BBLS (cumulative 1978 statistics) since discovery in 1923. The productive intervals include the Phosphoria, Tensleep, Amsden, and Madison Formations. Photo courtesy of J.D. Love, U.S. Geological Survey.

ROCKY MOUNTAIN FORELAND BASEMENT TECTONICS



Frontispiece: Southeast end of Wind River Range, central Wyoming. Wind River thrust fault subcrops along south and southwest margins of range. NASA LANDSAT image taken July 24, 1978. Approximate scale and north arrow in lower left corner.

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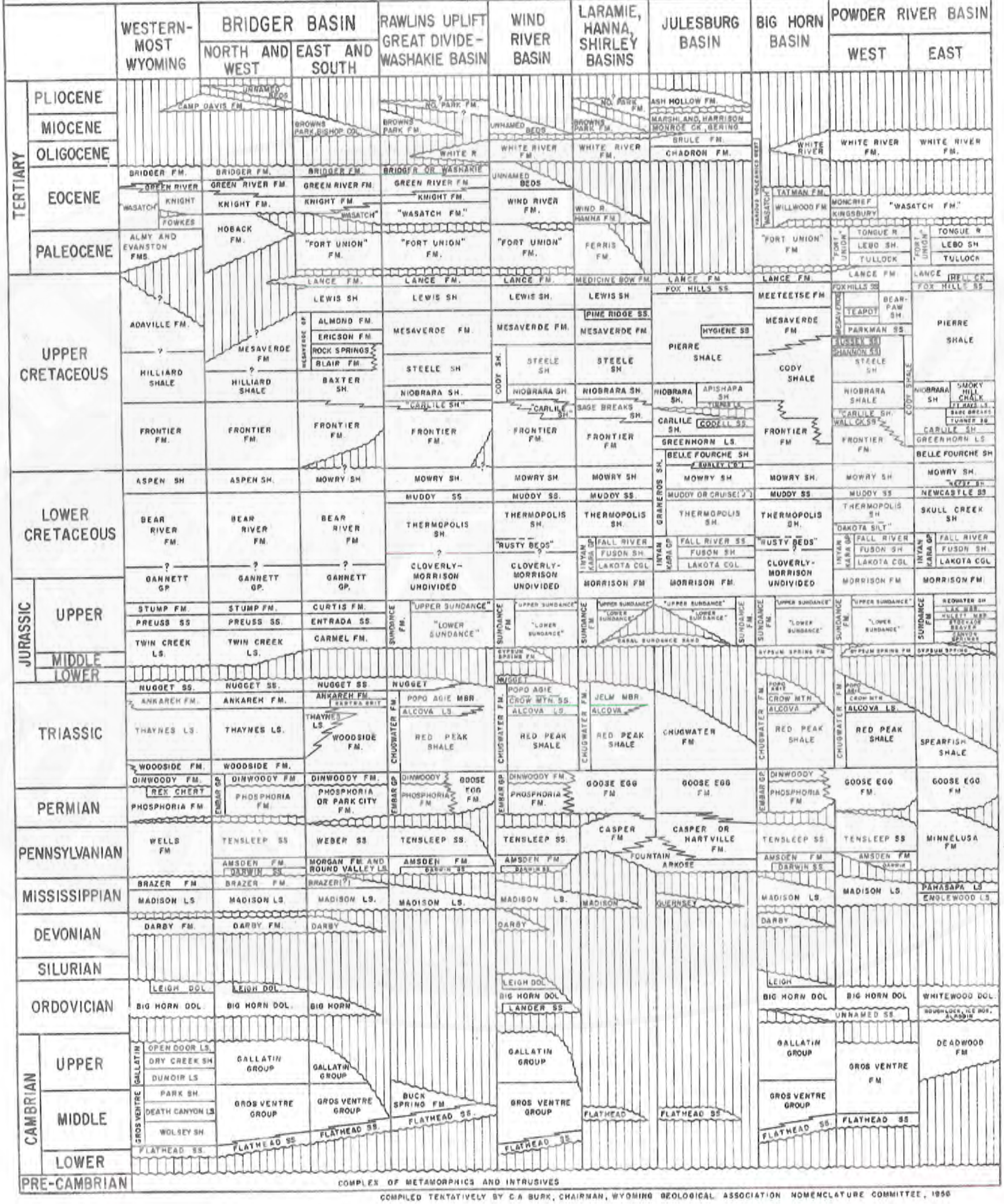
WYOMING STRATIGRAPHIC NOMENCLATURE CHART



COMPILED TENTATIVELY BY C.A. BURK, CHAIRMAN, WYOMING GEOLOGICAL ASSOCIATION NOMENCLATURE COMMITTEE, 1956

INTRODUCTION

by

David R. Lageson
Geological Survey of Wyoming
Laramie, Wyoming

We are pleased to dedicate this conference on Rocky Mountain Foreland Basement Tectonics to Dr. Donald L. Blackstone, Jr., Professor Emeritus of Structural Geology at the University of Wyoming. Dr. Blackstone joined the faculty at the University of Wyoming in 1946 and has since become a leading authority on the structural geology of the Rocky Mountain region. Dr. Blackstone's contributions to the petroleum industry and academia are paralleled by few men and exceeded by none. The topic that this conference addresses has been a major research subject by Dr. Blackstone throughout his career, and continues to demand much of his attention and interest. It is therefore highly appropriate that we honor Dr. Blackstone with this conference.

There is a fundamental polarity between structural geologists working with the subject of Rocky Mountain foreland basement tectonics. One school of thought, the "verticalists," maintain that the principal stress field was oriented vertically during Laramide deformation. That is, the major uplifts and basins developed by dominantly vertical motion with little or no horizontal shortening. This school is represented by the numerous papers contained in G.S.A. Memoir 151 (1979).

The second school of thought, the "compressionalists," maintain that the principal stress field was horizontally oriented during Laramide deformation resulting in a large component of horizontal shortening in addition to vertical offset. This school is receiving considerable support and enhanced credibility through recently acquired COCORP deep seismic reflection lines and other seismic lines by industry along numerous range fronts throughout the foreland. In addition, detailed geologic maps, coupled with balanced structural cross sections and geometrical principles of rock deformation, suggest that many major foreland fault systems have a significant component of horizontal shortening.

