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Major Structures of the Rocky Mountains of Colorado and Utah

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ABSTRACT

This paper describes the major structures of Colorado and Utah and presents a theory of origin based on new knowledge of the layering and constitution of the upper mantle and lower crust. It proposes that the Ancestral Rockies and the more modern ones of Cretaceous and early Tertiary age of both the shelf of Colorado and eastern Utah and the miogeosyncline of western Utah are the result of vertical uplifts of the silicic crust. The uplifts are caused by the rise, from the upper mantle, of basalt in scattered places to the base of the silicic crust. This rise domed the silicic crust and the overlying sedimentary veneer.

The surficial structures are viewed as gravity-caused mass movements along the flanks of the uplifts and in addition, particularly in the miogeosyncline of western Utah, as synclinoria of Paleozoic strata between uplifts where folding and considerable bedding plane thrusting occurs.

The theory also relates widespread magmatism to tectonism in a reasonable fashion. It recognizes that the Rocky Mountains have been a region of Cenozoic regional uplift in which possibly more energy was required than for the building of individual uplifts. This, too, is related to a transformation of the uppermost mantle into a lighter density state. And finally, the Basin and Range faulting of western Utah is viewed as the result of the rise of sufficient basalt from the mantle to form a continuous layer under the silicic crust of the miogeosyncline thus bringing into existence a new framework of forces. The surficial structures are framed about the primary uplifts, but the entire silicic crust becomes attenuated toward the Pacific as it is activated by a component of gravity on a mobilized lower crust.

INTRODUCTION

Shelf and Miogeosynclinal Divisions

The shelf and miogeosyncline of the Rocky Mountains are separated along a line that extends from southwestern to northcentral Utah and southeastern Idaho (Fig. 1). West of the boundary, a thick but irregular Paleozoic and Triassic sequence of sediments was deposited in a region which later became emergent and an area of erosion. East of the boundary, spreading across eastern Utah and Colorado, Paleozoic sedimentary rocks are thin, and certain systems in places are lacking. The boundary marks also a narrow Jurassic and Cretaceous trough of subsidence in which about 15,000 feet of sediments were deposited. East of the trough, about 5,000 feet of Mesozoic sediments accumulated on the thin Paleozoic shelf rocks.

Ancestral Rockies

The shelf division was deformed in Pennsylvanian time by several mountainous uplifts across Colorado and Utah and adjacent areas on the south that are known as the Ancestral Rockies. Those that concern the present article are the Colorado or Ancestral Front Range of central Colorado, the ancestral Uncompahgre Range of western Colorado and eastern Utah, and two somewhat positive areas in central and western Utah. The uplifts trended northerly and northwesterly. The Uncompahgre Range was marked by a near vertical fault on the southwest side along which it rose, the adjacent Paradox basin sank, and the Colorado Range was marked by a steep flank on the east side. The Uncompahgre remained as an erosional highland until Jurassic time, and the Colorado until Late Cretaceous time, before accumulating sediments on the shelf buried them. There seems little evidence of a post-Permian existence of the central and western Utah positive areas. At best they were platforms or gently emergent areas between deeper water and thicker sediment areas.

Late Cretaceous and Early Tertiary Crustal Movements

The shelf division is noted for the growth of large ranges which were separated by intermontane valleys during Late Cretaceous and very early Tertiary times, and although much denudation has occurred since, the ranges still are major relief features.

The miogeosyncline of western Utah is more complex structurally than the shelf, principally because the late Cenozoic Basin and Range block faults have been superimposed on Late Cretaceous and early Tertiary (Laramide) structures producing a multitude of smaller and younger ranges. The older structures are covered in places by volcanic rocks, and incident to block faulting, also by widespread Quaternary alluvium. It is commonly

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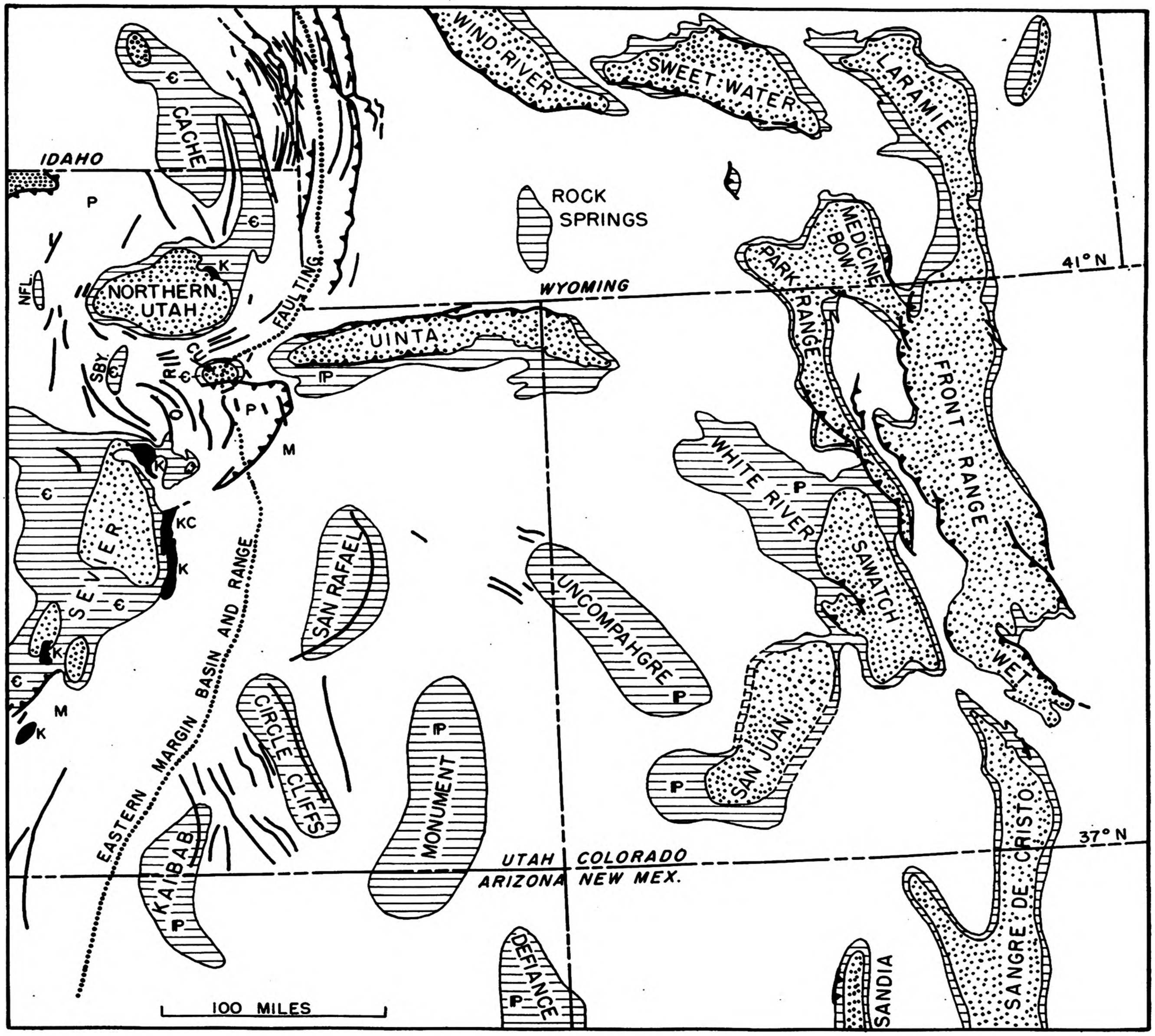

Fig. 1. Late Cretaceous and early Tertiary uplifts of Colorado, Utah, and adjacent areas on north and south. Stippled areas are Precambrian rock exposures; ruled areas of the shelf (eastern Utah and Colorado) are exposures of Paleozoic rocks, and are marked by: IP, mostly Pennsylvanian; P, Pennsylvanian and Permian. Ruled areas of the miogeosyncline (western Utah) are Cambrian exposures. K, major detached slide masses; KC, the Canyon Range slide mass; OR, Oquirrh Range; CU, Cottonwood uplift, M, Mesozoic sedimentary rocks. NFL, Newfoundland anticline. SBY, Stansbury Mountains. Both fold axes and thrusts faults in the miogeosyncline are shown by bold lines.

considered that the miogeosyncline has yielded by folding and thrusting in a trenchant manner, unlike the simple uplifts and basins of the shelf. The complexity of the miogeosyncline and its scattered exposures have delayed the analysis of the Laramide structures in a regional way, but in late years some interesting but controversial theories have been proposed. One school of geologists views the miogeosyncline as having been cut and displaced generally eastward by a number of thrust faults of great lateral dimensions. A master thrust of décollement nature is viewed as having had its roots in eastern Nevada and as having translated an imbricate sheet to central Utah, some 160 miles across. Several U.S. Geological Survey workers have stated such views (Roberts and others, 1965), and a similar thesis by Misch (1960), followed by several doctoral studies under his direction, expresses about the same concept. Possibly some differences exist. On the contrary, the writer has been espousing for several years a theory of vertical uplifts for the Laramide structures, much the same as for the large uplifts of the shelf province, and he opposes the idea of the great décollement sheet across the western part of Utah. General agreement prevails on the Basin and Range faulting, and the Tertiary volcanics are becoming better understood.

Magmatism Related to Crustal Deformation

It is becoming increasingly apparent that magmatism is related to crustal deformation. As the nature of the deep-seated crustal layering and the mantle are studied, the energy for surficial deformation appears to be the heat that is generated in, and rises from, the mantle. No less, the primary magmas stem from the mantle.

Both the shelf and the miogeosyncline are profuse in igneous rocks. Numerous stocks, especially in the miogeosyncline of western Utah, have been mapped and now dated by isotope methods. Large piles of volcanic materials occur in the shelf areas of Colorado, Utah, New Mexico, and Arizona, and western Utah is probably half blanketed by volcanic ejecta, largely in the form of ignimbrites. Significant intrusive activity started in Early Cretaceous time in easternmost Nevada and continued until the Miocene, thereby accompanying the principal crustal movements. It continued afterward. The extrusive activity in Colorado and Utah followed mostly after the major Laramide deformations and after a widespread erosion surface had been developed on the Laramide structures. Some of the late intrusions penetrate the volcanic flows.

In seeking the source and depth of the siliceous magmas which supplied the stocks, laccoliths, and volcanic outpouring of Colorado and Utah, it has been concluded that rising basalt from the upper mantle mobilized the lower siliceous crust (Eardley, 1960, 1962). Of greatest significance is the recognition of an intermediate velocity layer between the crust and the mantle that coincides in distribution with the Colorado and Utah, Late Cretaceous and Cenozoic mountain systems (Berg, and others, 1960; Cook, 1962; Pakiser and Zietz, 1965). This is the most hopeful explanation of the intrusive and extrusive rocks of the upper crust, but equally as well, of the cause and nature of upper crustal deformation.

