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MOUNTAIN FLANK THRUSTING IN ROCKY MOUNTAIN FORELAND, WYOMING AND COLORADO[1]

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ABSTRACT

The principal mountain ranges of the Wyoming and Colorado foreland were raised asymmetrically by Laramide uplift which began in latest Cretaceous time as dominantly vertical movement along arcuate trends. Uplift continued into the Paleocene, and the steeper flanks of some ranges developed into large overturned folds by local compressive forces marginal to the main uplifts. Along segments of maximum uplift, overturned folds were broken and thrust far over the basin synclines in latest Paleocene or earliest Eocene time. Throughout the long period of uplift the adjacent basins were downwarped continuously and received sediment from the rising mountains.

The process of uplift by folding and thrusting better explains observed structure of mountain flanks than the older ideas of block uplift along high-angle faults or thrust uplift by regional compression. Fold-thrust structures are best known along the major Wyoming thrust zones bordering, on the south, the Wind River and Granite Mountains and the Washakie and Owl Creek Mountains. Other examples of faulted overturned folds occur in Colorado along the Golden thrust of the Front Range and Willow Creek thrust in western Colorado. In all these areas thrusts are well documented by subsurface control which includes both deep wells and seismic data.

INTRODUCTION

For many years it was believed that the mountain ranges of the Rocky Mountain foreland originated primarily as vertical block uplifts bounded by high-angle faults. This idea was gradually replaced by the concept of thrust uplift by regional compression after many low-angle reverse faults were recognized in surface mapping. However, in recent years additional data from the subsurface lead to the conclusion that the thrust margins of uplifts originated by a process of deformation which began as vertical uplift but resulted in some places in the growth of overturned folds and culminated in thrusting. This fold-thrust idea gives a better understanding of the genetic relationships between mountain flank structures and adjacent basins and makes easier the interpretation of local structure as well as regional tectonic patterns. However, for some geologists the old idea of vertical block uplift persists today, as an exclusive process of foreland mountain building, to the detriment of tectonic understanding. Some recently published papers have concluded that thrusting is not common or significant in the Wyoming foreland. Therefore, this paper is a defense of thrusting and presents details of known thrust zones which are significant mountain flank structures. It is concluded that folding and thrusting on a grand scale were major factors in mountain flank deformation.

Exploration for oil and gas in the Rocky Mountains, especially in Wyoming, often has extended into the folded and thrust-faulted mountain flanks. In these areas structural interpretation is not simple, and in most places is exceedingly difficult because of the common occurrence of post-Laramide sediments which mask structure in the older rocks. A wider knowledge of mountain flank structure will aid exploration in these complex belts. Furthermore, the study of flank structure undoubtedly will lead toward a better understanding of Laramide history and the influence of uplifts on related sediments of adjacent basins, in which increasing amounts of oil and gas are now being found.

As used in the Rocky Mountain area, "thrust fault" is a low-angle reverse fault, especially one which has formed by compression, and "thrust zone" is a fault zone believed to consist of thrust faults as its major structure. It is shown that the large thrust zones of the Wyoming foreland have fault plane dips which range from an average low dip of about 20° to nearly vertical. Also, parts of these thrust zones appear to have originated by folding; that is, great vertical and horizontal displacements were attained primarily by overturn-

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ing of mountain flanks with minor amounts of displacement achieved by faulting alone. Therefore, in the following discussion, the use of "thrust" and "thrust zone" admittedly is not invariably precise, but no other names are suitable. However, there is the deliberate attempt to describe relative uplift in terms of total displacement of the Precambrian (sub-Cambrian) surface, and the use of the terms throw and heave is avoided except where specifically applied to faults.

Wyoming Flank Structure

MAJOR THRUST ZONES

Zones of thrusting are significant mountain flank structures in the Wyoming foreland. All are the result primarily of deformation of Precambrian crystalline rocks which makes them distinctly different from the thrust slices of sediments in the Overthrust Belt of western Wyoming.

The two major thrust zones of central Wyoming are dominantly west- to northwest-trending complexes of multiple thrust faults which form the south and southwest flanks of principal asymmetric mountain ranges (Fig. 1). The individual thrusts within these zones are arcuate in plan, convex toward the south or southwest, and form an *en échelon* pattern. The longest of these is the Wind River-Seminoe thrust system which bounds the central mountain masses from the Gros Ventre Range in the northwest, past the Wind River Mountains, and along the Granite Mountains in the southeast. Maximum vertical displacement is on the order of 40,000 feet and maximum horizontal displacement is estimated to be about 50,000 feet. A second zone is the Washakie-Owl Creek thrust system which extends along the south flanks of the Washakie and Owl Creek Mountains to the southern end of the Bighorn Mountains where the zone turns southeast and may continue along the west margin of the Casper arch. Maximum displacements along this zone are probably equal to those of the Wind River-Seminoe thrust zone, but here displacements are estimated because more precise data are not available.

These two major thrust zones are better known than others in Wyoming because of available detailed surface maps and a greater amount of subsurface information from seismic surveys, mountain flank test holes, and deep wells in the adjacent basins.

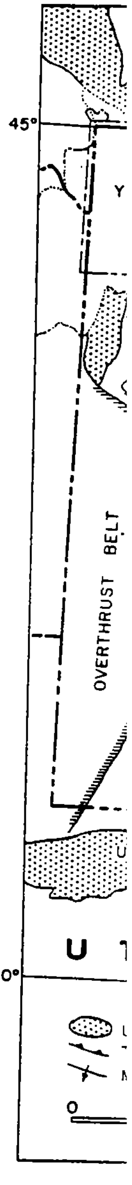
Two similar thrust zones are known in adjacent areas. One is the flanking thrust system of the Uinta Mountains in northeast Utah and northwest Colorado, which consists of the Henrys Fork, Uinta, and Sparks thrusts. The other is the Beartooth thrust zone extending from southwest Montana into northwest Wyoming, which is perhaps continuous with the steep west flank of the Bighorn Basin as far south as Oregon Basin. Both zones include thrust faults, but the nature of these faults at depth is still a matter of argument. Recent diagrams of both the Uinta thrust (Ritzma, 1959) and the Beartooth thrust (Foose et al., 1961) show them as markedly steepening with depth, essentially high-angle faults.

Other zones of less significant thrusting in Wyoming are located along the eastern flanks of the Bighorn and Medicine Bow Mountains, whereas the steep monoclines on the west side of the Rock Springs and the Rawlins-Sierra Madre uplifts are believed to be faulted at depth. However, the monoclinal zones are covered by a great thickness of younger Cretaceous and Tertiary sediments, and the exact nature of deep structure is unknown.

WIND RIVER THRUST

The Wind River Mountains are a northwest-trending asymmetric anticline that has an extensive exposed core of Precambrian crystalline rocks (Fig. 1). At the northwest end of the range significant thrust faults are exposed (Richmond, 1945), but for a distance of about 100 miles the southwest flank is overlapped by Eocene sediments which extend mountainward from the Green River Basin and obscure structure in the older rocks.