As with other geological controversies, it is important to avoid over-application of "dogmas." Scientific objectivity must be maintained through inductive processes of investigation. This has not always been the case with the foreland controversy, especially among "verticalists." It is hoped that this conference will show multiple possibilities for foreland structuring through an informal and open exchange of ideas.

Abstracts in this publication have been submitted by conference participants, and are listed alphabetically by author's last name.

This publication is intended to be a program for the conference and the abstracts contained herein should not be considered as complete papers.

I wish to thank Mr. Ralph Specht (Marathon Oil Company) for his help in coordinating this conference with the Wyoming Geological Association. I also thank the speakers and exhibitors for their willingness to participate. I thank Mr. Alan Ver Ploeg for organizing the exhibits and the other staff members of the Geological Survey of Wyoming. Finally, thanks are extended to the Department of Geology at the University of Wyoming for their cooperation and assistance; in particular Dr. R. S. Houston, Dr. Peter Huntoon and Dr. D. W. Boyd provided suggestions during the early organizational phases of this meeting.

PRE-LARAMIDE TECTONIC HISTORY OF COLORADO PLATEAU

D. L. Baars, Dept. of Geology, Fort Lewis College, Durango, Colorado

The tectonic framework of the Colorado Plateau country was already set by late Precambrian time. A conjugate set of basement rifts was active by about 1.7 bybp, with a dominant northwesterly series of major fractures along which the Paradox basin would subside in Pennsylvanian time and a subordinate series of northeast-trending fractures known as the Colorado Lineament. An orthogonal fracture pattern paralleling the major rifts was almost ubiquitous, but of minor structural magnitude. Sense of displacement on the northwest-trending faults was dextral, while the northeasterly set was sinistral, implying a compressional driving mechanism from the north. Second order structures were north-south oriented normal faults in the central Plateau and the Southern Rockies, and east-west oriented compressional folds in the Central Rockies (Uinta Mountains).

The basement framework was repeatedly rejuvinated throughout Paleozoic time. There is ample evidence from surface, subsurface and geophysical studies to demonstrate repeated vertical movements along the basement features sufficient to alter sedimentary facies during Cambrian, Late Devonian and Mississippian times throughout the Plateau. Subsurface data indicate that both the major and minor structures known at the surface today were in existence in Middle Pennsylvanian time, and continued to strongly affect facies distribution in Early to Middle Permian time. These paleotectonic elements served to localize Paleozoic reservoir facies in the northern San Juan Basin, the southern Paradox basin and the salt-intruded diapirs of the central Paradox. The structural configuration of the Monument Upwarp was virtually identical to the present day structure in late Paleozoic time, but of much lesser structural magnitude. Salt flowage, localized along basement structures, began in Middle Pennsylvanian time and continued through the Late Jurassic, further controlling local sedimentation. Thus, the tectonic stage was set by Laramide time.

Compressional forces from the west in late Mesozoic time only enhanced the pre-existing structural configuration of the Plateau. The Laramide overprinting increased the vertical relief of the monoclinal flexures that lay athwart the force field and overturned near-vertical features toward the east. Interestingly, structures directly or indirectly related to the large basement rifts were not noticeable affected by Laramide forces. The classical Plateau structure seen today as the surface was the result of Laramide compression superimposed over lesser but identical structural features in existance since middle Precambrian time.

REVIEW OF THRUSTING IN THE WYOMING FORELAND

Robert R. Berg, Department of Geology, Texas A&M University, College Station, Texas

The major foreland uplifts of Wyoming are asymmetric, fault-bounded folds of Precambrian crystalline rocks. Their structures are well documented in the Wind River Mountains by geophysical and subsurface data. Seismic surveys in the 1950's showed that the southwest flank of the Wind River is underlain by a thrust fault that dips an average 30° beneath the mountains. Horizontal displacement is greater than 12 mi (19 km), and total vertical uplift is on the order of 9 mi (14 km). Based on wells drilled through similar structures, the thrust zone was believed to consist of overturned Paleozoic and Mesozoic rocks. Interpretations of gravity data confirm the general configuration of the mountain flank but cannot establish the nature of deep-crustal structure.

Results of more recent drilling tend to support the structural interpretation of the Wind River flank as well as to document further the similarities in structural style of other foreland uplifts. In fact, all recent data continue to favor the hypothesis of "fold-thrust" uplift proposed earlier. However, major problems remain. These concern (1) the deformation of brittle, Precambrian rocks into antiform structure, (2) the nature of deep structure beneath the uplifts, and (3) the origins of compressive forces within the crust. Solutions to these problems will come primarily from objective examination and interpretation of subsurface and geophysical data, aided perhaps by studies of the exposed Precambrian rocks in the cores of uplifts.

COMPRESSION AS AN AGENT IN DEFORMATION OF THE EAST-CENTRAL FLANK OF THE BIGHORN MOUNTAINS, JOHNSON AND SHERIDAN COUNTIES, WYOMING

D. L. Blackstone, Jr., Professor Emeritus, Department of Geology, University of Wyoming, Laramie, Wyoming

A 60 km. (37 mile) section of the east flank of the Bighorn Mountains, Wyoming between the Tensleep and Shell lineaments is broken into fault bounded segments. The principal fault trends are: N 40°-45°E; N 60°E; and N 20°-25°W.

A major high angle reverse fault closely parallels the axis of the Powder River basin from Sheridan southward to the Casper arch. The fault location is based on seismic profile and drill records, and the displacement is in the order of 1250 m. (4000 ft.). Structural relief from the axis of the Powder River basin to the crest of the range is approximately 7800 m. (25,000 ft.).

Cross sections based on surface geology and well geology through Ts. 45 N.-53 N. demonstrate that movement on west dipping thrust faults accounts for much of the deformation. Tectonic transport is up and to the east on all recognizable northwest trending frontal faults. Asymmetry of the folds, faults and direction of tectonic transport is reversed to southwest in the mountain flank region north of the Shell lineament (T. 54-56 N.).

The major faulted segment along the mountain flank is the Piney Creek thrust, a plate 15 km. (9.3 miles) long by 5 km. (3 miles) wide, with approximately 5 km. eastward displacement. The plate is believed to be bounded by a west-dipping reverse fault of moderate dip.