Basin and Range Faulting

The block fault origin of the conspicuous ranges of the Great Basin is well known. The bounding normal faults of the ranges in western Utah have been fairly well defined, but in late years gravity surveys have defined others that are buried by the alluvium on the downthrown blocks (Cook and Berg, 1961). Troughs as deep as 10,000 feet are now known, and this with the added relief of certain range fronts indicates that the vertical displacement in places has been as much as 15,000 feet. Because the Basin and Range faults are younger than the Laramide structures and in most places cut them discordantly, the two structural systems have been considered to have evolved under strikingly different frameworks of forces. However, because the intrusive rocks are tied to the extrusive rocks in composition and origin and these in turn to the Laramide structures on the one hand and to the Basin and Range faults on the other (as will be pointed out), we should seek to bridge the two structural systems. Little thought has been given to a genetic relation of the two. They simply have been left as two separate entities.

As suggested under the preceding heading that magmatism is related to tectonism and that the upper mantle and particularly the intermediate layer between the crust and the mantle provide a hopeful common answer, it may be possible to find the relationship to the Laramide and the Basin and Range systems by turning to the deep-seated source of heat.

Regional Epeirogenic Uplift

The Rocky Mountains as well as the Great Plains on the east suffered a broad epeirogenic uplift in Cenozoic time. Beginning approximately at the Missouri River at the west boundary of the State of Missouri, the Great Plains were raised progressively westward until at the foot of the Front Range and Laramie Range the marine Cretaceous beds had reached a relief of at least 5,000 feet. The broad basins between the ranges of the Rockies may be taken as an index of the epeirogenic uplift in Wyoming and western Colorado which was 5,000 to 6,000 feet. The Colorado Plateau of eastern Utah was uplifted as a whole possibly more. The oval-shaped and irregular uplifts from which the major ranges of the shelf province have been sculptured are taken to be local uplifts above the general level of the epeirogenic uplift. The miogeosyncline of western Utah had already been broadly uplifted epeirogenically before and during the Laramide orogeny.

The mass of crustal material involved, and the energy required, exceeded that necessary for the building of the separate ranges. Any theory of tectonism and magmatism for the central Rockies must not fail to take into account the regional epeirogenic uplift. Again, the source of energy is the upper mantle. From this source, perhaps, we may find a common and plausible relation of the structures of the Laramide Rockies, the Basin and Range of western Utah, the attendant magmatism, and the broad epeirogenic uplift.

THEORY OF PRIMARY UPLIFTS

It is proposed that the Laramide Rockies of the shelf region of the western United States are the product primarily of vertical uplifts, and that the folds and thrusts are secondary features on the flanks of these uplifts. The secondary features are considered to be the result of gravity gliding or mass movement down slope.

Well-known examples of the uplifts of the shelf province are the Little Belt and Big Snowy structures of Montana, the Wind River and Bighorn uplifts of Wyoming, the Front Range and Sawatch uplifts of Colorado, the San Rafael and Monument uplifts of Utah, and the Sandia and Sand Andreas uplifts of New Mexico. Later Tertiary faulting has modified these Laramide uplifts considerably in places, and sediments and volcanic outpourings have partly or largely covered some of them.

Although the general anticlinal or domal form of the uplifts has been recognized for a long time, their origin has formerly been ascribed to horizontal crustal compression on a regional scale. Now, however, a number of writers propose that little, if any, horizontal compression on a regional scale occurred in the shelf Rockies, and that the so-called compressional structures (namely the folds and thrusts) are secondary gravity effects of the primary vertical uplifts.

The theory of primary vertical uplifts has been proposed by Wisser (1957), Osterwald (1961), and Eardley (1963), and detailed structural studies supporting it have been published by Foose (1960), Harms (1961), Wise (1963), Prucha and others (1965), Evans (1966), and others.

GENERAL CHARACTERISTICS OF THE SHELF PROVINCE

The major Laramide structures of the shelf province in Colorado and Utah are shown on Figure 1. They are oval or irregularly broad in shape and generally lack a narrow or sinuous aspect. They range in length from 50 to 200 miles and in width from 10 to 30 miles. The structural relief ranges from 500 to 40,000 feet.

Some of the uplifts are conspicuously asymmetrical; the beds on one flank are turned up to steep angles, or in addition, are overthrust as a sheet from within the uplift. If the thrusts and folds of the province are observed in relation to the broad uplifts, they will for the most part be recognized as flank structures.

The sedimentary rocks of Paleozoic, Triassic, and Jurassic age constitute a fairly thin veneer which rests on the Precambrian crystalline complex in all places of the shelf province except in the region of the Uinta uplift of Utah and the Little Belt uplift of Montana. In these places, a thick Precambrian sequence of strata intervenes. The sequence of Cretaceous sedimentary rocks in most places is as thick as, or thicker than, the Jurassic, Triassic, and Paleozoic strata together. Sediments of Late Cretaceous age accumulated in the basins between uplifts in the early stages of uplift. As uplift progressed, the Paleozoic strata, and in places even the Precambrian rocks, were faulted up against Cretaceous sedimentary rocks, and further, as the early Tertiary clastics were unloaded in the basins from the rising uplifts, they, in turn, in places were offset and overridden.

In the region of the Ancestral Rockies, the setting for the Laramide uplifts was one in which the sedimentary veneer on the Precambrian crystallines was either very thin as the result of the previous uplift and cycle of erosion or rather thick as the result of basin sedimentation in Pennsylvanian time.

From inspection of the geologic maps of the shelf province, the conclusion is drawn that the uplifts, in which the rise was sufficient to result in exposure of the Precambrian rocks in a central core, have more intense flank structures and marginal thrusts.

COLORADO AND UTAH SHELF STRUCTURES

Figure 1 has been prepared to show the uplifts of the central part of the shelf province. We should note that the Sweetwater uplift is not evident today, because after it formed it sank and was mostly buried by middle and upper Tertiary sediments. The uplift as shown is restored to the time before collapse. Also, the Rocky Mountains through central Colorado may be interpreted as a group of closely packed uplifts with the Front Range being exceptionally long and wide. The Ancestral Colorado Range was an uplift almost as large as the entire cluster of ranges in the central Colorado belt, but the later Laramide uplifts developed as independent units, not much controlled by

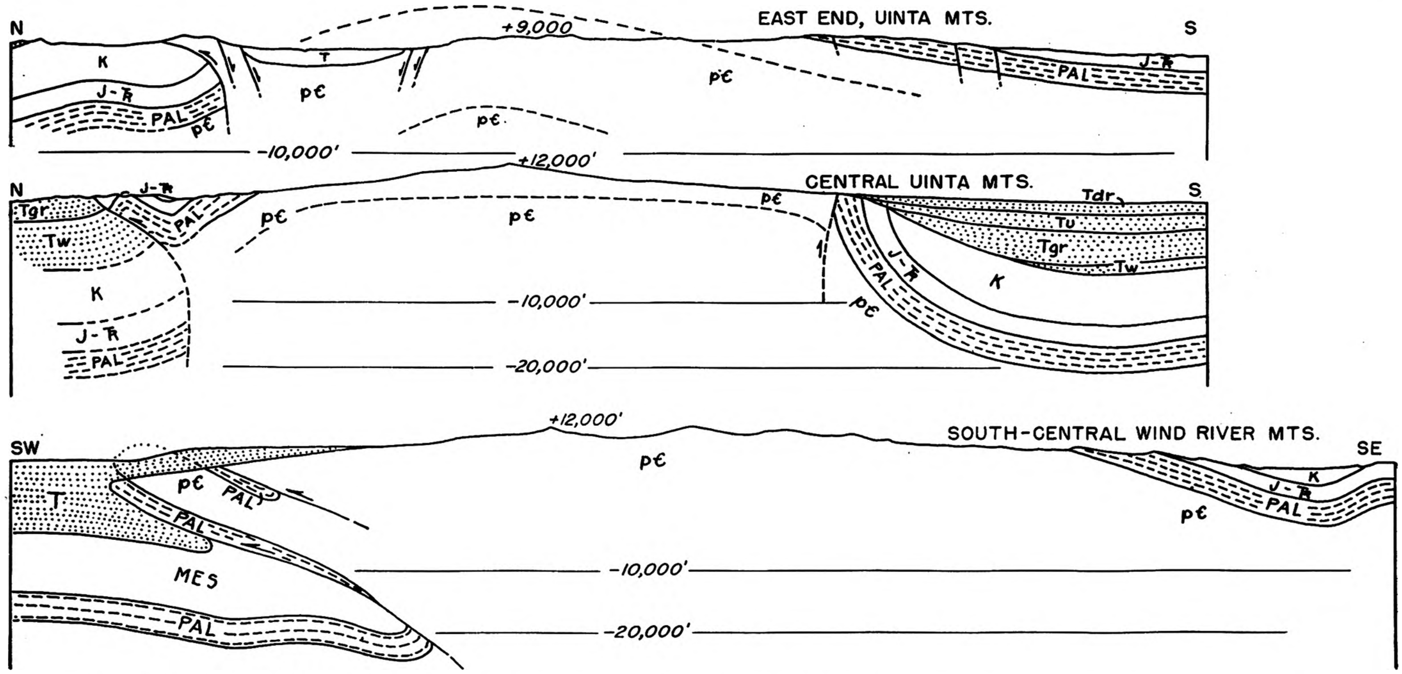

Fig. 2. Cross sections of the Uinta and Wind River Mountains showing nature of the border faults.

the ancestral uplift. The flanks of the central Colorado ranges are replete with thrusts and apparently reflect the superior uplift of the Front Range.

The uplifts of the Colorado Plateau are comparable in area with the others of the shelf province, but they have not been of sufficient amplitude to have resulted in the exposure of Precambrian rocks in the cores. The widespread rise of the Colorado Plateau in late Cenozoic time has resulted in the transportation of sediments from the local uplifts to remote regions and not simply to the basins between them.

Again, it is evident that where the uplifts have been sufficiently high and the Precambrian basement extensively exposed that thrust faults occur on the flanks of such uplifts. The San Juan uplift may appear to be an exception, but it is largely covered by volcanic rocks, and its flanks are not exposed for examination.

NATURE OF BORDER THRUSTS

The border thrusts of the Uinta Mountains are shown in the upper two sections of Figure 2. The thrust interpretations along the north side are by Ritzma (1959) and on the south side by Childs (1950). The Uinta uplift is particularly instructive, because the nature of deformation of the core can be seen by the Precambrian strata that compose it. For most of the length of the Precambrian exposure, the beds are bent into a flat-topped anticline, as shown by the dashed line in the second cross section.

The southwestern flank of the Wind River uplift has been traversed seismically by Berg and Wasson (1960), and they report a thrust that dips as low as 18 degrees and carries under the range about 8 miles. Their interpretation is shown in the bottom section of Figure 2 which was sketched hurriedly by the writer from a slide projection. It may not be exactly right in all details. In both the Uinta and the Wind River uplifts, the thrusts are interpreted as convex upward and steepening downward. The amount of vertical uplift in the Uinta Mountains is in excess of 32,000 feet and in the Wind River Mountains in excess of 35,000 feet.