For many years it was apparent that great structural relief exists between the southwest flank and the adjacent syncline of the Green River Basin, but the nature of flank structure was unknown. It was suggested that the mountain flank is bounded by a reverse fault (Coffin, 1946; Eardley, 1951), and Love (1950) inferred that the flank is bounded by a thrust fault having 20,000 feet or more of throw. Then more definite evidence became available from seismograph surveys in the Big Sandy area (Berg, 1961b). From this data the Wind River thrust is interpreted to have an average dip of 20° NE., a vertical displacement of 30,000 feet or more, and a horizontal displacement approaching 50,000 feet (Fig. 2). The seismic survey does not extend far enough mountainward to show the relationships in the root zone of the



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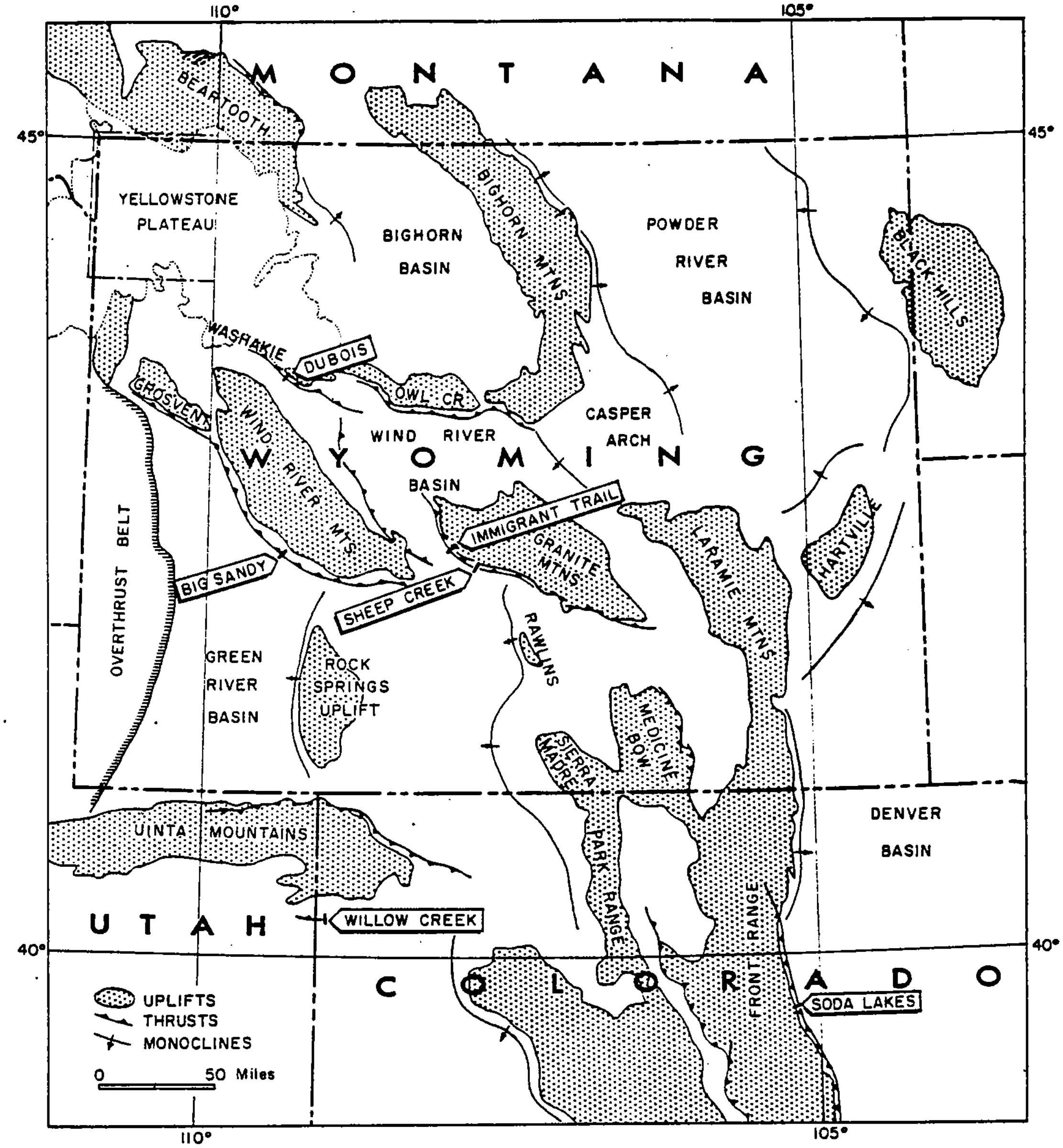

FIG. 1.—Index map of foreland, Wyoming and adjacent areas, showing principal Laramide uplifts, major thrust zones, and location of cross sections.

thrust, but steepening of the fault plane here is expected, based on analogy with other thrust faults at the surface (Berg, 1961b, p. 74).

A prominent feature of the seismograph profile is a strong reflection band that dips northeast and is believed to represent the base of the Precambrian thrust wedge (Berg, 1961b). The thickness, uniformity, and persistence of this band suggest that the thrust is not a simple plane but is a zone 1,000–2,500 feet thick which consists of layered rocks. By comparison with similar thrusts that have been drilled, it is likely that the thrust zone consists of a sheet of sediments, largely Paleozoic in age, deformed by folding and minor faults, but essentially in regular but inverted stratigraphic sequence. Therefore, the Wind River thrust appears to be the faulted limb of a huge, overturned fold. Projection of the possible original Precam-