The pattern of deformation of the mountain flank is that of differential eastward movement. The Bighorn Mountains are essentially a double plunging anticline with Precambrian basement exposed in the core. The segmented flank lies opposite the region of maximum differential elevation of the Precambrian basement, and is the response of an upward and eastward bulging crust under compression. The reverse fault pattern is pervasive in the sedimentary rocks, and the faults are believed to be rooted in the basement.

The geometry of the deformed rocks supports the concept that the mountain flank deformation took place under compression rather than as simple vertical block uplift.

REPROCESSING OF THE COCORP WIND RIVER FAULT SEISMIC LINE 1

Mark A. Bronston, Amoco Production Co., Denver, Colorado, and Scott B. Smithson, University of Wyoming, Laramie, Wyoming

In the past three years since COCORP (Consortium for Continental Reflection Profiling) obtained seismic reflection data across the Wind River Mountains of Central Wyoming, much data manipulation and interpretation has been done on the final stack data provided by the contractor.

In reprocessing the COCORP data we have determined that: 1) the original velocities applied are too fast in the sedimentary section and too slow in the Precambrian basement; 2) Certain basement events previously interpreted as primary reflections are multiples, as evidenced by their low stacking velocities; 3) Proper migration of the stacked data has been hampered by the application of incorrect velocities in previous processing. These problems in the stacked data have made a valid geologic interpretation of the Wind River fault difficult.

To obtain a reasonable geologic interpretation from the seismic data the following trace processing was applied: 1) Determination of a new velocity function; 2) Autocorrelation to determine multiple periodicity; 3) Predictive deconvolution to eliminate multiples; 4) Removal of residual statics; 5) Near range, middle range, and far range stacks to minimize raypath complexity; 6) Migration of the data using the correct velocity function.

SURFACE AND SUBSURFACE EXAMPLES FROM THE WYOMING FORELAND AS EVIDENCES OF A REGIONAL COMPRESSIONAL ORIGIN FOR THE LARAMIDE OROGENY

W. G. Brown, Senior Staff Geologist, Chevron U.S.A. Inc., Central Region, Denver, Colorado

Deformation of the Wyoming Foreland within a regional compressional field during the late Cretaceous-early Tertiary Laramide Orogeny can be interpreted from the geometric principles displayed by subsurface control and surface exposures. For example, the geometry at the top of the Precambrian basement is depicted as being planar on both up- and down-thrown blocks by those interpreting the structural development via vertical uplift. To the contrary, many field examples display an upturned Precambrian surface on the downthrown block or footwall. When the effects of faulting are backed-out, an anticlinal structure remains at the Precambrian level, indicating a compressional origin for the entire structure. The position of the fault is also seen to be in the crest of this fold, at the Precambrian level. The crustal shortening aspect of a compressional structure can therefore be preserved on the downthrown or footwall block. The footwall geometry is usually buried and therefore not observable; also, this portion of the structure is less clearly defined by reflection seismic methods and, for obvious reasons, is seldom drilled.

The angle of dip of the controlling fault is also indicative of a compressional origin. Many of the controlling faults exposed, or drilled, throughout the Wyoming Foreland are mapped as reverse faults dipping 60° or less at various stratigraphic levels. This geometric relationship clearly demonstrates crustal shortening (i.e., basement over basement) and, therefore, a compressional origin. Other faults dip more steeply and the concept of the downward steepening fault has become the dominant style of many Foreland-workers. However, the constraint of structural or volumetric balancing requires that many faults must be interpreted to dip less steeply at depth. The effect of flattening the fault with depth is two-fold: first, space is thus available on the footwall for the upturned geometry previously described, and, secondly, the sledrunner geometry of the fault plane clearly indicates a compressional origin. Seismic reflection data across several Wyoming ranges demonstrate this basic style.

Surface outcrops expose many subsidiary structures on the flanks of major anticlines in the form of thrust faults and smaller folds. It should be remembered that the flank of an anticline is also the flank of the adjacent syncline, and thus the origin of these subsidiary thrust faults and folds may be more related to the development of the syncline than to the major anticline. Subsurface well control located on numerous anticlinal features often displays stratigraphic sections which are duplicated by thrust faults. The increase of structural complexity downward in the anticlines and upward in the adjacent syncline (subsidiary structures) can best be related to the concept of flexure-slip folding, as a result of regional compression.

Contrary to the view of many authors, the trends of Laramide structures in Wyoming are not random, but are systematic and understandable. The predominant trends are northwest and the less predominant trends vary from north, to northeast, to east-west. It should be pointed out that these latter trends are the same as the trends of Precambrian lineations mapped throughout the Wyoming Foreland. The basic pattern resulting from these various trends is a predominant northwest trend of the major faults and folds, which are terminated laterally by the less predominant north, northeast and east-west trending features.

Berg has documented several examples of what he called the fold-thrust model in many areas of the Wyoming Foreland. All of his documented examples have the predominant northwest Laramide trend. All of them are also clearly compressional in origin, as attested to by: 1) wells which drilled through thousands of feet of Precambrian basement, then faulted into overturned Paleozoic sections, and finally faulted into a right side-up Mesozoic section which dips under the uplift, and 2) good seismic reflection data showing the large amount of Precambrian basement overhang. In addition to Berg's documentation of the ultimate development of the fold-thrust model, there are numerous examples of the various intermediate stages in the development of Berg's model. In the initial stage of development, the upturned basement surface is present on the footwall. The intermediate stages display the development of a dual-fault zone, with a rotated flank encased between the dual faults, which eventually develops into the overturned Paleozoic section sandwiched between the basement overhang and the regional dipping Mesozoic section beneath.

Several authors have erroneously applied the fold-thrust model to the less predominant north, northeast and east-west trends which, as already pointed out, are oblique to the predominant northwest trending fold-thrust features. These oblique trends are actually terminations or interruptions of the fold-thrust trends and therefore should exhibit a different geometry. The northwest trending features already have been shown to have been generated within a regional compressional field, the orientation of which is assumed to be at right angles to the major trends - therefore, northeast-southwest. The oblique-trending features result from oblique-slip along high-angle faults which steepen as the trends become more nearly parallel to the northeast/southwest direction of compression.