A similar cross section of the Front Range of Colorado has been produced by Evans (1966) and is here shown as Figure 3.

Harms (1961) has studied the sandstone dikes of the eastern margin of the Front Range south of Denver and presents a convincing case for gravity tectonics there. Large Laramide faults place Precambrian rocks in contact with sedimentary rocks as young as Tertiary in age. The stratigraphic displacement in places is 15,000 feet and the structural relief 15,000 to 25,000 feet. He concludes that the stress distribution causing the injection of the sandstone dikes was governed by dip-slip movement along steeply westward-dipping, convex-upward, fault surfaces, and that, there-

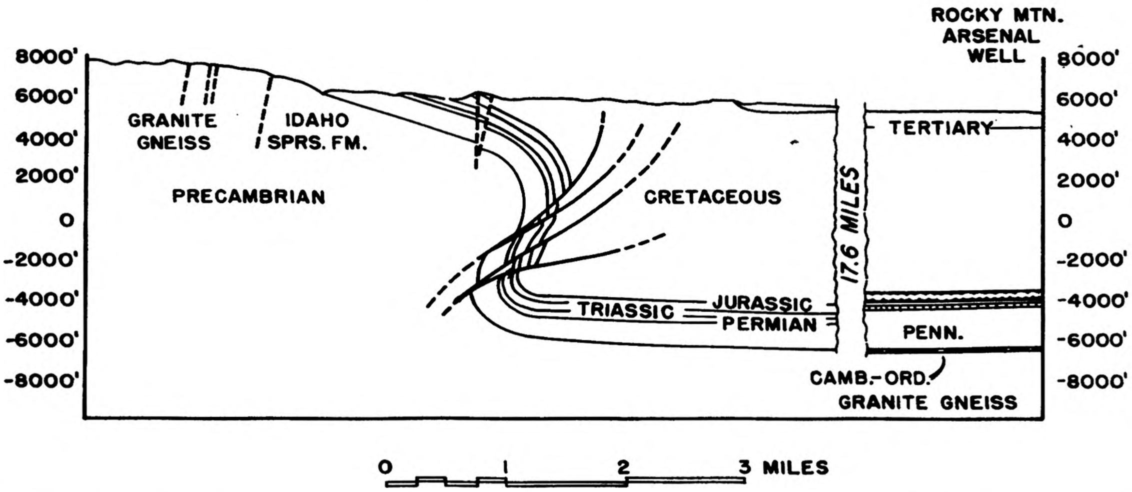

Fig. 3. Cross section at Denver showing Front Range uplift and Denver basin; after Evans (1966) which is after M.F. and C.M. Boos and Odiorne.

fore, the major structures outlining the flank of the range are high-angle reverse faults which steepen with depth. Gravity movement toward the basin is indicated.

Assuming that the cross sections correctly illustrate the faulting for the uplifts concerned and recognizing an oval shape in plan view, then a corollary assumption is evident that the primary deforming force is upward and that the overthrusting is literally a spilling of the sharply uplifted flank over the adjacent plain. It could be a matter of mass movement down slope, and when viewed grossly, a case of flowage. Of course, intrinsically it would be a matter of adjustment along joint planes, bedding, and foliation surfaces, with many small faults and much shattering. Berg and Wasson (1960) report complex faulting in the Precambrian core of the Wind River Range. The writer views the above concept of faulting and adjustment by mass movement as the basic aspect of development of those uplifts which exceed about 20,000 feet in amplitude. The border fault, which at depth appears to be vertical, would be a primary structure, but the upper part that flattens to a low-angle thrust would be secondary to the uplift. A primary fault would then be considered as passing into a secondary fault.

In the course of secondary mass movement basinward, it seems possible that a sole thrust might develop and facilitate the movement down slope. The idea is illustrated in Figure 4. The thrusts of the Bearpaw uplift illustrate the concept in the form of a bedding-plane thrust or glide surface (Fig. 4). Closely related to bedding-plane thrusts are detached blocks, such as the Heart Mountain, which have glided a number of miles basinward (Pierce, 1957, 1960). According to Blackstone (personal communication), there are several known examples of such glide blocks in Wyoming in addition to those along the west side of the Bighorn basin.

DEEP-SEATED CAUSE OF UPLIFTS

The evidence seems convincing that the uplifts of the shelf province are caused by vertical pressures, and this, together with the

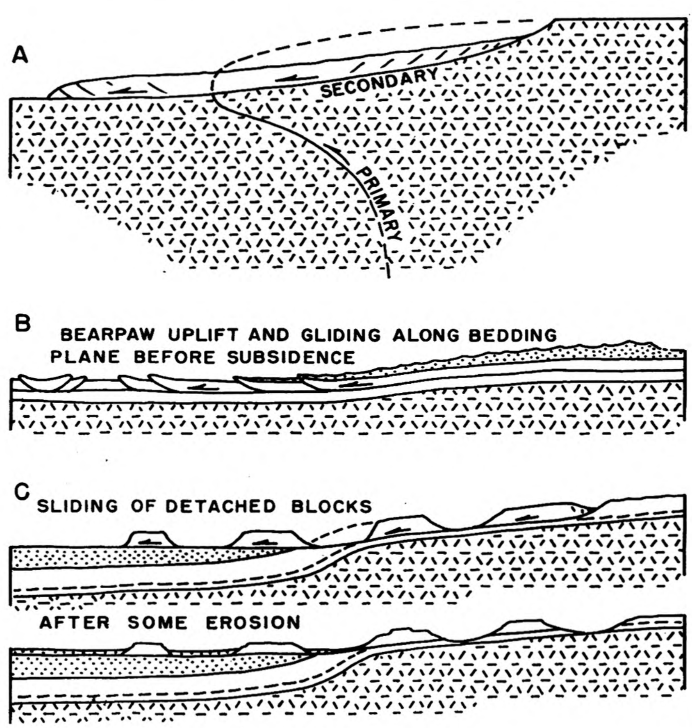

Fig. 4. Types of secondary movement on the flanks of the uplifts.

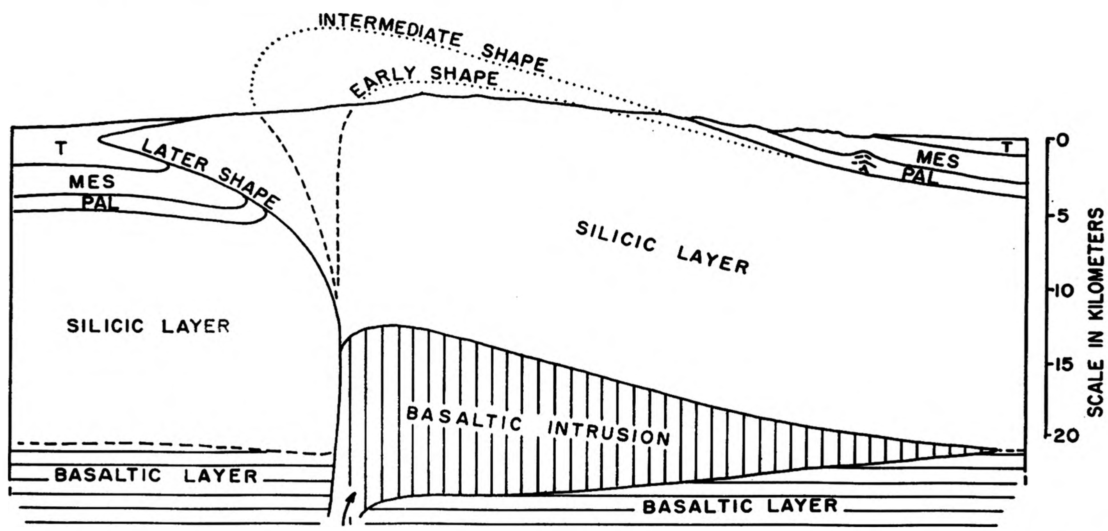

Fig. 5. Postulated origin of the uplifts by deep-seated basaltic intrusion. The early shape of the uplift is attained after about half of the basaltic pluton is intruded. The intermediate shape is attained after all the pluton is intruded. The final stage is attained by mass movements under the duress of gravity.

general broad oval shape of the uplifts, leads directly to the postulate of a large intrusion beneath each in the silicic crust. The concept is portrayed in Figure 5.

The intrusion is in the shape of a giant laccolith or thickened sill and is believed to be of basaltic composition for the following reasons. The shelf province of the western United States is the alkalic and calc-alkalic igneous rock province, and all major workers on the igneous rocks exposed at the surface from Montana to New Mexico have concluded that these represent considerable assimilation of crystalline rock rich in mica, orthoclase, and albite by olivine basalt. Fractional crystallization of the assimilated magmas, filter pressing, and in places, mixing of fractionated magmas have resulted in the unusual suites of high alkalic and calc-alkalic rocks found there. The assimilation would have occurred along the roofs of the giant laccoliths.

Basalt is also the only magma considered available from the underlying mantle. (For a review of the igneous province and the source of its magmas, see Eardley, 1960.)

The volume of basaltic magma involved in an intrusion responsible for an uplift of the size and amplitude of the Wind River Range would be about 10,000 cubic miles. This may be appreciated by comparison with the volume estimated for the San Francisco volcanic field of northern Arizona of 80 cubic miles and the volume of the Columbia River basalt field of about 40,000 cubic miles.

The postulated origin of the uplifts is a subject suited to model experimentation, and from such work the size and shape of the intrusion, the rate of intrusion, and the nature of the border faults may be better understood.

FRACTURE PATTERNS IN THE SHELF

If the border structures of the uplifts of the Rocky Mountains shelf province are due primarily to vertical uplift and secondarily to adjustment of unstable density relationships brought about by the uplifts, then the fracture patterns of the margins of the uplifts should be re-examined in this light. The restudy might be facilitated by model experimentation. Most fracture patterns mapped to date in this province have been analyzed in a framework of horizontal compression, tension, or coupling.