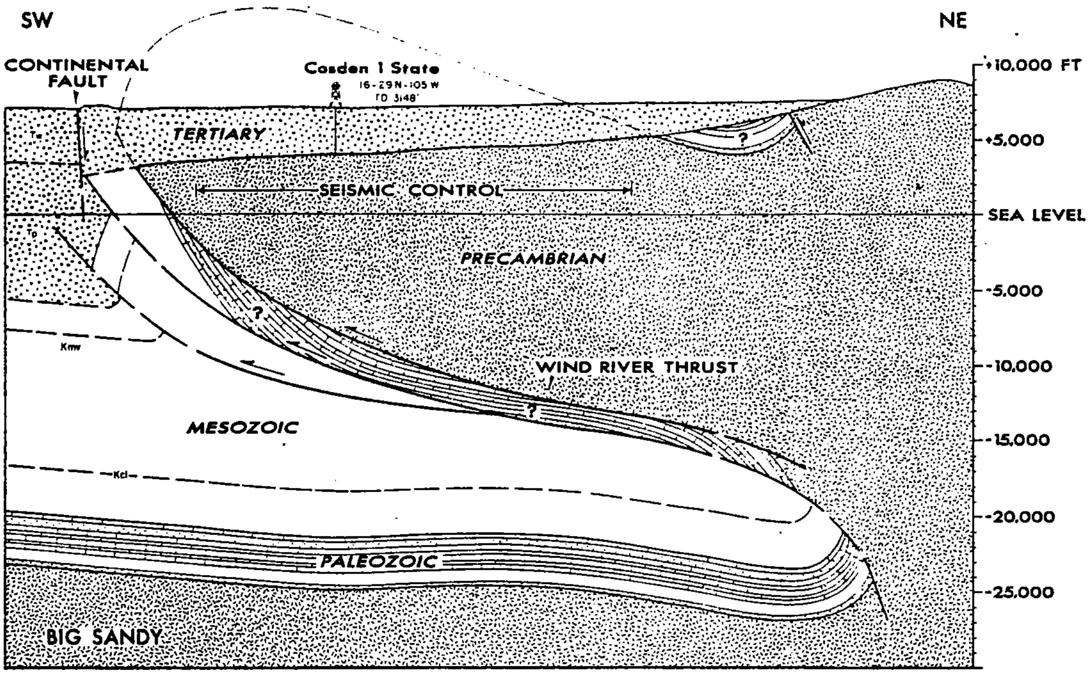

FIG. 2.—Wind River thrust interpreted from seismograph data in Big Sandy area, Sublette County, Wyoming. Kcl is Lower Cretaceous Cloverly Sandstone, Kmv is horizon near top of Upper Cretaceous Mesaverde Formation. Modified from Berg, 1961b, Fig. 3.

brian surface shows that the crest of the fold might have been displaced as much as 45,000 feet above the adjacent syncline.

Other structures associated with the Wind River flank are of interest. The root zone of a second thrust is located toward the northeast. This fault is inferred from gravity data, and relations shown along it are hypothetical. Just southwest of the granite wedge is the Continental fault, a normal fault along which throw has been estimated to be 250–1,000 feet (Nace, 1939; Berman, 1955). The fault dies out downward and represents post-Miocene collapse along the toe of the thrust wedge. The trace of the Continental fault zone along the south flank of the Wind River Range approximately parallels the pre-Wasatch trace of the thrust.

The subthrust sediments of the Green River Basin syncline are remarkably uniform in dip and show no evidence of strong deformation. A gentle, low relief fold is shown in the subthrust section, but this fold may be merely a velocity anomaly resulting from laterally increasing velocity in the subthrust section.

The interpretation of seismic data, without deep well control, does not give an infallible interpretation of structural details, but the seismic control does show a significant thrust fault underlying the mountain flank. From scattered surface and subsurface control, it is probable that the thrust as here depicted is typical of the entire length of the southwest flank of the Wind River Mountains. The relationships along the thrust zone must be inferred from other areas in which similar faults have been drilled.

IMMIGRANT TRAIL THRUST

In other areas of central Wyoming, drilling has revealed overturned sections beneath thick Precambrian thrust wedges. One such area is Immigrant Trail where a Carter Oil Company test well drilled through the Immigrant Trail thrust which forms the southwestern bounding fault of the Granite Mountain uplift. The Carter No. 1 Unit (sec. 32, T. 30 N., R. 93 W.) penetrated 1,200 feet of flat Tertiary beds then 1 900 feet of Precambrian granite, and 880 feet of overturned rocks ranging in age from Cambrian to Jurassic before encountering a normal sequence of Upper Cretaceous sandstone and shale which dip 13° NE. (Fig. 3). The overturned section itself is partly repeated by minor faults, and the Paleozoic formations are represented by limited thicknesses of only the most competent beds. In the cross section, no attempt is made to show the structural complexity of this section. The Immigrant Trail thrust dips 20° NE., an estimate based on all available data; these include a published cross section drawn from seismic data (Wyoming Geological Association, 1951), shallow core holes in the vicinity of the pre-Eocene trace of the thrust, and a second well recently drilled through the same thrust zone, The Atlantic Refining Company No. 1 Unit (sec. 9, T. 29 N., R. 93 W.). Total vertical displacement of the Precambrian surface has been about 13,000 feet, and horizontal displacement is estimated to be 16,000 feet. The known extent of the inverted section below the granite is nearly half of the horizontal displacement; therefore, it appears that a significant part of this displacement has been accomplished by overturning. The Precambrian surface has been restored in the structure section to show the outline of an overturned fold.

Osterwald (1961, p. 229) interprets the Immigrant Trail fault as dominantly high-angle despite the relatively abundant subsurface control to the contrary. His interpretation rests largely on the fact that one well, the Stanolind's Scarlett Ranch Unit No. 1 (sec. 22, T. 31 N., R. 94 W.), drilled 2,600 feet of Tertiary and Paleozoic sediments and 5,400 feet of Precambrian granite without penetrating the fault. This well is located 9 miles northwest of the Carter No. 1 Unit, generally along strike of the thrust, and only 1½ miles from the pre-Eocene fault trace. The position of the Scarlett Ranch well relative to the Immigrant Trail thrust is indicated by its projected location in Figure 3.

Rather than disproving a thrust, the Scarlett Ranch well shows that the fault is deep at this location and that it is overlain by a greater thickness of Precambrian in the superthrust fold. Therefore, both the overlying fold and the subthrust syncline plunge northwestward between the two wells. These conclusions are supported by other subsurface data from nearby wells and seismic surveys.

SHEEP CREEK THRUST

The Sheep Creek thrust, another major fault of central Wyoming, bounds the Granite Mountains on the south from the vicinity of Crooks Gap to Muddy Gap. The Immigrant Trail thrust may be the northwestward extension of the Sheep Creek thrust, but the relation between the two is not clearly established. Osterwald (1961, p. 230) presents a cross section in the vicinity of the Sheep Creek oil field which shows the Sheep Creek thrust as a high-angle fault at depth, an interpretation based only on surface exposures and incompatible with available subsurface data. The exposed thrust dips 5°–18° NE. (Reva, 1959), and seismic control indicates that this dip persists at least 1 mile north (Fig. 4). Underlying the granite thrust wedge are steeply overturned Paleozoic and Mesozoic sediments, bounded below by a second thrust.