These oblique trends are the expected sites of the upthrust (Prucha) and the drape-fold geometry (Stearns). The various models suggested for the Wyoming Foreland have specific geometries which are not interchangeable with one another. This serves to restrict their interpretation to particular areas within the Foreland. In fact, there are specific geometries which are to be expected in specific trends within the Wyoming Foreland, but one specific geometry should not be forced into every structural setting.

The next item to be considered is that of crustal shortening. Without belaboring the point, the theory of plate tectonics as applied to the North American plate during the time of the Laramide Orogeny necessitates that the area of the Wyoming Foreland was under compression at that time. Also, the evidence already presented attests to the compressional nature of the origin of Foreland structures. With this background, it is time to consider crustal shortening as the corollary of regional compression.

The idea of crustal shortening in the Foreland has been vigorously opposed by many workers - mostly those employing a vertical uplift model for the structural style. Part of the negative attitude, I believe, has been generated as reaction to proposals that the Wyoming Foreland was deformed in a wrench fault terrain. The use of the term "wrench faulting" is unfortunate since, to many, it implies a San Andreas-like system, with hundreds of miles of offset. When the dust of the controversy finally settles, the answer will be found somewhere between the extremes of "no lateral movement" and "San Andreas-like" movements. Indeed, some of the noted opponents of lateral movements and crustal shortening have recently begun to shift their positions, pun intended.

The presence of major fold-thrust features such as the Wind River Range and others documented by Berg is devastating to those who oppose crustal shortening. The COCORP seismic line, as well as industry data, clearly show an overlap of the Precambrian basement surface on the order of 20 kilometers. This figure represents the minimum crustal shortening present, and additional shortening can be accounted for by the fold-like shortening at the basement level on both hanging wall (Wind River Range) and footwall (Green River Basin) of this major reverse fault. Therefore, we must consider that this amount of crustal shortening is only one part of the total crustal shortening across the Wyoming Foreland. Additional shortening must be accounted for in various other mountain ranges and basins across the province. The crustal shortening displayed by the Wind River Range appears to be the greatest single component of the total; other features, when correctly restored palinspastically, have somewhat smaller but equally significant amounts of shortening.

If we can establish these magnitudes of crustal shortening what, then, is the possibility of large lateral displacements? If the Wind River Range were a discrete structure on an otherwise featureless foreland, the recognition of the amount of associated lateral movement would be simple. As it is, there are numerous other structures which play an interrelated part in taking up the crustal shortening lost when the Wind River Range dies out along trend. One thing is certain, the amount of crustal shortening displayed by the Wind River Range is a minimum measure of the lateral movement in one part of the Foreland, and represents only one component of the total lateral movement across the entire Foreland.

Finally, when all the trends and specific fold-geometries are reconstructed, it can be seen that the Laramide Orogeny resulted in primary yielding of the crust along major northwest trending features, both mountain ranges and basins, which are of the fold-thrust model. Subsidiary structures located on the flanks of these major features display to a high degree the geometry anticipated from flexure-slip folding processes. Many of these major structures plunge out, with the attendant loss of structural shortening taken up by other features along trend, or en echelon with them. Some of these features terminate abruptly along secondary trends of east, northeast and north. These oblique-trending features are the sites of upthrust and drape-fold geometries. This is the environment where vertical forces are most likely to occur as a result of yielding along high angle, oblique-slip faults, which, fortuitously or not, parallel Precambrian zones of weakness. More work needs to be done to define unique stratigraphic/tectonic markers which can be used as piercing points. The offset of such piercing points is the only true measure of offset across faults and of lateral offset in particular.

OIL AND GAS PROSPECTING THROUGH THRUSTS OF PRECAMBRIAN ROCKS IN THE ROCKY MOUNTAINS

Robbie Gries, Mabee Petroleum Corporation, Denver, Colorado

Exploration through mountain flank thrusts has increased as seismic techniques have been refined to better define thousands of square miles of sedimentary provinces beneath Precambrian rocks and adjacent to petroleum rich basins. Eleven wells in the Rocky Mountain region have been drilled through Precambrian rocks to date, and three more are currently drilling. Seismic work and oil and gas leasing are active on many more Precambrian exposures, if not every uplift in the Rockies.

Significant oil and gas reserves may well be discovered in this new area. In addition, seismic interpretations tied to well logging and well samples will greatly enhance our understanding of the mechanics of mountain flank thrusts.

PLATE-TECTONIC SETTING OF LARAMIDE DEFORMATION

Warren Hamilton, U.S. Geological Survey,
Denver, Colorado

The paired Laramide uplifts and basins produced on the cratonic crust of the Rocky Mountain region during late Late Cretaceous and early Paleogene time define a zone of distorted miniplates between the main North American lithospheric plate and the Colorado Plateau subplate. The amount and direction of relative motion can be deduced from structural patterns. The ranges splaying westward to northwestward across the Uinta-Wyoming-southern Montana region require oblique, left-lateral convergence, the Plateau having moved at least 100 km northeastward relative to the continental interior. The ranges trending south through Colorado and New Mexico show a gradual southward change from major convergence, with a right-lateral component, to a lesser amount of total motion that is largely right-lateral. These constraints indicate that the Colorado Plateau rotated clockwise through about 3 to 5 degrees of arc, as though about a pole in southwestern Texas or northeastern Mexico, relative to interior North America. The time of relative rotation, from about 80 to 40 million years ago, coincides with a period of rapid absolute southwestward motion of the North American megaplate, so in a mantle framework the Plateau subplate was moving in the same direction but at a rate that became slightly lower northward.

Early Cretaceous and early Late Cretaceous subduction-generated magmatism of Andean type formed the Sierra Nevada-Idaho batholithic belt. Gravitational spreading of the batholith may have been the major drive for the eastward spreading, by imbricate thrusting above basement and toward the craton, of the composite wedge of preexisting miogeoclinal strata. The increase in velocity and change in direction of North American motion about 80 million years ago caused the continent to override Pacific lithosphere more rapidly, and the magmatic locus swung irregularly inland during late Late Cretaceous and Paleogene time, then retreated as overriding slowed.

The Colorado Plateau subplate again rotated clockwise, relative to interior North America, during Neogene time, when the motion amounted to about 2 degrees of arc and had a pole of relative rotation near north-central Colorado. The southward - increasing extension recorded by the Rio Grande rift system is the best-known product of this motion. The complex Cenozoic extension that disrupted the northwestern Rocky Mountains represents partial coupling to Pacific plates.