Regional alignments of various geologic features, called lineaments, have been emphasized by Blackstone (1951, 1956) and others in the shelf province. Geofractures, defined as regional fracture zones that have had recurrent movement possibly from Precambrian time to the present and that bound possibly great polygons of the earth's crust, are visualized as tectonic features of the foreland by Osterwald (1961), but, as yet, these are of uncertain existence, position, and significance. The lineaments or geofractures commonly singled out within the shelf province are the Lake Basin fault zone and the Nye-Bowler fault zone of Montana. These belts of fairly regularly staggered faults undoubtedly represent strain and horizontal coupling on a regional scale in the crust below the sedimentary veneer. Some other alignments of geologic features within the province may mean the same, but as pointed out by Osterwald (1961) the evidence for the continuity of such features is definitely not clear, and more will need to be known about the Precambrian rocks before conclusions can be drawn. The postulated lineaments or geofractures trend mostly in a northwestern direction, whereas, the orogenic belts of the Precambrian trend to the east-northeast (Gastil, 1960). Fracture zones of great horizontal and vertical movement may bound the shelf province in places, but these constitute a subject beyond the scope of the present paper. The writer, in summary, concludes that the crust of the shelf province has been strained on a regional scale, but that horizontal dislocations have been moderate, perhaps amounting to 1 or 2 miles at the most. On the other hand, the vertical uplift of the numerous oval-shaped mountain masses in Laramide time has been the dominant tectonic activity. Really, more profound than the uplifts has been the rise of the High Great Plains, the shelf province including the Colorado Plateau and the Great Basin of eastern California, Nevada, and western Utah, in amounts ranging from 1,000 to 8,000 feet. Such movements undoubtedly spring from polymorphic changes or partial melting of the upper mantle; the oval-shaped uplifts as here depicted are related to the associated deep-seated magmatism.

PRIMARY UPLIFTS OF THE MIOGEOSYNCLINE IN WESTERN UTAH

Defining the Cretaceous and Early Tertiary Uplifts

Without the new Geologic Map of Utah (Stokes, 1961-64), the recognition of past tectonic elements would hardly have been possible. It is assumed that block faulting (the Basin and Range orogeny) and attendant alluviation on the downthrown blocks has occurred as a last major phase of evolution of western Utah, and that the block faulting followed an older phase of folding and thrusting. (For a general review of time and spatial relations, see Eardley, 1962). It is also assumed that much of the volcanism was postfolding and thrusting. By a careful analysis of the map, the effects of the Basin and Range orogeny can be deleted, and the Tertiary volcanic materials can also be eliminated. Contacts of Precambrian, Paleozoic, and Mesozoic rocks can then be projected across the blank areas. The bold features are shown in the western part of the map of Figure 1.

The major display on the interpreted map consists of uplifts with Precambrian cores surrounded by Paleozoic sedimentary rocks. The Pennsylvanian and Permian strata are generally limited to narrow or restricted synclinoria between the uplifts. The pattern is one of deeply eroded domal uplifts, and it seems evident that this concept must dominate any structural analysis of the region. The uplifts are of about the same size as those of the shelf province to the east. It will be noted that a zone of uplifts is evident which extends from southeastern Idaho and northern Utah to southwestern Utah. This zone appears immediately as the source highland for much of the Cretaceous and early Tertiary clastics of the Wasatch Mountains and High Plateaus of Utah. The provenance of these sediments and the chronology of rise of the uplifts will be reviewed later.

The west-central and southwestern part of the zone of uplifts has already been recognized by Harris (1959) who called it the Sevier arch and related its history of uplift to the Cretaceous and early Tertiary sediments along the east flank. Costain (1960) found a major fault system in the Gilson Mountains of central Utah that has a vertical displacement of 16,000 to 20,000 feet, and he recognized it as an east-flank boundary fault of the "Sevier arch". The Canyon Range and Pavant Range thrust faults lie immediately to the south of the Gilson Mountains, and Costain and Christiansen (1961) interpreted these thrust sheets as secondary to the primary vertical uplift along the steep eastern flank and as having moved from the interior of the uplift (west) to the east.

Relation of Folds and Thrusts to Uplifts

The thrusts with some exceptions are flanking features of the uplifts, especially of uplifts where Precambrian and Cambrian rocks have been exposed. Conspicuous folds and some thrusts are characteristic of the Pennsylvanian and Permian strata in down-folded synclinoria between the uplifts. These observations lead forthwith to the conclusion that the thrusts and folds are secondary to the primary uplifts and that they are gravity slide masses on the flanks of, or squeeze structures, between the uplifts. A few of the local structural settings in the region will be discussed next in light of this framework and concept. Several others that are not yet well in hand and which require further analysis will be left for a more detailed treatment in a later paper.

INTERPRETATION OF SPECIFIC STRUCTURES

Central Wasatch Folds

The folds and thrusts between the Cotton-

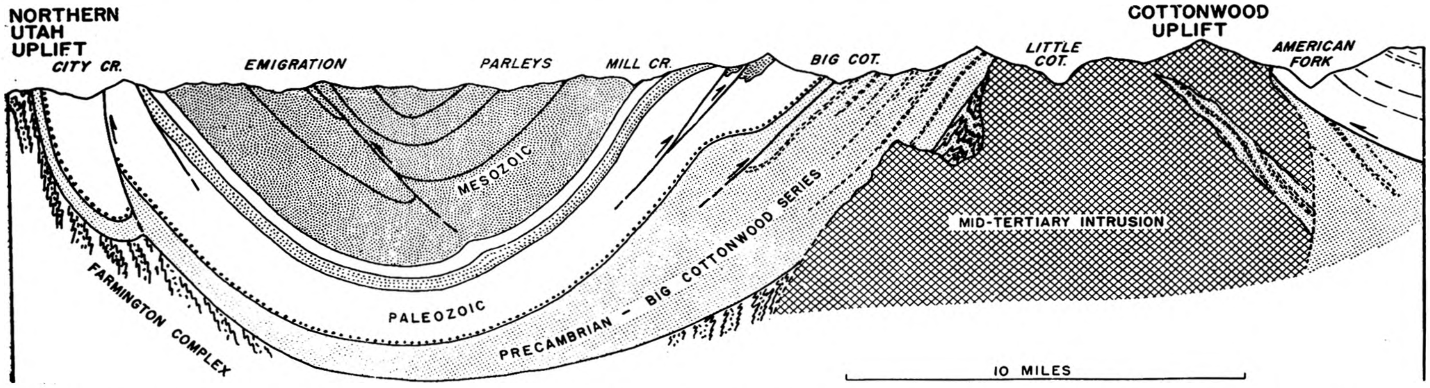

Fig. 6. Cross section in the Wasatch Mountains from the Cottonwood uplift to the Northern Utah uplift.

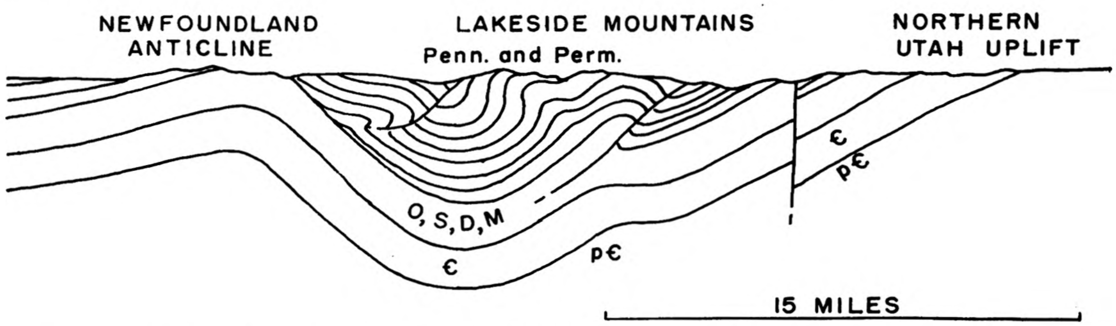

Fig. 7. Generalized structure of the Lakeside Mountains, after Doelling, 1964.

wood uplift and the Northern Utah uplift are clearly examples of minor compressional structures in the upper part of a thick stratified sequence which has been deformed in a large syncline (Fig. 6). The syncline is the result of the adjacent uplifts, and the surficial layers are caught in a squeeze between the uplifts.

Structures in the Lakeside Mountains

Structures in the Lakeside Mountains involve a very thick Pennsylvanian and Permian section. They have been interpreted by Doelling (1964) as formed most logically between two uplifts, the Northern Utah on the east and the Newfoundland on the west (Fig. 7).

Structures in the Confusion Range

The Pennsylvanian and Permian strata of the Confusion Range lie in a narrow synclinorium between the Snake and Sevier uplifts. The shallow cross sections of Christiansen (1951) and Hose (1963, 1964) were interpreted at depth and extended laterally to arrive at Figure 8 which appears to show the squeezing of beds near the surface without similar deep-seated deformation. The cause is concluded to be the rise of the two adjacent uplifts.

Oquirrh Mountains Structures

The Oquirrh Range (O.R. on Figure 1) is situated between the Northern Utah uplift,

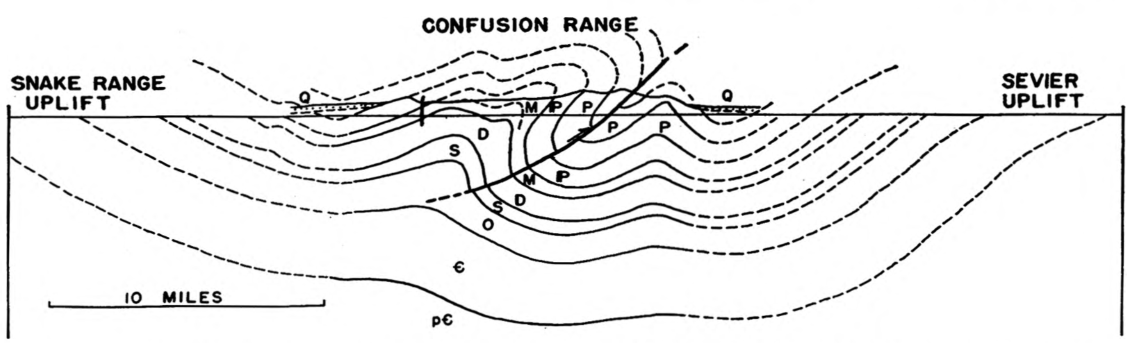

Fig. 8. Structure of the Confusion Range. Surficial structure taken from Christiansen (1951), and Hose and others (1963, 1964). Deep structure interpretive between the Snake and Sheeprock uplifts. Intrusions and block-faulting that have complicated the uplifts, not shown.

the Sevier uplift, the Stansbury Mountains (SBY on Figure 1) and the Cottonwood dome (CU on Figure 1). The large folds of the very thick Pennsylvanian and Permian beds of the central and southern Oquirrh Range appear to be chiefly due to a squeeze between the northern part of the Sevier, Cottonwood, and Northern Utah uplifts. The thrust, sharp folds, and nearly vertical beds at the north end of the Oquirrh Range conform to the flank of the Northern Utah uplift.

Two structures should be noted here which complicate the picture, namely, the Cottonwood uplift and the Stansbury anticline. The Cottonwood uplift of much smaller size than adjacent uplifts could be of later age. Whereas, the Northern Utah and Sevier uplifts are of Cretaceous age and the Uinta chiefly of early Tertiary, the uplift of the Cottonwood dome could have been increased in mid-Tertiary time by the forceful injection of the Little Cottonwood stock. The Stansbury anticline developed as a sharp fold of Late Devonian age and then was accentuated in Cretaceous time (Arnold, 1956; Rigby, 1958). Thus it's apparent incompatability to the folds and thrusts of the Oquirrh and to the Northern Utah uplift is partly understandable.