Immediately in front of the thrust zone is the strongly asymmetric and faulted Sheep Creek

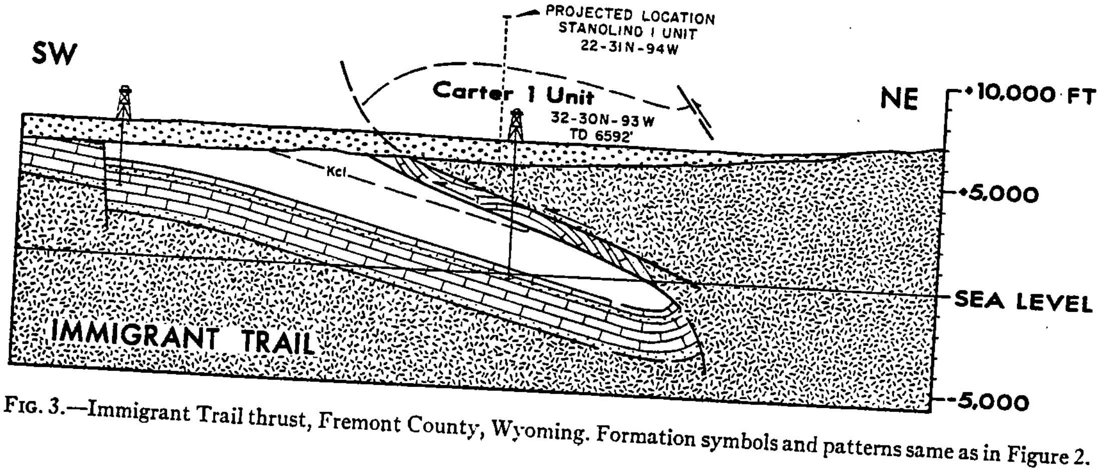

FIG. 3.—Immigrant Trail thrust, Fremont County, Wyoming. Formation symbols and patterns same as in Figure 2.

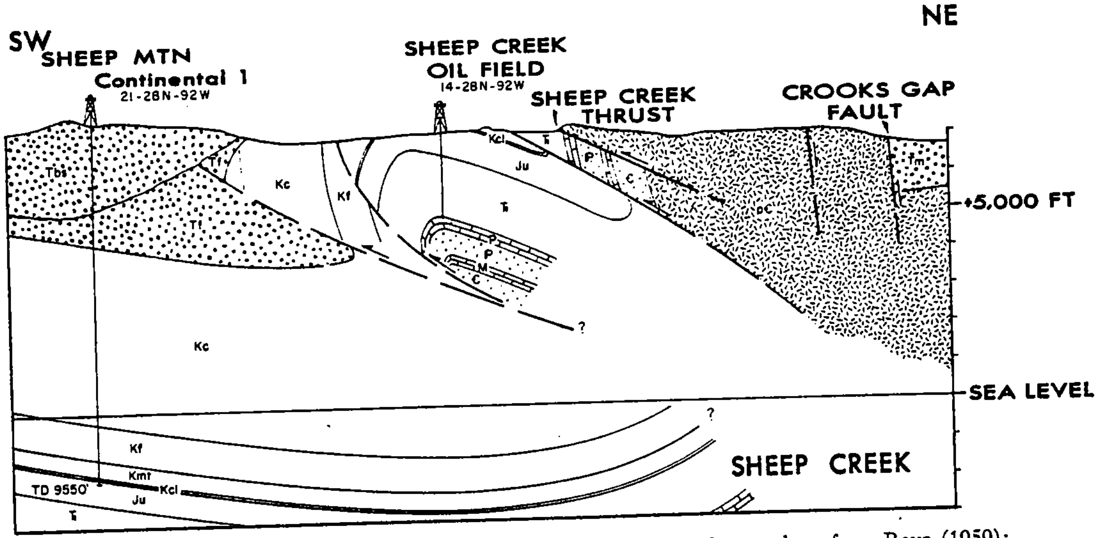

FIG. 4.—Sheep Creek thrust, Fremont County, Wyoming. Surface geology from Reva (1959); structure of Sheep Creek anticline simplified.

anticline. This fold may lack a basement core. Its limited areal extent, sharp asymmetry, and absence of deep folding all indicate that it is truncated below by another relatively shallow thrust. Therefore, the fold lies within a strongly deformed slice in front of and below the main thrust. Not shown on the section (Fig. 4) is another major thrust, located below and south of the Continental's Sheep Mountain well No. 1 (sec. 21, T. 28 N., R. 92 W.). This unnamed fault separates the Crooks Gap-Happy Springs folds from the deep syncline on the south in which the top of the Precambrian surface lies at an elevation of about −15,000 feet.

The root zone of the Sheep Creek thrust is unknown because of limited subsurface control, but enough data are available to show that the thrust is a major low-angle fault. More definitely, the same thrust has been drilled recently at a location 8 miles east of the Sheep Creek field. The Sinclair's Cooper Creek well No. 1 (sec. 19, T. 28 N., R. 90 W.) drilled 2,100 feet of Precambrian granite below which were near-vertical Paleozoic beds, a thrust zone section similar to that shown at Sheep Creek. At a depth of 3,444 feet the well passed through the thrust zone and entered a normal Upper Cretaceous section to total depth of 12,225 feet in the Frontier Sandstone. This well is situated only 1 mile north of the surface trace of the Sheep Creek thrust and confirms an average low dip of about 25° NE. for the fault plane.

EA THRUST

Another drilled thrust is located near Dubois in the northwestern Wind River Basin (Fig. 1). Here a Shell Oil Company test (sec. 9, T. 42 N., R. 105 W.) penetrated the EA thrust, one of the bounding faults of the Washakie Mountain uplift (Fig. 5). This well drilled 7,400 feet of Precambrian schist and found an inverted section 800 feet thick which consisted of 500 feet of deformed and sheared rocks of Mississippian, Pennsylvanian, and Permian age underlain by 300 feet of Triassic redbeds. Below this was about 700 feet of steeply dipping Cretaceous Mowry shale, possibly dragged along the fault, and then a normal section of Lower Cretaceous and Jurassic rocks which dip 15° NE. Here again is an inverted section which exists for a considerable distance beneath a thrust. Folded Precambrian rocks above the EA thrust are well shown by the overlying Paleozoic sediments, and the total vertical elevation of the granite is estimated to be 17,500 feet above the sub-thrust syncline. Horizontal displacement is believed to be about 22,000 feet because seismic surveys indicate that sediments extend at least that far beneath the thrust. The dip of the fault plane is not definitely known, but projection of all subsurface information indicates an average dip of 20° NE.

A subsidiary structure is the additional slice directly in front of the main thrust mass. This frontal zone was drilled nearby and consists of

Cretaceous shales and sandstones, in part folded and overturned. It is similar to the Sheep Creek frontal slice (Fig. 4) but more strongly deformed.

OTHER THRUSTS

Few areas in Wyoming show the nature of mountain flank thrusts as well as those described where wells have actually penetrated a Precambrian thrust wedge. However, similar thrusts of smaller size are known, and one of these was drilled at Sage Creek anticline in the southwest Wind River Basin. The Amerada's Tribal No. 1 (sec. 21, T. 1 N., R. 1 W.) penetrated a Paleozoic section on the steep west flank of the fold. Near the base of the Orodovician the well passsed through a thrust fault and encountered an overturned section of Pennsylvanian and Permian rocks nearly 1,200 feet thick. Then it drilled a second thrust and entered a normal Paleozoic section to bottom in the Tensleep Sandstone at a total depth of 7,390 feet. This is another low-angle fault with dip estimated to be 30° E. and with a typical overturned section in the thrust zone. Here total vertical displacement is only 6,500 feet. The thrust penetrated is part of a fault zone which extends northward along the entire Sage Creek-Steamboat Butte line of folding on the west flank of the Wind River Basin (Fig. 1).