The structural character of the craton-deforming uplifts and basins of the Oquirrh-Uncompahgre-Wichita system, the "Ancestral Rocky Mountains" of Pennsylvanian age, is known only at the Oklahoma end, where the structures are of Laramide type. The system may record the motion relatively eastward or northeastward of the southwest part of the continent, as a byproduct of the final jostling together of North America with Africa plus South America.

GRAND CANYON MONOCLINES - VERTICAL UPLIFT OR HORIZONTAL COMPRESSION?

Peter W. Huntoon, Associate Professor, Department of Geology, University of Wyoming, Laramie, Wyoming

The dominant type of structure associated with Laramide uplift of the Colorado Plateau is monocline separating large crustal blocks that were differentially elevated and gently warped. The monoclines in the eastern Grand Canyon characteristically are underlain by high-angle reverse faults. If it is assumed that the crystalline basement rocks under the monoclines were homogeneous and isotropic before Laramide stresses developed, the steep dips of the faults could be used as evidence that the structures resulted from block uplift in which vertical forces dominated. However, eight decades of mapping in the eastern Grand Canyon have revealed that the high-angle reverse faults beneath the monoclines are reactivated Precambrian normal faults. Precambrian crystalline rocks were anisotropic at the onset of Laramide time, and favorably trending and dipping pre-existing basement faults provided zones of weakness that accommodated stress. With this information, it is no longer necessary to rely upon vertical stress to account for emplacement of the monoclines. Anisotropy of basement rocks allows alternate interpretations, including horizontal compression.

The sinuous trends of the monoclines coincide with changes in orientations of underlying basement faults. Not all Laramide stresses were relieved by reactivation of Precambrian high-angle faults; some Precambrian faults had unfavorable orientations or they did not exist in appropriate areas. In rare cases, new faults of Laramide age developed in the Precambrian crystalline basement rocks, usually linking reactivated parallel or en echelon Precambrian faults. One example is the fault underlying the east-trending segment of the Meriwhitica monocline in Milkweed Canyon, western Grand Canyon district. The importance of these younger basement faults is that they developed in locally homogeneous rocks, and, therefore, can be used as indicators of probable stress patterns responsible for development of the monoclines. The east-trending segment of the Meriwhitica monocline is underlain by a synthetic thrust fault that dips between 17 and 25 degrees. Additionally, more than half of the vertical offset across the overlying fold was accommodated through flexing of the crystalline basement rocks. I conclude from this pattern of strain that lateral compression was responsible for the development of the monocline.

The concept of lateral compression is supported further by observed styles of deformation within the Paleozoic rocks. First, shortening across the fold was in part accomplished along conjugate sets of small-displacement, laterally discontinuous, low-angle thrusts that parallel the fold axis. Second, there is a radical change in dip between the high-angle basement faults and thrusts found in the overlying Paleozoic rocks along segments of the fold developed over reactivated Precambrian faults. Typically the high-angle basement faults terminated in the basal Paleozoic rocks and strain higher in the section was transferred to a series of imbricated low-angle thrusts, rather than to en echelon high-angle reverse faults. Implied is that stresses responsible for deformation in individually homogeneous Paleozoic units were horizontal rather than vertical, supporting the contention that the monoclines were the result of horizontal compression instead of vertical uplift.

GRAVITY INTERPRETATION AND DEEP CRUSTAL STRUCTURE OF THE WIND RIVER RANGE, WYOMING

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Oklahoma city, Oklahoma

Analysis of 1800 gravity stations over the southern part of the Wind River Range and the adjacent basins shows that a positive Bouger anomaly of 85 mgal. is associated with the Wind River uplift. The gravity field parallels the structural trend of the uplift but the axis of the gravity field is displaced to the northeast of the axis of the uplift. Modeling indicates that about 80 percent of the Bouger anomaly is due to the density contrast between the pre-Cambrian core of the uplift and the sedimentary rocks of the adjacent basins. The balance of the Bouger anomaly is attributed to a positive density contrast deeper in the crust.

The COCORP seismic profile over South Pass shows that the Wind River thrust continues into the lower crust with a moderate dip. Gravity models, constrained by the seismic data, indicate that uplift of either dense, lower crustal or upper mantle rocks could account for the residual Bouger anomaly and the shift of the gravity field to the northeast. The best fit gravity model suggests, but does not prove, that lower crustal rocks are offset by the Wind River thrust but the Moho is undeformed. This implies that Laramide deformation of the Moho has recovered by creep or that the Wind River thrust decreased in dip and paralleled the Moho. In either case, the Wind River thrust is a major tectonic feature which offsets the entire crust.

LARAMIDE CRUSTAL SHORTENING IN THE NORTHERN WYOMING PROVINCE

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Stanford University, Stanford, California
Theodore E. Dohmen, Louisiana Land Exp. Co.,
New Orleans, Louisiana

COCORP seismic data across the Southern Wind River Mountains indicate that horizontal compression and resulting crustal shortening and thickening played a major role in Laramide deformation. The Wind River thrust maintains an apparent dip of about 30° to a depth of about 24 km, where it begins to shallow (Lynn, 1979). The Wind River uplift and adjacent basins seem to be representative of the structural style of the entire Wyoming Province. We have applied the fault geometry observed in the Wind River area to other Laramide-age structures in the Northern Wyoming Province (38° to 45°N latitude), and calculated a first order estimate of regional crustal strain using several methods. The upper crust was shortened and thickened approximately 5% in Laramide time, with the shortening directed mostly NE-SW.

Lynn, Heloise B., 1979, Stanford University unpublished Ph.D Thesis.

THE PACIFIC CREEK ANTICLINE: BUCKLING ABOVE A BASEMENT THRUST FAULT

Heloise B. Lynn, Cheryl D. Cape, Mark K. MacLeod,*
Dept. of Geophysics, Stanford University, Stanford,
California

The Pacific Creek Anticline in the Green River Basin, Wyoming is shown to be a classic example of folding and buckling above a basement thrust fault. The Pacific Creek Thrust is observed on the migrated Wyoming COCORP deep seismic profile. From the seismic section, the thrust has an apparent dip of 38 degrees northeast and can be followed to an approximate depth of 12.5 km. The maximum vertical offset of the Paleozoic sediments is observed seismically to be 600 m. Thinning of the sediments over the anticline in the late Cretaceous (possibly Lewis or earliest Lance time) indicates that the anticline is a result of Laramide deformation. The anticline continued to grow with faulting and buckling in the lower 2 km of sediments and folding in the upper sediments through latest Cretaceous and Paleocene time. Although the offset on the Pacific Creek Thrust is 1/50th that of the nearby Wind River Thrust, both have conspicuous reflections. The reflectivity of the thrusts is attributed to changes in the seismic impedance of the fault zone constituents.