Canyon Range Klippe

The eastern flank of the Sevier uplift is marked by a number of thrusts which are here interpreted to define five rather large detached slide masses from the west—see black areas on Figure 1. Their definition must be accompanied by detailed maps which will be left for another paper, but as an example, the Canyon Range "Klippe" will be briefly described. It has been clearly delineated on east and west sides and northern end by Christiansen (1952), and is the northern one of two klippen on the central east flank of the Sevier uplift (KC on Figure 1).

Figure 9 shows three steps by which the downfolded detached mass of the Canyon Range is presumed to have formed. The major uplift of the Sevier arch first occurred, then extensive erosion exposed considerable Precambrian rock, then the detachment and gravity sliding occurred, and finally the Basin and Range faulting took place.

Southern Wasatch Thrust Complex

The Charleston thrust zone (Baker, 1964a and b; Baker and Crittenden, 1961), the Strawberry thrust (Bissell, 1952), and Nebo thrust have been related by several authors and conceived as parts of a single sheet that has moved eastward. That the three thrusts are part of a single sheet of appreciable movement seems likely when the Upper Cretaceous beds of the foredeep are represented by thickness contours—see Figures 11 and 22-4 in Eardley (1962). The arcuate front of the large sheet appears to have ridden out over the Cretaceous a few miles.

The arcuate, thrust front faces a basin which subsided about 15,000 feet in Late Cretaceous time and 5,000 to 10,000 feet in Late Jurassic time, and thus the sheet could represent gravity movement toward the deepening trough (Figs. 10 and 11). The klippen

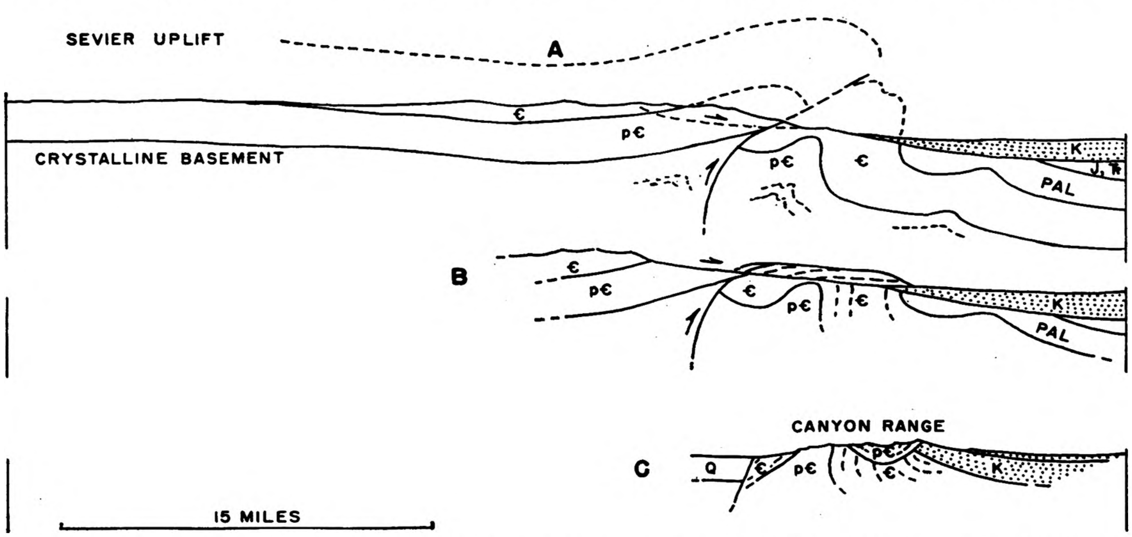

Fig. 9. Suggested origin of Canyon Range structure by gravity induced sliding on east flank of Sevier uplift. A, major uplift, early gravity sliding, erosion, and deposition of Middle Cretaceous clastics; B, sliding of detached mass; C, continued down-flank movement and folding of detached slide mass. Also Basin and Range faulting. Canyon Range structure from Christiansen (1952).

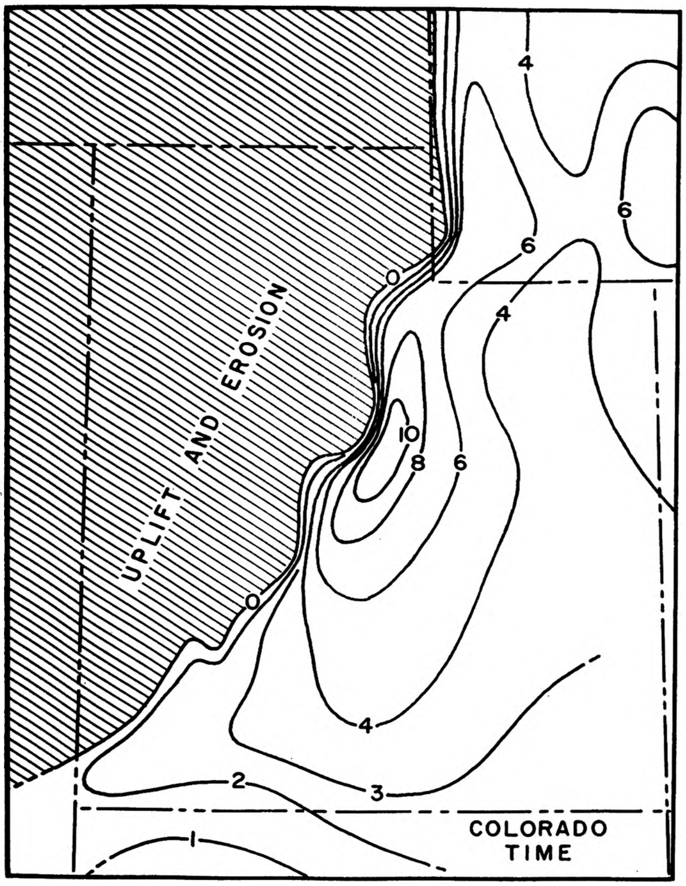

Fig. 10. Isopach map of deposits from the western uplifts in Colorado time (Cenomanian, Turonian, and lower Senonian). Contour interval 1,000 feet.

immediately east of Provo, collectively called the Big Baldy thrust by Baker (1964a and b), appear to be detached masses that slid mostly along bedding planes.

The concept that the Charleston-Strawberry-Nebo thrust sheet is but a part of a much larger one, both in north-south and east-west dimensions is supported by Crittenden (1961, 1964) and by Roberts and others (1965). This postulate is opposed to the concept of gravity slipping induced by trough subsidence. The stratigraphic displacement of Cambrian over Jurassic at one place on the Charleston thrust, and the Sulphur Springs window 2 to 4 miles back of the frontal trace, no doubt impress them that major horizontal translation has occurred. The Nebo thrust as part of the frontal trace of the postulated broad sheet is extended westward to the Leamington Canyon fault which is interpreted as a shear by Crittenden (1961). By means of this shear, the sheet was translated east-northeastward. The connection route, however, is marked by insignificant stratigraphic offset and no clear evidence of a fault. The Leamington Canyon fault is in part at least the northern thrust limit of the Canyon Range klippe and thus not easily construed as a tear fault with considerable strike-slip movement. Also, the Nebo thrust and associated overturning is toward the southeast which is not in alignment with the postulated east-northeastward translation.

The Charleston-Strawberry-Nebo thrust is considered by the writer to be a flank structure of the Sevier uplift caused by gravity-induced mass movement toward the sinking Cretaceous and Jurassic basin.

Fold and Thrust Belt of Southeastern Idaho

In a recent paper, the author (Eardley, 1967) examines the fold and thrust belt of southeastern Idaho and western Wyoming and recognizes that the structures are clustered together in several complexes. The thrusts of one complex are probably not continuous with those of an adjacent complex but circumscribe

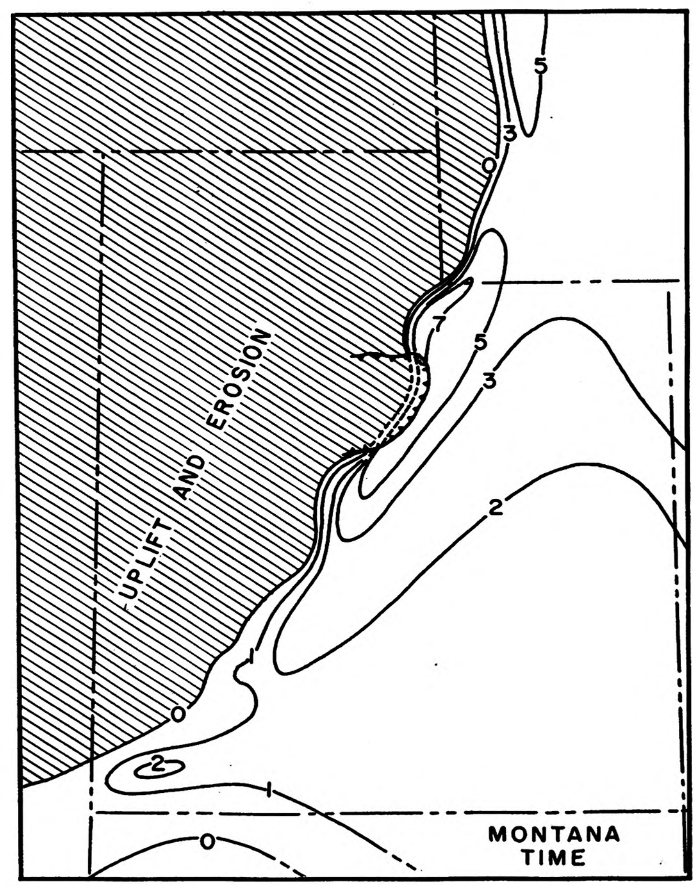

Fig. 11. Isopach map of deposits from the western uplifts in Montana time (Upper Senonian, Maestrichtian, and Danian). Southwestern Utah compiled by J. C. Lawrence. Contour interval 1,000 feet.

discrete gravity slide masses generally piled on top of each other in imbricate fashion. The slides of each complex occurred within a relatively short time, but the complexes evolved successively spatially from west to east and in time from Early Jurassic to early Tertiary. The postulated model is as follows:

(1) An uplift and forerunning basin migrated from west to east during the Mesozoic and early Cenozoic eras.

(2) The crest of the advancing uplift was fully 10,000 feet above the seas of the foredeep basin and 20 to 30 miles distant. In the course of time, the site of original centralized uplift, about 100 miles to the west, was denuded to the Precambrian.

(3) The thick sediments of the foredeep basin were progressively uplifted, tilted, and eroded on the advancing front of the uplift. This created a system of aquifers and aquicludes in which abnormal fluid pressures were developed in the aquicludes (clays).

(4) In the course of time as the foredeep basin grew deeper, the down-slope component of gravity and reduced friction incident to abnormal fluid pressures conspired to release various large glide masses.

(5) Further advance of the uplift and foredeep basin resulted in the release of a second set of major glide masses, this time involving part of the previous slide masses and the sediments of the previous foredeep. The coarse marginal facies of the new foredeep basin were overrun by the leading toe of the thrust sheet.