COLORADO FLANK STRUCTURE

GOLDEN THRUST

The Front Range of the Southern Rocky Mountains west of Denver is bounded by a complex reverse fault zone, the Golden thrust. Along much of its extent fault relationships must be inferred, for nowhere is it well exposed so that dip may be accurately determined. The Golden thrust previously was thought to be a high-angle reverse fault (Zeigler, 1917), but later it was believed to be a low-angle thrust based largely on sparse seismic data (Stommel, 1951). Osterwald (1961, Fig. 3) used a single well for subsurface control to show that the fault dips westward at a rather high angle, about 60°. Recently Harms (1961) has further concluded that "the major structures outlining the flank of the range south of Denver are high-angle reverse faults whose dips steepen with depth." However, when all well control is used, the Golden thrust appears to be less a simple thrust and more a faulted and overturned fold (Fig. 6). The overturned limb is complexly thrust faulted, but the individual thrusts have relatively small throws of approximately 1,000 feet or less, whereas the total vertical displacement of the Precambrian surface is more than 13,000 feet. The thrusts dip 35°–50° W. between the wells. They disappear upward in the thick Cretaceous Pierre Shale (Kp) and are not seen in the near-vertical beds at the surface.

Unfortunately, the Golden fault must be interpreted only from the two deep wells and their relation to outcrops, because other data, such as adequate seismic control and dipmeter surveys, are lacking. It appears, however, that the overturned fold is the primary mountain flank structure and that the faults are a secondary feature of the overturned limb. At the town of Golden, 7 miles north of Soda Lakes, the thrust has greater throw, for the Fountain Formation (IPf) is faulted against Pierre Shale (Kp) (Van Horn, 1957). Therefore, the fold at Soda Lakes passes northward into a more prominent thrust fault.

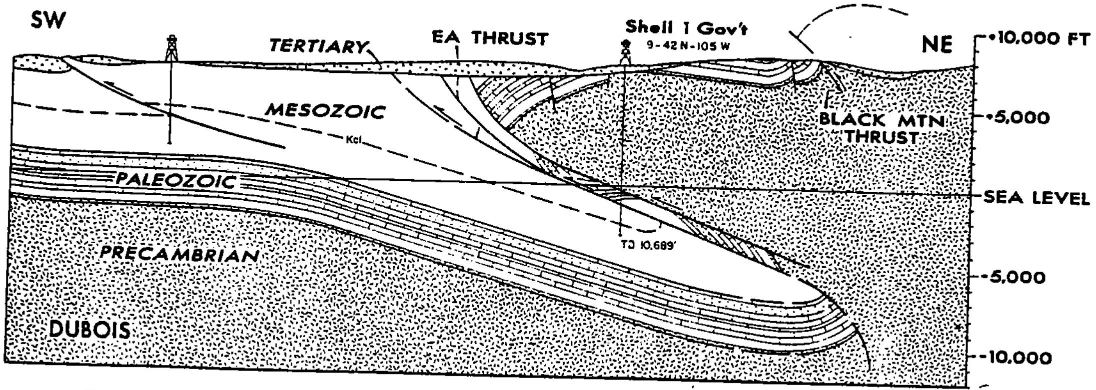

FIG. 5.—EA thrust near Dubois, Fremont County, Wyoming. Kcl is Lower Cretaceous Cloverly Sandstone; surface geology from Love (1939).

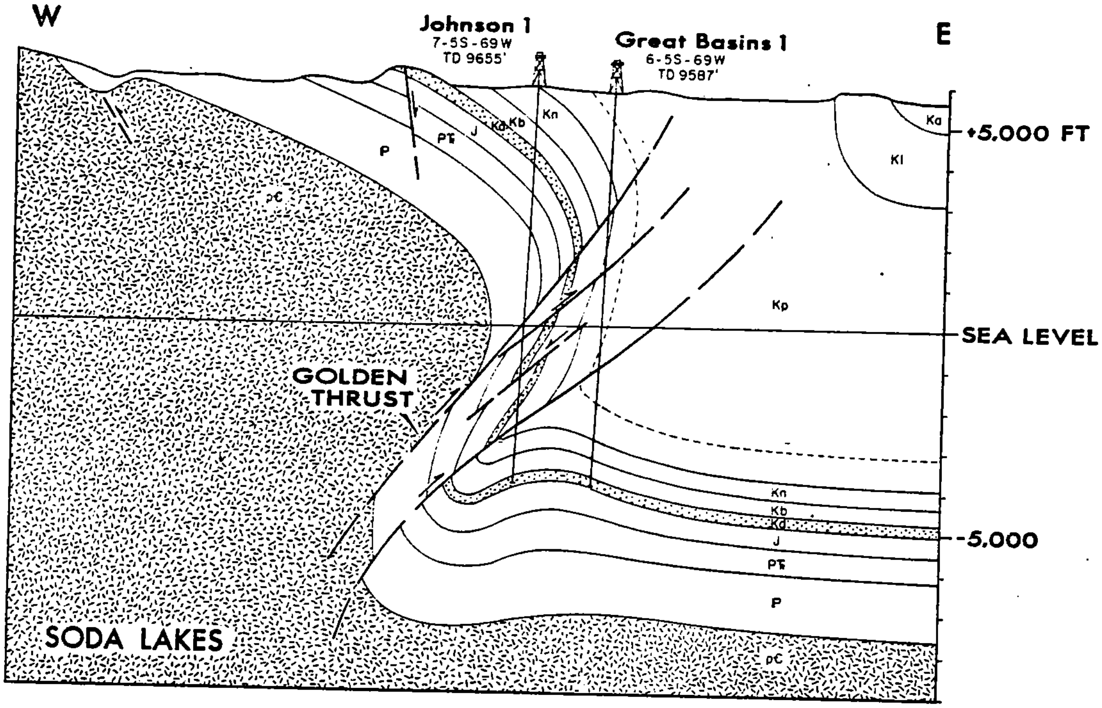

FIG. 6.—Golden thrust in the Soda Lakes area, Jefferson County, Colorado. From Berg (1962).

WILLOW CREEK THRUST

A smaller but better known thrust was drilled in western Colorado on the south flank of the Blue Mountain anticline, a subsidiary fold nearly parallel with the east plunge of the major Uinta Mountain uplift. Here, at Willow Creek, subsurface control shows a major overturned fold with thrust-faulted limb (Fig. 7). The Tennessee's Gov't. well No. 1-A (sec. 3, T. 3 N., R. 103 W.) drilled the overlying sediments and then penetrated 2,000 feet of Precambrian rock, the Uinta Mountain quartzite. Below the first thrust was a 500-foot inverted section of Pennsylvanian, Permian, and Triassic beds, and then a second thrust followed by an 800-foot normal section to total depth of 9,371 feet in the Pennsylvanian Weber Sandstone. Figure 7 is adapted from a cross section by Anderman and DeChadenedes (Anderman, 1961, Fig. 2) which was constructed with the aid of dipmeter and core dip control. The Willow Creek thrust has an average dip of 25° N. and grades upward into steeply dipping Upper Cretaceous Mancos Shale (Kmc). Here again is a low-angle fault zone associated with the overturned limb of a major fold.