* presently at Amoco Production Co., Box 3092, Houston, Texas 77001

REGIONAL STRESSES AND DEFORMATION ASSOCIATED WITH ARC-TRENCH COMPLEXES AND THE WYOMING FORELAND PROVINCE

Vincent Matthews, III, Amoco Production Company,
Denver, Colorado

Deformation of the upper crust in modern and ancient arc-trench systems is coeval with subduction of oceanic lithosphere beneath the deformed belt. Stress indicators in both ancient and modern arc-trench systems suggest that a horizontal compressive force applied to the margin of the overriding plate is not the sole cause of the stress field in the overriding slab.

Deformation in the backarc area is primarily a result of an extensional stress system in the crust. Deformation in the arc-massif occurs in response to a stress field generated primarily by differential vertical forces acting on the base of the brittle crust. Deformation in the subduction zone probably results from an inclined shear couple rather than from a horizontal compressive force.

Laramide deformation in the Wyoming Foreland Province is the result of a stress field somewhat analogous to that of the arc-massif in modern subduction zones.

NEW EXPLORATION CONCEPTS AND OBSERVATIONS ALONG THE WESTERN MARGIN OF THE LARAMIE BASIN

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Past exploration efforts in the Laramie Basin have concentrated on drilling along the western anticlinal trend and isolated structures in other parts of the basin. There also has been some minor effort exploring for stratigraphic traps in the off structure areas. The western margin of the Laramie Basin presents the opportunity to explore along one of the many foreland type thrust faults in the Wyoming Rockies; the Arlington Thrust. The Arlington Thrust dips westward thrusting the Precambrian rocks that form the Medicine Bow Mountains to the surface. The Precambrian rocks overlie Mesozoic and Paleozoic rocks along the west flank of the Mill Creek-Arlington Syncline.

The thrusting of the Precambrian rocks over the younger sedimentary rocks offers the possibility of hydrocarbon accumulations beneath and hidden by the Precambrian at the surface. This exploration concept has been lightly evaluated in other areas of the Rockies, but is new to the Laramie Basin. With the new seismic techniques, which were developed for other areas of difficult terrain and complex geology, the exploration for subthrust accumulations along foreland thrust faults such as the Arlington Thrust is possible.

The first attempt at shooting seismic in the Medicine Bow Mountains resulted in marginal quality data. However, a sedimentary section and possible structure beneath the Precambrian of the upper plate were interpreted from the data. Only one well had been drilled between the Rock River-Seven Mile structural trend and the Arlington Thrust and it did not penetrate any rocks of the upper plate because the well is approximately one mile east of Precambrian outcrops. Early in 1980, one test based on the new seismic data available was drilled by Exxon. The well reached a total depth of 4,573 feet in Precambrian rocks. Although disappointing, the Exxon well does not condemn the concept of subthrust potential. It does necessitate the re-evaluation and reinterpretation of the geology along the frontal edge of the Arlington Thrust. The trace of the Arlington Thrust probably subcrops beneath the Quaternary rocks east of the present proposed trace of the fault. Also, the dip of the Arlington Thrust appears to be steeper in the area of the Exxon well than the observed dip at Corner Mountain near Centennial, Wyoming. With only one well drilled for the entire length of the Arlington Thrust the exploration concept of the possibility of subthrust hydrocarbon accumulations cannot be condemned.

Other new seismic shot in the Laramie Basin has provided some new observations concerning the geology of the basin. The Arlington Syncline lying between the Rock River-Seven Mile anticlinal trend and the Arlington

Thrust is not manifested in the deeper Mesozoic and Paleozoic rocks. These deeper beds are nearly horizontal and appear to form a platform between the Rock River-Seven Mile trend on the east and the Arlington Thrust on the west.

The structure in the Seven Mile Field area as revealed by new seismic is far more complex than previously thought. The east flank is dominated by west dipping faults and the west flank is dominated by east dipping faults. There is a second west dipping fault zone through the Paleozoic rocks with west to east movement. The core of the Seven Mile structure does not share the geometry of the Upper Cretaceous beds. The core is complexly faulted and there is no simple closure. This suggests that the Permian has not been drilled in a hydrocarbon trapping location, possibly explaining why the Permian has not been productive to date along this trend.

The new seismic data also indicates the Mullen Creek-Nash Fork Shear zone extends northeastward from the Medicine Bow Mountains into the Arlington Syncline area, south of Seven Mile Field, across the southern end of Quealy Field, and across the central portion of the basin. This feature is a major fault with significant offset and may extend to the east into the Laramie Mountains. This regional zone of weakness may help to provide traps for hydrocarbon accumulations in the proven producing units of the basin.

MECHANISMS OF DEFORMATION WITHIN LARAMIDE AND PRECAMBRIAN DEFORMATION ZONES IN BASEMENT ROCKS OF THE WIND RIVER MOUNTAINS

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The geometry of the Wind River anticline and the presence of Precambrian basement at its core require that the basement be internally deformed during the Laramide orogeny. At least three generations of deformation zones are seen within the Precambrian rocks, the youngest of which may account for the Laramide deformation.

The earliest deformation zones (which probably represent several different deformation episodes that are not distinguishable as separate events) formed before or during the upper amphibolite facies metamorphism which affected most of the rocks in the Wind River range. These zones have undergone extensive recrystallization, and probably do not represent weak zones along which later defomation could have taken place. These zones do not stand out as zones of preferential weathering and are hard to see on air photos.

Shear zones and associated tension fractures which are accompanied by characteristic greenschist facies retrogression cut all Precambrian rocks in the Wind River range, with the possible exception of the latest generation of diabase dikes. The zones are characterized by the development of chlorite and fibrous quartz, together with small amounts of actinolite and epidote; this assemblage indicates temperatures of 300 to 400°C, which are too high for Laramide conditions. In addition, the zones are never seen to cut into the Paleozoic cover rocks. On this basis, the zones are inferred to have formed in the latest Precambrian. The zones range in width from microscopic dimensions to several meters, usually have steep dips, and display a strong topographic expression.