The model illustrating these conditions leads to the following inferences:

(1) The slide masses may be 30 miles wide and 75 miles long, but current extension of certain individual thrusts over much longer distances is questioned. The thrust sheets are in many respects like giant landslides.

(2) The break-away upper limits need not be marked by tensional graben-producing faults.

(3) The glide surfaces may be 30 miles wide, but probably not wider. The amount of horizontal translation is less, probably not more than 10 miles. The postulation of thrust fronts that have traveled scores of miles is questioned.

(4) The glide masses are shallow, not much more than two miles in thickness, and as such the strata have been badly broken, especially near the leading edge, but little metamorphosed.

(5) The Basin and Range type normal faults (bounding graben, horst, and tilted block) at the northern end in the Hoback Range and Jackson Hole are strikingly discordant, as they are farther south in Utah. Of course, vertically they are discordant everywhere.

THEORY OF DÉCOLLEMENT THRUSTING

A widely divergent theory of the structure of western Utah, than here pictured, has been proposed. Accordingly, the outcrop pattern is interpreted as the result of a vast allochthonous mass whose sole extends from eastern Nevada to central Utah. In the past few years Misch (1960), Crittenden (1961; 1964), Roberts and others (1965), and Miller (1966) have espoused the concept of a thrust sheet not only 160 to 170 miles wide but more than 200 miles long. It has been folded, faulted, eroded through in places, left as remnants in others, and mostly covered by Tertiary volcanic outpourings and Tertiary and Quaternary clastics. In eastern Nevada and westernmost Utah particularly, a number of bedding plane thrusts have been recognized, and these have been carried from one range to another. The careful study of facies of the Pennsylvanian and Permian sequences also has induced these writers to conclude that major, large-scale translations have taken place. The reader should study the article by Roberts and others (1965) particularly in order to appreciate the interpretations made. Also, Dr. Roberts is contributing to this symposium, and the sharply divergent interpretations which exist between a group of U.S. Geological Survey geologists and the writer will be more than apparent by comparing the side-by-side articles. Some brief criticisms to the 1965 article were expressed in a letter to Dr. Crittenden, one of the coauthor's, as follows:

> 1. The facies changes in both Oquirrh basin and Phosphoria basin beds are not sufficiently varied and distinctive to convince me of the propriety of the concealed thrusts *west of the Wasatch* that you visualize. The ribbon diagrams of Fig. 18 show, it seems to me, that you are stretching to see the need of the "Tintic Valley", "Skull Valley", and extensions of the Midas and Ochre Mountain thrusts. You could have constructed the ribbons logically without the thrusts. The thinner Missouri and Virgil section in the Stansbury Mountains and its absence in the North Oquirrh Mountains are suggestive of the influence of the northern Utah uplift in Late Pennsylvanian time, rather than translation of western facies over eastern. The treatment of the "Newfoundland" thrust is somewhat confusing; I imagine that this is in part the "Silver Island" tear fault, which is very hypothetical. I realize that the Midas fault is made up of two exposures, one in the

Oquirrh Mountains and one in the Timpanogos Wasatch, but in neither place is much of a facies or thickness break evident between the sequences on either side. In fact, I think most any objective geologist would see in these ribbon diagrams vertical uplifts within the Pennsylvanian Period as the dominating control, rather than major horizontal translations.

2. Referring to Fig. 19, I am struck by the evident gradual change in character of the beds of Park City age from west to east across northwestern Utah. Why you need major thrust faults to break up and translate parts of this sequence is a mystery to me. You speak of the facies difference between the Hogup section and the Jim Thomas Canyon section. These are 60 miles apart and a thickness difference of 1,500 feet in this distance is hardly the evidence you want for a major thrust.

3. I am concerned also about the interpretation you give to the thrusts in the Wasatch Mountains. No one can doubt the thrusting approximately eastward of some 26,000 feet of Pennsylvanian and Permian strata of the Oquirrh basin over 2,500—1,400 feet of equivalent shelf strata. The problem here is the depth and extent westward of the Nebo-Charleston thrust. And as far as I can see now, the interpretation one gives to it depends on the theory he holds, that is; major décollement-type thrust sheets or gravity-caused mass movement.

Going to the Willard-Bannock thrust relation, you attempt to demonstrate the transposition of thick Precambrian, Cambrian, and upper Paleozoic sections from the west over thin sections on the east, and thereby justify the connection of the Willard with the Bannock. Built on this presumption you connect the Willard with the Charleston. I would say (A) that your Fig. 16 speaks clearly for little need of west to east translation as far as the Pennsylvanian strata are concerned, and (B) regarding the Cambrian and other Paleozoic and Mesozoic strata I refer to Armstrong and Oriel (1964) who do not believe that a large-scale thrust sheet is indicated.

In my opinion, then, the interpretation you make of the Willard-Bannock thrust looks weak, if not imposible, and this in turn weakens materially your interpretation of the associated Nebo-Charleston thrust as you extend it downward and westward.

4. Cambrian strata are very thick and varied, and according to Dr. Richard Robison who refers to Palmer's work, translation of facies is not necessary or indicated.

5. A last criticism deals with the cross section of Fig. 20. I have tried to tie it to the NW quarter of the Geologic Map of Utah, and have real difficulty in crossing the Sheeprock Mountains. I know you have had to generalize in making the section, but still I can't come up with the surficial distribution that you show. I have looked this area over fairly carefully because it is the core of my postulated Sevier uplift, and have been curious to see what you make of it.

Mechanically, I think the section and the theory it presents is impossible. You have a thrust sheet 160-170 miles wide (west to east) and I judge originally 3-10 miles thick. If moved by a horizontal force from the rear (the traditional concept involving crustal compression) the strength of such a thin sheet may not have been sufficient to allow the forces to push the broad sheet ahead, Rubey and Hubbard notwithstanding. A more significant point concerns the shear that must be created to get the broad sheet in motion. You shear the entire Paleozoic section in places. The same criticism is leveled here as against Mansfield's Bannock Thrust interpretation—it is simply an impossibility from any analysis of stress and strain relations. You might reply that the postulated sole thrust is an erosion thrust, but then this requires the translation of the Timpanogos block from eastern Nevada, and I'm sure you do not imply this to have happened. I can see that the nature of your article, in attempting to describe a basin that may have oil and gas possibilities, precludes an excursion into causes and origins of the structures, but nevertheless the question of "how" rings clearly.

6. The definition of the pre-Basin and Range and pre-volcanics outcrop pattern into uplifts and basins is, finally, the most decisive argument against the grand décollement theory.

CHRONOLOGY OF UPLIFTS

Voluminous quantities of sedimentary rocks in central and eastern Utah record the progressive rise of western Utah, a region that was a former miogeosyncline.

A few patches of Triassic and Jurassic rocks occur in western Utah and eastern Nevada. Stokes (1960) concludes that the Early Triassic, marine, fossil-bearing sedimentary rocks are in the central basin areas of the Pennsylvanian and Permian beds and, hence, record lingering seaways that continued in the general basin areas until this time. In Middle Triassic time, he concludes that the area was uplifted and became a permanent barrier between the Pacific and the interior seas as follows:

> During the Late Triassic and Early Jurassic the continental divide may have lain in central or western Nevada. Sediments similar and perhaps equivalent to the Chinle and Glen Canyon groups were originally more widespread than indicated by present exposures and may have extended in unbroken sheets across the site of the Wasatch-Las Vegas line into

east-central Nevada. The volume of sediments of this age that were available to later erosion is one of the unknown quantities of the geology of the region.

That the Mesocordilleran Highland was a very effective source of sediment after the Middle Jurassic is proven by the large volumes of clastic sediments derived from it. Coarse debris commenced to spread into the Colorado Plateau area in San Rafael time and continued to do so through Morrison and Early Cretaceous time. During this interval, the larger derived fragments and presumably much of the finer material appear to have come chiefly from high ground in southern Nevada, the Mojave section of California and west-central Arizona. During a portion of Brushy Basin (late Morrison) time the stream systems appear to have reached into central or western Nevada where geosynclinal siliceous rocks were picked up. (Stokes, 1960, p. 121).

The major rise of the belt of uplifts occurred in Middle Cretaceous time, as attested by the volume of clastics shed from the west and deposited in a subsiding trough to the east. Figure 10 shows the deposits of Colorado time (Cenomanian, Turonian, and lower Senonian). They are thickest and coarsest opposite the Sevier uplift. The volume is great, and if spread over western Utah would represent the erosion of at least 6,000 to 10,000 feet from the belt of uplifts and about 4,000 feet from the region of easternmost Nevada and western Utah. It should be noted that the uplifts of the Colorado Plateau, including the Uinta Mountains, had not begun to rise at this time.

Another wave of coarse clastics was spread from the belt of uplifts in mid-Late Cretaceous time, and accumulation continued in the form of sandstones, siltstones, and shales to the end of the Cretaceous (Fig. 11). Another 2,000 to 5,000 feet of rock was eroded from western Utah to make up the sediments deposited. The uplifts of the Colorado Plateau were still not in evidence.

During Paleocene and Eocene time, the Uinta uplift dominated the tectonics, as may be seen on the map of Figure 12. It rose to acquire an amplitude in excess of 32,000 feet (Eardley, 1962). The Uinta basin on the south subsided about 12,000 feet, and the anticlinal uplift was denuded at least as much.

The belt of uplifts in west-central Utah probably rose no more but being high continued to suffer erosion. Another 1,000 feet of rock was probably stripped from western Utah during this time. All told, the dominant belt of uplifts lost during the last half of Cretaceous time and Paleocene and Eocene time a layer of rock about 15,000 feet thick and west of this a layer about 7,000 feet thick. The chief rise of the belt of uplifts is then clearly documented as occurring during Late Cretaceous time, and it will now be interesting to observe the isotope dates that have come from the intrusions.

It should be noted that the figures given above of the amount of erosion of western Utah are minimal, because much of the Paleozoic rock removed was limestone and dolomite which did not result in clastic accumulations. Where Precambrian cores are exposed, and consequently a greater amount of rock removed, the greatest amount of sediments accumulated in the Cretaceous foredeep.