ORIGIN OF THRUSTS

BLOCK UPLIFT

The mountain ranges of Wyoming and Montana have long been the subjects of tectonic study, but strong differences of opinion still exist on the interpretation of flank structure. Geologists responsible for early geologic mapping did not recognize thrust faulting. Later when extensive low-angle faults were mapped many geologists persisted in the belief that these were not significant flank structures but only secondary phenomena which occurred in the least competent of the overlying sediments.

The concept developed that the ranges were the result of vertical block uplift during which upward movement of rigid basement blocks took place along high-angle faults. Such mountain ranges were described as block-like in outline, and their forms were believed to be controlled by basement fractures, or conjugate sets of joints. The block uplift hypothesis was widely used to explain regional tectonic patterns, and its foremost proponents were Thom (1923) and R. T. Chamberlin (1945). As block uplift gradually came to be accepted and applied to nearly all of the major uplifts of the foreland, marginal thrusting was relegated to a minor role in deformation. Thus, the thrust structures of the Gros Ventre Range were described as "trap door" uplifts, an asymmetric variation of block uplift, by Horberg, Nelson, and Church (1949). Later, Bengtson (1956) applied the same interpretation and offered a mathematical explanation for thrust faults related to vertical movement. Recently, Osterwald (1961) has presented the extreme view that thrust faults are rare, and he has applied vertical block uplift principles to structural interpretation throughout the entire Cordilleran foreland.

The principles of block uplift are illustrated in Figure 8A. Great vertical displacement is attained by movement along an essentially high-angle reverse fault. The major conclusions of this idea are that the mountain ranges moved upward as rigid basement blocks; that uplift was along vertical fractures developed from pre-existing conjugate joint patterns in the basement; and that thrusts are not major flank structures.

According to the "block-uplifters," all features not compatible with vertical uplift are considered to be of minor importance. Thus Richmond (1945), in discussing thrust faults at the northwest end of the Wind River Mountains, states that "they do not extend beneath the range for any great distance . . . and that more likely they represent local planes of lateral relief" formed during vertical uplift. Osterwald (1961, p. 234) says that "structures that superficially resemble overthrusts are probably subsidiary breaks resulting from rigid basement blocks crowding aside thick sequences of relatively non-resistant sedimentary rocks." These views seem to be extensions of the older idea expressed by Chamberlin (1945, p. 110) that "in a later episode of the orogeny, further easement by horizontal thrust movements became increasingly prominent." In other words, Chamberlin and other proponents of vertical block uplift did not deny the occurrence of thrusts as many have done, but merely assigned their formation to a late period of mountain uplift.

THRUST UPLIFT

Beginning in the 1930s, large-scale thrust faults were recognized more widely in central Wyoming, and it became generally accepted that low-angle

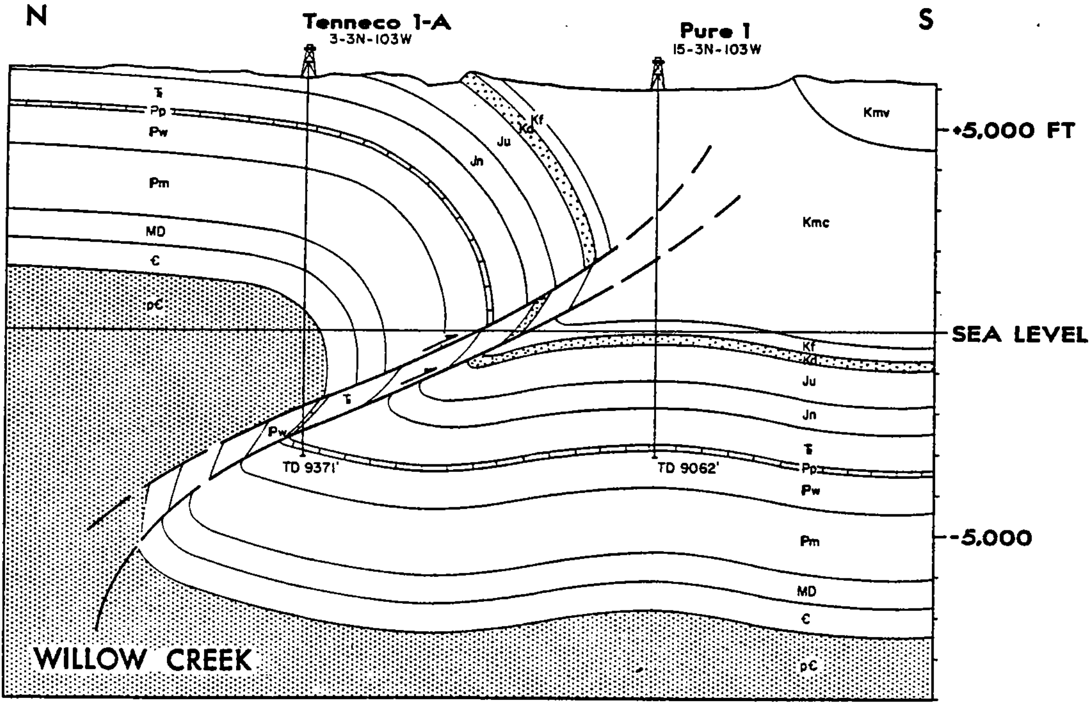

FIG. 7.—Willow Creek thrust south of Blue Mountain, Moffat County, Colorado. After Anderman (1961).