Laramide deformation zones may range from microscopic shear fractures to zones several meters wide. There is a considerable variation from shallow to steep dips, although the widest zones are usually gently dipping. These zones often follow earlier chloritized zones, but they form a distinctly different pattern from the chloritized zones where they cut across otherwise undeformed granite. Locally these deformation zones can be seen cutting up into the basal Flathead sandstone of the cover sequence. Deformation within the zones is characterized by little or no neomineralization or recrystallization, and appears to have taken place under dry conditions at low temperatures and pressures. Quartz and feldspar grains in granitic rocks are highly fractured and granulated, but no distinct foliation develops within the zones. Strain within these zones may account for the shortening of basement in the Wind River anticline.

SOME TECTONICS DETAILS OF THE CASPER ARCH, AS SEEN ON A REGIONAL REFLECTION SEISMIC LINE

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A southwest trending, 300 mile long regional seismic line was surveyed in 1973 for Gulf Oil Corporation across the State of Wyoming from the northeastern edge of the Powder River Basin to the northern rim of the Washakie Basin proper.

This presentation concerns that portion of this line which traverses the Casper Arch. The direction of this line segment is not ideal, as it forms an angle of about 45 degrees with the main axis of the arch. Nonetheless, the following interesting observations on the structural make-up of the arch can be made:

The arch appears as a wide and relatively flat topped welt of rocks which separates the Powder River Basin from the Wind River Basin. The seismic information shows that the tectonics affecting the eastern side of the arch is significantly different from that affecting the western side. In the east, the relatively undisturbed and subhorizontal sedimentary sequence present in the Powder River Basin elevates into a gigantic drape fold, as the Casper Arch is approached. At depth, and within the nucleous of the fold, we can see some evidence of reverse faulting and possible incipient thrusting. In the west, the boundary between the arch and the Wind River Basin is represented by a high angle reverse fault of major proportions.

Additional evidence of reverse faulting is also observed across the entire width of the arch. However, the fault planes seem to be dipping to the southwest over the eastern three fourths of the width of the arch, and to the northeast over the remaining western fourth.

The resulting image of the arch is that of an ensamble of partly imbricated sleeves of rock, which was wedged and elevated between the two semirigid and foundered sialic blocks which represent the basement of the contiguous basins.

The seismic appearance of the nucleous of the arch is in many ways similar to that of many portions of the thrust belt.

It can be speculated that the tectonic adjustments of the arch have been episodically active from late Madison times to the present.

GRAVITY INTERPRETATION OF THE WIND RIVER MOUNTAINS, WYOMING

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The Wind River Mountains of west-central Wyoming are a large, asymmetric, basement-controlled uplift. A positive gravity anomaly of 85 mgal is associated with the range. A new gravity interpretation was made for the Wind River Mountains for the purpose of evaluating previous structural and gravity interpretations. Evaluation is possible because significant new structural and density control have become available from deep wells and seismic surveys.

Bouguer anomalies range from -149 mgal over the core of the range to -222 and -226 mgal over the sedimentary rocks of the Wind River and Green River basins, respectively. Analysis of the anomaly confirms that the southwest flank of the mountains is underlain by a major thrust fault which extends with a dip of 30 degrees to a depth of at least 9.1 km. Approximately 70% of the gravity anomaly results from the juxtaposition of low-density sedimentary rocks with dense, Precambrian crystalline rocks. The remaining 30% of the gravity anomaly can be accounted for by more dense metamorphic bodies within the mountains at depths less than 6.1 km. The presence of such hypothetical bodies is supported by high-density rocks of the Atlantic City roof pendant in the southeast part of the range.

Models based on cross sections presented by others were evaluated and found to produce poor fits. The models require offsets of deep, high-density crustal layers, either on a low-angle fault which is a projection of the Wind River thrust to depths of 30 km or on a high-angle fault which offsets a deep layer at 15 km. Anomalies produced by these models are too wide to be accommodated by the observed Wind River anomaly.

CRUSTAL MECHANICS OF CORDILLERAN FORELAND DEFORMATION: A REGIONAL AND SCALE-MODEL APPROACH

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Foreland Rockies deformation was caused by compressive stresses transmitted tangentially through the continental basement and the overlying geosynclinal prism from the Pacific continental margin. The stresses probably originated from relative overriding of that ocean block by the continental block as a result of drag on the bottoms of the blocks by convection cells in the mantle.

Dissipation of these stresses by deformation has altered through time from the continental margin to the foreland, depending on the ability of the geosyncline to transmit the stress. Through Mississippian time, Pacific-margin deformation continually thickened the geosynclinal prism. Permo-Pennsylvanian stress transmission through the thickened prism caused deformation of the Ancestral Rocky Mountain foreland. A change in Mesozoic time to hydraulic stresses while batholiths developed in the geosyncline halted foreland deformation by relieving tangential stresses. Stress transmission resulting from Late Cretaceous solidification of the batholiths caused Laramide breakup of the foreland. Tertiary development of northwest oblique yield at the continental margin (San Andreas and Basin-Range structure) again dissipated tangential stress, halting Laramide breakup.

A west-northwest left-lateral couple superimposed on this compression, and caused by greater resistance of the Canadian shield to compression, caused weakening and deformation of the foreland. Eastward movement of the Colorado Plateau block caused the couple to be accentuated in Wyoming and diminished in Colorado. This caused crust-thick, drag fold-slabs in Wyoming. North-south compression between the "Wyoming couple" and the Colorado Plateau caused the Uinta uplift. Release along the south margin was by left-lateral yield on the Wichita lineament. The deformation has been duplicated in models using similar stress.