RELATION OF UPLIFTS TO IGNEOUS ACTIVITY

Intrusive Rocks

The intrusive rocks of the Rocky Mountains, including those of the shelf and the miogeosyncline in western Utah, occur in both the basins, or synclinoria, and the uplifts. There seems to be a majority of plutons that have

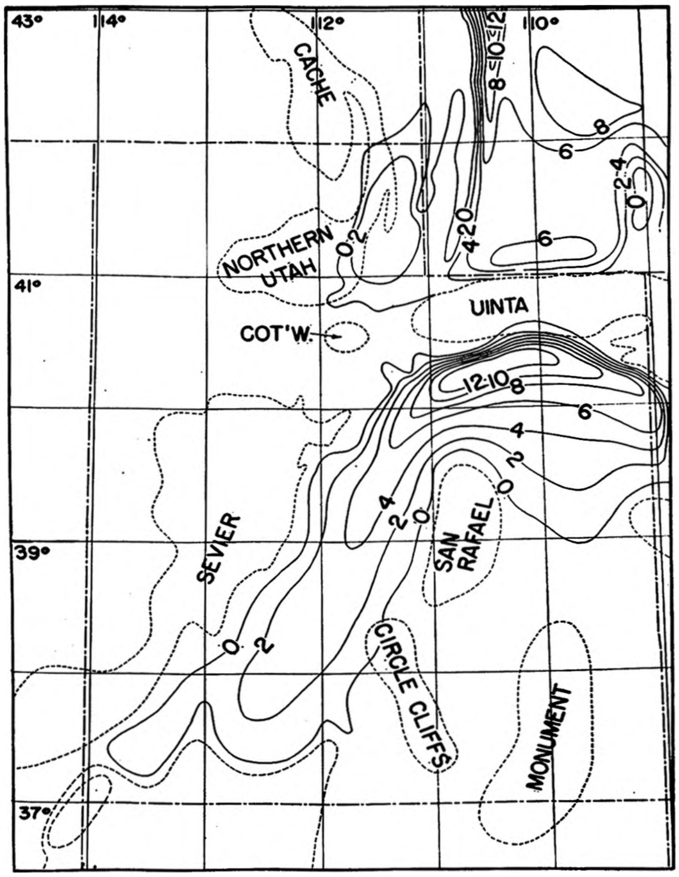

Fig. 12. Isopach map of deposits from uplifts in Paleocene and Eocene time. Uplifts outlined by dashed lines. Contour interval 1,000 feet.

intruded the uplifts, but in any theory of magmatism provision must be made for the arrival of the plutons in the sedimentary sequences of the basins.

The numerous stocks of the porphyry belt of the Front Range, Sawatch Range, and the San Juan Mountains include not only those that intrude the major uplifts but almost an equal number that have penetrated the thick sequence of Pennsylvanian and Permian sediments of the Colorado basin.

The stocks in the Cottonwood uplift of Utah are the only ones that appear to have helped in doming the sedimentary rocks of the uplift. The rest are discordant, seemingly passive emplacements. The Paleozoic stratigraphy of the Cottonwood uplift is clearly that of the shelf province; the other stocks westward are in the miogeosyncline.

The laccolithic clusters in the Colorado Plateau are in the basin sediments between the Laramide uplifts. The laccoliths of southwestern Utah are in a marginal belt between the shelf and miogeosyncline but also in a basin between the Kaibab and Sevier uplifts.

The alignment of the Uinta and Cottonwood uplifts, the stocks and mineral deposits of the Cottonwood uplift and Oquirrh Range, the mineral deposits, and the associated volcanic fields is conspicuous. Another east-west alignment may be seen in southwestern Utah from the Marysvale district through the Mineral, Star, and Wah Wah Ranges to the Needles Range near the Nevada border. This zone extends approximately along lat. 38°30′ N.

The paucity of Late Cretaceous or Tertiary stocks in other areas is conspicuous. It must be understood, however, that these and most other areas are at least half concealed by alluvium and Teritary volcanic rocks so that many other stocks may be present.

The majority of the isotope ages in western Utah so far determined are between 20 and 40 million years (James Whelan, personal communication; R. L. Armstrong, 1966). A meaningful distribution pattern of this group is not evident. If these isotope dates are accepted at face value, the stocks which they represent cooled during the Oligocene and early Miocene.

Several Cretaceous and Jurassic dates have been listed for intrusions in the southern part of the Snake Range and one for the stock in the Dolly Varden Mountains, all in easternmost Nevada beyond the western limit of Figure 1 (R. L. Armstrong, 1966).

Three Permian and Triassic dates have come to light. One is a potassium/argon (K/Ar) date from Precambrian schists in the Northern Utah uplift, and one is a lead/alpha date from a granite in the Mineral Range. The K/Ar date probably means the resetting of the isotope clock by a temperature rise at the time indicated, and the lead/alpha date on the granite needs confirmation by a K/Ar analysis.

Six early Paleozoic dates have also been listed (Hashad, 1964) that range from 484 to 647 m.y. Four of these are from the Farmington Canyon complex of the eastern side of the Northern Utah uplift. One is from the Precambrian, Little Willow Series adjacent to the Cottonwood stock, and one comes from the Gold Hill stock of western Utah. These dates may not be significant, but they call to mind the early Cambrian-latest Precambrian orogeny in the western margin of the continent (Purcell orogeny, Eardley, 1962).

Regarding the K/Ar dates on the stocks, it may be said immediately that they are minimum ages and theoretically should not mean the time of crystallization of the magmas but the time in the course of cooling of the solidified rock when it reached some critical temperature. If all stocks were emplaced at the same time, it follows that those most deeply emplaced below the surface would reach the critical temperature later than those closer to the surface and would yield younger dates.

K/Ar dates on the metamorphic rocks are variable, but as expected biotites from those near stock contacts reveal the same ages as the stocks. Biotite from the Little Willow Series near the stock contact yielded the same age as the stock, but hornblende yielded an age of 560 m.y. Biotite from schist in the Raft River Mountains near the roof of granitic instrusions yielded Tertiary ages. Precambrian rocks in the Deep Creek Range yielded Tertiary dates, although the rocks were some distance from exposed Tertiary stocks. Hornblende is less susceptable to loss of argon than mica (Hashad, 1964) and yields older figures.

Many of the stocks post-date the uplifts—a few by as much as 80 million years—for the most part they are passive, discordant intrusives. The stocks are also acidic in composition (Eardley, 1962; Gilluly, 1963).

Extrusive Rocks

The Tertiary extrusive rocks are acidic and closely resemble the stocks in composition (Eardley, 1962; Gilluly, 1963). They range in age from latest Eocene to Pliocene. They cover extensive areas in central and southwestern Utah and spread over a thick Cretaceous sequence in the High Plateaus westward across the southern extension of the Sevier uplift

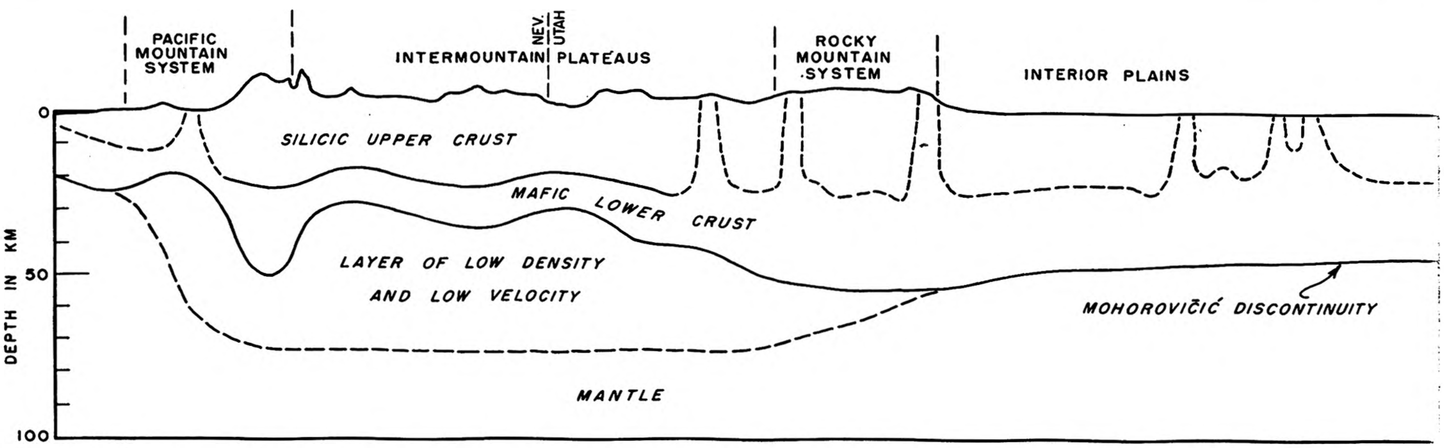

Fig. 13. Crustal and upper mantle layering of the western United States along the 38th parallel, approximately after Pakiser and Zietz (1965).

and adjacent synclinoria. They originally constituted a layer that averaged about 3,000 feet thick. They are part of a much larger acidic volcanic province that spreads over much of Nevada.

The distribution of eruptives seems as unrelated to the uplifts as the intrusives. About the only observation that can be made is that a major area of extrusive activity occurred in southcentral and southwestern Utah. The eastern part of this large field lies in the High Plateaus and covers the Late Cretaceous and early Tertiary clastics shed from the uplifts to the west, whereas the more westerly parts of the field covers Paleozoic and Precambrian rocks variously. Quaternary basalts follow very approximately the areas of the Sevier and Kaibab uplifts and increase in volume from central Utah southward into northern Arizona.

The large volcanic field of south-central Idaho and northeastern Nevada is part of the Snake River downwarp or downfaulted basin, contains much basalt, and is probably a different igneous province than that of southwestern Utah.

The uplifts and synclinoria were considerably eroded before the acidic volcanics were erupted. Possibly the Basin and Range faulting started at the same time as the earliest volcanic rocks were erupted, but most of the displacement along the faults has occurred since the volcanism. The Quarternary basalts have been displaced somewhat along the Hurricane fault.

BASIN AND RANGE FAULTING

In addition to the features of Basin and Range faulting recounted in the introduction of this paper, the following should be mentioned. The faults are normal and dip 50 to 70 degrees, and all significant movements in western Utah have been vertical. The amount of extension in an east-west direction amounts to about 30 miles from the Wasatch Range to the Sierra Nevada (Thompson, 1959) or about 10 miles across western Utah. Earthquake foci in western Nevada indicate that the faults may extend downward to 18 km (Thompson, 1959).

DEEP-CRUSTAL AND UPPER MANTLE LAYERING

The Transcontinental Geophysical Survey, recently reported on by Pakiser and Zietz (1965), is intended as a coordinating geological and geophysical study across the continent between the 35th and 39th parallels of latitude. A summary of the crustal and upper mantle layers beneath the Great Plains, Rocky Mountains, the Colorado Plateau, the Great Basin, and the Pacific border chains, as given by Pakiser and Zietz, is shown in Figure 13. Note the thin mafic lower crust and the shallow depth to the Mohorovičić discontinuity under the western mountain systems. Note also the layer of low density and low velocity at the top of the mantle (the 7.6 km/sec layer). The properties of the crustal and upper mantle of the western mountainous region that differ from that east of the Rocky Mountains, are listed by Pakiser and Zietz as follows:

1. The average crust is relatively thin, low in mean velocity and density, and weakly magnetic. The crust is predominantly silicic and is separated into two distinct layers (a silicic upper layer and a mafic lower layer) by a discontinuity or narrow transition zone. The lower layer may be, in general, hotter than the Curie temperature.
2. The velocity and density of the upper mantle are also low. The uppermost mantle may consist of a mixture of about 4 parts

peridotite and 1 part basalt, and the basaltic fraction may grade into eclogite at a depth of about 70 km. Thompson and Talwani have also suggested that the anomalous upper mantle in the Sierra Nevada and the Basin and Range province may be made up of a mixture of peridotite and basalt, or feldspathic peridotite. Other possible explanations for the low velocity and density of the upper mantle include partial melting, real differences in chemical composition, partial serpentinization of peridotite, and thermal expansion. It is unlikely that any single explanation is adequate to account for the anomalous upper mantle.