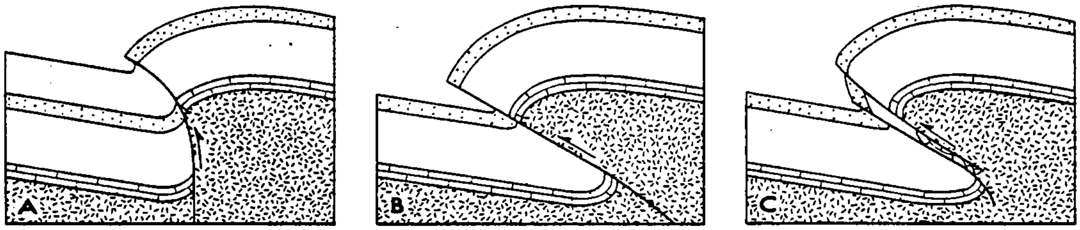

FIG. 8.—Diagrams illustrating hypotheses of mountain flank deformation: A—Block uplift, B—thrust uplift, C—fold-thrust uplift.

faulting observed or inferred at the surface was actually an indication of significant thrust structure at depth. Thrust faults of great magnitude were believed to occur on the flanks of the arcuate ranges which are asymmetric toward the south and southwest, such as the Owl Creek Mountains (Fanshawe, 1939), the Washakie Range (Love, 1939), and the ranges bordering the Granite Mountain uplift (Lovering, 1929, Carpenter and Cooper, 1951, Heisey, 1951). Extensive thrusting was also mapped in other areas, such as along the east flank of the Medicine Bow Range (Beckwith, 1938), and in the Beartooth Mountains. The general character of the thrust-bounded uplift now is known rather well, although the details of the thrust zones at depth are obscure in most places. For many, the idea of thrust uplift has replaced the theory of block uplift. Thrust uplift is illustrated in Figure 8B, in which great vertical displacement is attained entirely along a low-angle fault. The chief difference between thrust uplift and block uplift is the amount of inferred horizontal displacement; genetically, the difference is one of compressive as opposed to vertical forces. Many geologists believe that compression of the entire foreland was necessary to produce large-scale thrusts, and those who favor thrust uplift retain the idea of basement rigidity (D. L. Blackstone, Jr., personal communication).

FOLD-THRUST UPLIFT

A characteristic feature of all major thrusts seems to be the overturned beds beneath them, both in exposures and in the few drilled sections. The subsurface evidence shows that these beds have too great an areal extent to be merely isolated blocks dragged along fault planes, and therefore they must represent the distorted limbs of folds. This leads to the conclusion that thrusts developed from uplift by folding, which progressed into overturning that produced great horizontal displacement, and was followed by thrusting to give an additional but minor amount of horizontal displacement. This mode of mountain flank deformation has been termed fold-thrust uplift (Berg, 1961a, b) and is illustrated in Figure 8C, where great vertical and horizontal displacements are attained primarily by overturning.

Fold-thrust uplift explains an extensive overturned sequence beneath the fault plane whereas uplift by thrusting alone does not. It suggests moderate to extreme deformation of the Precambrian crystalline rocks as opposed to the rigid basement of both block and thrust uplift.

The idea of related overturning and thrusting is not new in Rocky Mountain structure, but its significance has not been recognized. In fact, folding is commonly found in association with major thrusting, and Beckwith (1941) actually showed overturned fold axes above the Elk Mountain thrust while attributing major horizontal displacement to thrusting alone. Large-scale folding which requires extreme deformation of the Precambrian crystalline rocks seems to suggest plastic deformation at relatively shallow depths. Bucher (1933) pointed out that "plastic"-like deformation of the Precambrian does occur in the Southern Rocky Mountains where the Ute Pass fault of the Colorado Front Range was observed to pass laterally into a recumbent fold in the granite. The Rocky Mountains exhibit only a mild form of "plastic" deformation when compared with other great mountain systems of the world, but the mountain flanks do show a marked degree of "plastic" yielding similar to Bucher's mountain welts.

Although basement rigidity during Laramide deformation has been accepted previously, basement folding is possible without plastic flow. On the northwest flank of the Bighorn Mountains, Wilson (1934) observed slickensided, secondary joints in Precambrian granite along a flexure in the Five Springs Creek area. Because there was no evidence of internal deformation, he concluded that granite folding was accomplished by small movements along a large number of closely spaced joints. This may be the manner of deformation of crystalline rocks along thrust zones.

A possible objection to large-scale overturned folding is the missing volume of sediment on the overturned limb. Some of this sediment was eroded during an early stage of uplift when movement was dominantly vertical. Some of it was pushed ahead of the fold in thick frontal slices and partly eroded. Also, there was probably compaction of younger sediments beneath the heavy Precambrian thrust wedge. However, there seems to be a remaining bulk of sediments not accounted for beneath the thrust zones such as in the Wind River thrust (Fig. 2). This may be a failure in structural interpretation rather than in mechanics of folding.

FOLD-THRUST CHARACTERISTICS

The features of the major foreland thrust zones are particularly useful in local structural studies as well as in regional tectonic interpretation. Besides the thrust faults themselves and great displacements, these characteristics may be important, individually or severally, in diagnosing the significance of local structure in exploration along the flanks of major uplifts.

1. Multiple fault planes are common, but usually two faults are prominent, one between Precambrian and Paleozoic rocks, and another between Paleozoic rocks and Late Cretaceous or early Tertiary beds.

2. The fault zone consists of overturned Paleozoic and early Mesozoic sediments, generally a reduced thickness of only the most competent rocks. The inverted section may be relatively undisturbed, somewhat folded and faulted, or highly deformed and jumbled. Its thickness ranges from about 500 feet to several thousand feet.

3. Dip of the main fault plane is variable, and its amount at any place depends on the position of the exposed or drilled part of the thrust. Dips range from very high to vertical at the point of greatest horizontal displacement and in the root zone, to only a few degrees at a location along the middle of the overturned limb. The observed angle of dip may be a real help in determining local position along a fault plane.

4. Stratigraphic throw is variable when measured in different places along the thrust, and apparent throw is least in the root zone.

5. One or more frontal thrusts are known in some places. These frontal slices involve chiefly Mesozoic sediments, are up to 5,000 feet or more in thickness, and do not include Precambrian rocks. They may be strongly folded and faulted, defying a simple structural interpretation even after drilling.

6. Transverse shear faults of major horizontal displacement up to several miles may offset the thrust zones. These result from breaking and lateral movement in a late stage of fold-thrust development. Examples of lateral shearing occur along the Beartooth thrust near Red Lodge, Montana (Foose et al., 1961).

7. A large anticlinal fold involving basement rocks may suggest the presence of deep-seated thrusts. Conversely, the presence of significant thrust faulting may indicate that major Laramide folding is present in the exposed Precambrian core, a feature usually not mapped but often suggested by structures along mountain fronts. Such folding can be observed in Precambrian sediments along a portion of the Uinta thrust (Hansen, 1957).

8. The overlying major fold may have backthrusts on its flank, but these are relatively minor when compared with the total displacement of the mountain flank.

9. Significant normal faults are associated with those fold-thrust zones that have greatest horizontal displacement, such as the Continental fault at the toe of the Wind River thrust (Fig. 2). These faults represent post-Miocene collapse of the thrust wedges. Other normal faults occur behind the thrusts and are downthrown toward the mountains, such as the Crooks Gap fault north of the Sheep Creek thrust (Fig. 4) and the Pathfinder fault north of the Seminoe thrust (Carpenter and Cooper, 1951). Significant normal faults are not recognized where horizontal displacements are small (Figs. 6, 7).

10. Subthrust sediments of the deep basin synclines are not strongly deformed. In most cases the subsurface evidence indicates only more or less uniform dip into the root zones, thereby arguing against the possibilities of subthrust anticlinal prospects for drilling.