The Wyoming crust was flexed into combinations of three basic configurations: (1) a slab compressed tangentially into a sine curve with negative parts subsiding as positive parts rose; (2) overlapping slabs caused by failure of the mutual limb of this sine curve; and (3) isostatically collapsed slabs. Basin-margin depression by surrounding uplifts caused the Rock Springs uplift. Isostatic collapse of overlapping slabs during and after compression caused the high south rim of the Sweetwater uplift. Post-compression "rheid" crustal thinning, failure of the mutual limb (fold-thrusting), late removal of basin sediments, and the effect of the left-lateral couple have caused collapse. Bounding structures are aggregates of monoclines, upthrusts, sheared-out and overturned limbs, basin-block swells, second-order faults and folds, isostatically reversed thrusts, and several types of collapse structure. The mechanical functions of these diverse structures can be isolated.

STRUCTURE OF THE NORTHERN MARGIN OF THE GREEN RIVER BASIN, WYOMING

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The uplifts that bound the northern Greater Green River Basin are dominately fold-thrust south and westward over the basin block. Basin deeps are immediately adjacent to or under the overhang of the adjacent fold-thrust, creating characteristic structural relief in the range of 20,000 feet to 40,000 feet. The Wind River structure has been geologically and geophysically interpreted by Berg, (1961) and Berg and Romberg (1966), as a huge fold-thrust of about 40,000 feet of structural relief and at least 65,000 feet of overhang of the range core over basin sediments; and, containing the characteristic sheared-out, overturned limb that has been penetrated in several wells in several other frontal structures. The overturned limb of this structure is, however, everywhere buried and unavailable for direct geological survey.

By contrast the south bounding structure of the Granite Mountains uplift east of the Wind River Range is more complex since the range core has suffered major late-stage collapse, but much better exposed since the structure plunges strongly eastward. This creates an obliquely beveled natural cross-section from deep in the basin block below the level of the overturned, sheared-out limb at Muddy Gap, through the overturned limb in the Sand Pass-Bradley Peak area to high on the unbreached. Paleozoic covered crest of the uplift in the Freezeout Hills. Analysis of this structure suggests that (1) it is bounded on the south by the fold-thrust upon which the Granite Mountains uplift was raised and on the north by the normal fault upon which that uplift collapsed; (2) for isostatic reasons this zone of normal faulting took place essentially back down the root zone of the fold thrust and can be used as an indicator of the amount of overhang on the fold thrust; (3) the entire South Granite Mountains structure has been cross-flexed by the Rawlins-Lost Soldier monocline so that the entire overthrust block has been removed in the area from Green Mountain eastward to Sand Pass, but is still in the ground from Sand Pass eastward and for a short distance under Green Mountain to the west; (4) folding seen in the Mesa Verde sediments south of Bradley Peak is a direct response to southward push from the fold-thrust and probably involves considerable décollement and severly flattened axial planes in the soft Cretaceous shales so that folds at deeper levels are well under the overhang of the fold-thrust; and, (5) overturned slivers of Paleozoic strata on the north side of Ferris Mountain are merely remnants of lower portions of the overturned limb of the fold-thrust, down dropped, on the later down-to-the-uplift normal fault, and are not remnants of a second thrust from the north.

RECURRENT MOVEMENT ON BASEMENT FAULTS, A TECTONIC STYLE FOR COLORADO AND WYOMING

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Recurrent movement on Precambrian-age basement fault systems has influences the origin, thickness and distribution of Phanerozoic strata in Colorado and Wyoming. Three study areas in Colorado are used to illustrate the importance of recurrent fault block movement. Outcrop and subsurface data on the west and northwest margin of the San Juan dome in southwestern Colorado (Area 1) show post-middle Permian-pre Late Triassic truncation of more than 2,000 ft (610 m) of strata over known Paleozoic paleostructural elements. Surface and subsurface data in the Canon City area (Area 2) are used to establish a Paleozoic paleostructural history of the Brush Hollow anticline and then to relate thinning in the Carlile and Niobrara formations to recurrent fault movement during the Cretaceous. The Wattenberg field (Area 3), the largest gas accumulation in Colorado, shows paleostructural movement during deposition of the late Niobrara and early Pierre formations. More than 100 ft (30.5 m) of upper Niobrara strata have been removed by erosion over the top of a paleostructure over an area 10 mi (17 km) wide and 50 mi (83 km) long. The area of the field was in a high structural position during much of the Late Cretaceous and was later deformed into the present structural low portion of the Denver basin.

The tectonic and sedimentation model of recurrent movement on basement faults, as documented in this paper, has important applications in petroleum and mineral exploration. The use of the abundant Cretaceous well data in the Denver and Powder River basins to define paleostructures believed to be related to Precambrian faults should significantly aid exploration programs in the search for deep Paleozoic petroleum accumulations. Isopach data of the Niobrara Formation outline several possible paleostructural trends in the northern Denver basin of Colorado and Wyoming. A knowledge of the fault movement history on these paleostructures will also assist in generating new ideas for Lower Cretaceous sandstone and shallow Niobrara chalk plays on the east flank of the Denver basin. This model may also be applied to other petroleum basins in the Rocky Mountain area.

THE WIND RIVER COCORP PROFILE: SEDIMENTARY DEFORMATION AND DEEP REFLECTION INTERPRETATION PROBLEMS

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COCORP (Consortium for Continental Reflection Profiling) deep crustal reflection data has defined the Wind River thrust as a fault of 30°-35° apparent dip. Maximum true dip is 48° and average true dip is 40°-45°. Numerous deep reflections occur in seismic sections over the Green River and Wind River Basins. The dip and character of these deep reflections is similar to those in the overlying sedimentary rocks. Autocorrelograms and other evidence suggest that some of the deep reflection energy may result from multiple generating systems. Velocity surveys and well logs from the Pacific Creek Anticline, the Precambrian granite of the Wind River Mountains, and the southern section of the Green River Basin were used to determine the velocity distribution, study multiple generation and to construct a migrated section of the thrust and disturbed sediments immediately in front. Synthetic seismograms have been employed in modeling the seismic signature of the sedimentary section. Events on these synthetic seismograms match the time position and character of reflections in the COCORP profile, thus establishing the accuracy of the velocity distribution and inferred Palezoic stratigraphy. The sedimentary velocity distribution is lower than expected, particularly in the Baxter shale where overpressuring is present. Complex velocity structure around the fault makes migration difficult. Deformation of sediments at the thrust varies laterally. Upturned beds, possibly overturned beds, and splays may be present. Lower sedimentary units dip gently under the thrust before eventual truncation. The structural pattern is further complicated by the Continental Fault which intersects the Wind River thrust just south of the COCORP line.


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