TIME OF DEFORMATION

The time of deformation in the Wyoming Mountain ranges seems to be largely Laramide, that is, uplift began in late Cretaceous time, Lancian or even earlier, and ended in latest Paleocene or earliest Eocene time. Evidence from the basins suggests continuous downwarping and more significant, a continuously growing uplift. This is indicated by the influx of coarse clastics of increasing age which were derived from the rising mountain flank. The sedimentary evidence leads to the conclusion that uplift of the mountains progressed uniformly with downwarp of the basin (Berg, 1961, a, b). This conclusion stands in opposition to some former interpretations of Laramide history derived from areas of uplift. These have stressed numerous repeated uplifts followed by long periods of widespread erosion. Locally, tectonic events may have been episodic and deformation may have been limited and intense, but these interpretations give an erroneous regional history. In considering the basin-mountain relationship on a larger scale, a continuous sequence of uplift and downwarp is suggested.

As defined here, "Laramide" deformation is restricted to the period in which greatest uplift was achieved; it does not include subsequent minor movements of the middle and late Tertiary. Some smaller thrusts are post-early Eocene, even post-Oligocene in age. For example, the Piney Creek thrust on the east flank of the Bighorn Mountains pushed Paleozoic rocks over the early Eocene Wasatch conglomerates. Such faults are not major flank structures but are the result of final lateral push toward the basin following the main period of uplift. Perhaps the motivation for some of these thrusts was gravity. In the case of the Piney Creek thrust, it does not effect great vertical displacement, but rather it forms a cap on the monoclinal fold which is the main flank structure.

Although fold-thrust structure may be present along the margins of some ranges, it is an extreme condition for the foreland as a whole. Great horizontal displacement is not a universal condition, and thrusting is limited or absent in parts of many uplifts such as the Bighorn Mountains, Laramie Range, Hartville Uplift, Black Hills, and the Colorado Front Range. Therefore, fold-thrust may represent the final phase of mountain flank deformation opposite only the areas of maximum downwarp of the intermontane basins. Maximum uplift probably was attained only along relatively limited parts of the major thrust zones. It is assumed that less intensely deformed structures are present laterally from areas of maximum deformation.

Uplift began during the late Cretaceous with dominant vertical movement, not of blocks but along linear and arcuate trends. This resulted in asymmetry of basin and range and possibly some high-angle reverse faults at points of great stress (Fig. 9A). Vertical displacement of the Precambrian surface probably attained 10,000–15,000 feet relative to the adjacent basins. During this early period compressional features were weakly developed.

Upwarp continued during the Paleocene. Moderate to high-angle reverse faulting and perhaps gentle folding in the basin sediments accompanied strong arching in the Precambrian rocks of the uplift (Fig. 9B). Vertical relief of 15,000–25,000 feet was attained, and moderate compression of the mountain flank resulted in overturning of major folds.

Uplift culminated in latest Paleocene or earliest Eocene time with dominant compression of the flank which resulted in strong overturning and finally thrusting of the overturned limb (Fig. 9C). Maximum foreland relief ranging from 25,000 to 40,000 feet was achieved. Later Tertiary uplift was largely epeirogenic.

Some uplifts did not progress beyond the first stage while others reached the second stage, and along the major Wyoming thrust zones the mountain flanks reached the final stage of maximum overturning and structural elevation. As shown in Figure 9, erosion of the rising uplifts was continuous, and deposits in the adjacent basins consisted of three facies. Nearest the uplift were conglomeratic sandstones of the flank facies containing pebbles derived first from the sediments, and then from the Precambrian core of the rising mountains. In the basin syncline was a fine-grained shale and siltstone facies representing a non-marine, quiet-water environment of basinal deposition. This facies constitutes the major part of the Hoback Formation in the Green River Basin and Waltman shale member of the Fort Union Formation in the Wind River Basin (Keefer, 1961). Toward the gentle flank of the basin were the interbedded sandstones and coal-bearing shales of the marginal facies that was deposited in a fluvial and fresh-water swamp environment which completely surrounded the non-marine basin. Overturning and thrusting of the mountain flank in the final stage of uplift brought older rocks over the Paleocene sediments that were deposited earlier.

SUMMARY

The structures observed on the mountain flanks of the foreland show that there are thrust zones along the major asymmetric uplifts. Great structural elevation of the uplifts was attained by folding and along significant low-angle faults. There is no subsurface evidence for an exclusive block uplift theory with its rigid basement rocks and dominantly high-angle faults. Neither is compressive thrusting of Precambrian rock wedges an adequate answer, for it does not explain the extensive overturned sequence beneath the thrust planes. Rather, it appears that Laramide basin and mountain flank deformation began with vertical movement along arcuate trends and developed linear upwarps and downwarps with local compressive features. In some places uplift culminated in overturned folding and thrusting. All of this was accompanied by an increasing degree of deformation of the crystalline crust. The entire process was carried on continuously throughout the long duration of Laramide time, from late Cretaceous into the early Tertiary with no significant interruptions either of uplift or of deposition in the adjacent basins.

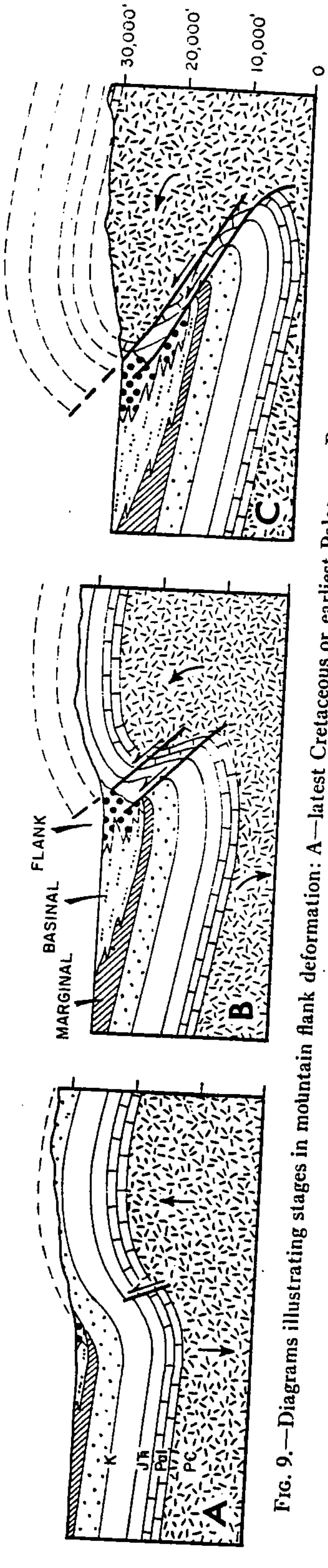

FIG. 9.—Diagrams illustrating stages in mountain flank deformation: A—latest Cretaceous or earliest Paleocene, B—middle Paleocene, C—earliest Eocene.

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