3. Late Mesozoic and Cenozoic diastrophism, plutonism, and volcanism have been widespread during the past 100 million years or so. The crust and upper mantle can be thought of as youthful in the sense that they are still in the process of evolution. This statement is not meant to imply that the western crust does not contain very old rocks. The crust is now receiving mafic and probably also silicic material from the mantle by the familiar geologic processes of intrusion and volcanism. Silicic material is being removed from the upper surface of the western continental crust by weathering and erosion and is being transported to the oceans by streams.

The crustal properties we have been describing are best explained by assuming that the primitive crust that evolved from the mantle was silicic and that it has been made slowly more mafic by addition of mafic material from the mantle accompanied by removal of silicic material from the earth's continental surfaces by erosion and stream transport (Pakiser, 1965). The process of evolving silicic material from the mantle may still be continuing in tectonically active areas where Cenozoic silicic igneous activity has been widespread, but some silicic igneous rocks of Cenozoic age are probably reworked crustal material.

Gilluly has pointed out that the continents can be maintained against erosive destruction and their isostatic equilibrium preserved only by some process of subcrustal flow that replaces the material that has been carried away by streams. We speculate that molten basalt may flow laterally in a solid matrix of mantle peridotite from beneath parts of the ocean basins and into the upper mantle beneath the active areas of the continents, thus replacing the silicic material removed by erosion and replenishing the supply of mafic material that has been migrating upward from the mantle and into the crust. This process of subcrustal flow may occur in the low-velocity layer of the upper mantle at a depth of about 100 km where, at a temperature of about 1,200°C, a minor basaltic fraction of the mantle would melt while the predominant peridotite would remain solid.

The continental surfaces in active regions such as the western United States slowly rise, for basalt added to the crust from the mantle below expands by about 10% if it was in the form of eclogite before melting, and the continental crust grows thicker. Additional uplift may come about because of the transformation of mantle garnet peridotite into plagioclase peridote, which is accompanied by expansion of about 3%.

Buildup of the mafic lower crust was probably accomplished by widespread intrusion of dikes, sills, and mafic plutons. Addition of mafic material to the silicic upper crust was probably accomplished by these same intrusive processes, plus the building of volcanoes and thick sheets of flood basalt.

PROPOSED THEORY OF COMMON ORIGIN OF SURFICIAL STRUCTURES, IGNEOUS ROCKS, AND EPEIROGENY

With the role which the upper mantle played in crustal tectonism and magmatism, above depicted by Pakiser and Zietz, a summary of the origin of primary uplifts, the siliceous intrusions and extrusions, epeirogenic uplift, and Basin and Range faulting of Colorado and Utah will next be attempted.

The theory has already been proposed that the acidic stocks and volcanic rocks of the Great Basin have originated from the melting of the basal part of the granitic complex. The heat necessary to cause the melting is presumed to come in good measure from molten basalt that has risen from the mantle. With the recognition of the vertical uplifts in the shelf and the western Utah portion of the miogeosyncline, it is now postulated that the rising basalt had arrived irregularly and had blistered up the granitic layer and overlying sedimentary rocks. More melting is generally required in the miogeosyncline because of the greater volume of volcanic rocks and stocks there than in the shelf. This would presume the rise of more basalt in the miogeosyncline under the granitic layer than in the shelf (Fig. 14).

With this concept of the origin of the uplifts and surficial igneous rocks as a premise, the following history is proposed.

It is postulated that basalt first began rising from the mantle in Early Pennsylvanian time in large volume in Colorado and easternmost Utah to cause the primary uplifts of the Ancestral Rockies and in less volume to produce the positive areas of the miogeosyncline of western Utah. The basins between the uplifts sank somewhat as the result of the weight of their own sediments, and thus the structural relief was accentuated. The shelf generally subsided until the close of Cretaceous time,

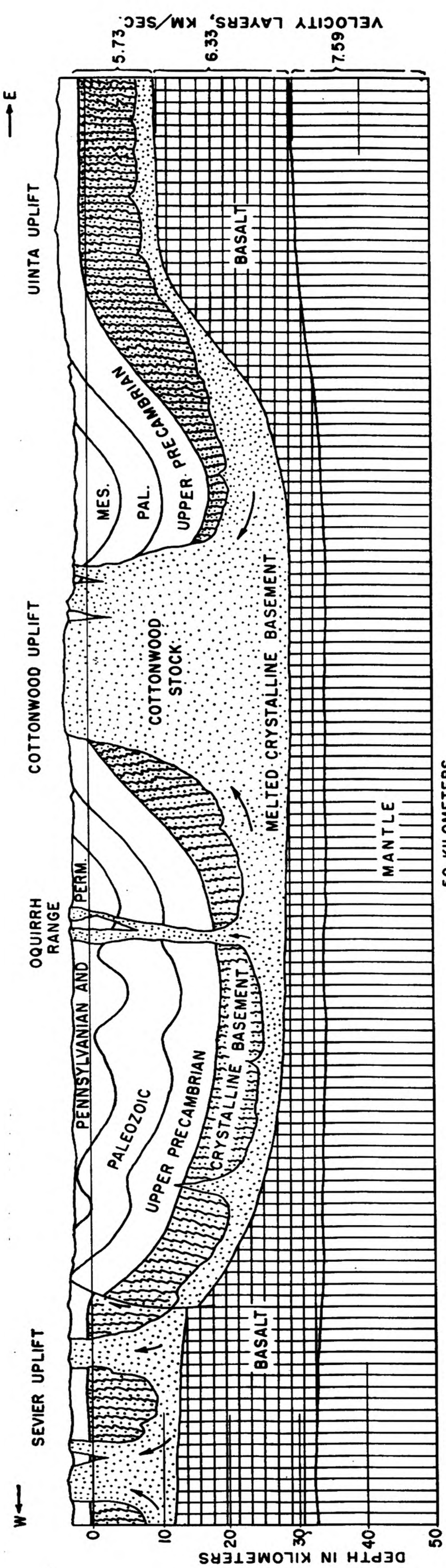

Fig. 14. Reconstruction of uplifts before block-faulting and volcanic activity, illustrating theory of melting of basal part of crystalline complex. Cross section is from Sevier uplift northward to stocks of Oquirrh Range and then eastward through Cottonwood uplift to the Uinta uplift. Horizontal scale same as vertical. The intrusion of the stock of silicic rock is viewed partly as the cause of the Cottonwood uplift, but the deep-seated megalenses of basalt are postulated as the cause of the Sevier and Uinta uplifts.

and the uplifts were eroded and gradually buried. The miogeosyncline of western Utah was finally drained of all seas in Early Triassic time, and all western Utah changed to a regimen of erosion. The reason why the shelf should subside during Mesozoic time and the miogeosyncline should become gently positive, at least until Middle Cretaceous time, is not apparent.

During Middle and part of Late Jurassic time, a seaway existed east of the uplifted geosynclinal region, and a narrow basin developed along the hingeline of the former geosyncline and shelf where a thick limestone and shale deposit formed.

In Middle Cretaceous time, a major surge of basalt from the mantle elevated the uplifts of the belt from southeastern Idaho to southwestern Utah, and the Northern Utah, Cache, and Sevier uplifts rose abruptly about 10,000 feet. Again in mid-Late Cretaceous time, another doming occurred in the belt of uplifts to the extent of 5,000 to 10,000 feet. Each time, great floods of clastics were washed to the east-flanking piedmont and basin.

The oversteepened flanks of the uplifts shed various slide masses mostly along bedding surfaces, and the Paleozoic sediments between uplifts were compressed. The upper layers, particularly, were folded and thrust faulted.

The rise of the uplifts in the shelf began in mid-Late Cretaceous time. Each one somewhat had its own history, with the Uinta uplift noted for the major uplift not until at least middle Eocene. This history attests to the somewhat later rise of basalt from the mantle under the shelf than the miogeosyncline.

The hot basalt started mobilizing the lower part of the silicic layer, probably first under the uplifts but eventually under the basins also. A large stock from the acidic magma was emplaced in the southeastern flank of the Sevier uplift possibly in Early Triassic time, several granitic stocks were intruded and cooled in about Middle Cretaceous time along the Nevada-Utah border, and finally in Oligocene and early Miocene time much acidic magma made its way in a number of places into the overlying rocks of western Utah.

The early and mid-Eocene fresh water lakes north and south of the Uinta Mountains indicate that these basins stood at about 1,000 feet above sea level. Similarly a large lake in eastern Nevada lying west of the Snake uplift should be regarded as occupying a basin whose surface was not far above sea level. So probably in mid-Eocene time, we should consider the terrane of Utah and Colorado as marked by ranges of fairly high relief in the sites of the uplifts, with two basin areas not much above sea level. The uplifts of the shelf region must have been particularly high, but those of the miogeosyncline were more subdued, being older. This concept of relief is significant in shaping ideas about the magmatic and tectonic events, because the geomorphic and paleontologic record of Oligocene and Miocene time indicates regional uplift in the order of 5,000 to 8,000 feet (Eardley, 1962). Accordingly, it is postulated that by early Oligocene time the liquid basalt layer and the overlying partially melted silicic crust had become a continuous liquid layer under the entire miogeosyncline of western Utah and, in the generation of basalt and the change to lighter density of the upper mantle (the 7.6 km/sec layer), had expanded vertically, and the entire region had been elevated so that the average relief approached several thousand feet above sea level. The mid-Eocene lake basins were now several thousand feet high. Thereupon, the overlying crust with a mobile subcrust was attenuated and responded by fracturing and faulting, and the tilted blocks and the graben and horst structure of the Great Basin came into existence.

With the inception of normal faulting, the silicic magma surged upward to the surface in many places. Its temperature and water content were just right to result in voluminous and blanketing ignimbrite flows over southwestern Utah and adjacent Nevada. In places, the ignimbrite eruptions probably issued from long fissures. It appears that the main phase of volcanic activity extended from early Oligocene to early Miocene time, but the fault block adjustment continued, and the volcanic masses were broken and much displaced. The silicic crust or western Utah subsided somewhat incident to the block-faulting volcanism.

It may be conceived that the silicic magmas were exhausted in places or cooled and solidified, whereupon, and lastly, the underlying basaltic magma was tapped and rose to the surface along the faults in Quaternary time.

The early rise of basalt was irregular spatially, and first formed the hydrodynamic primary uplifts of the silicic crust. The surficial structures were thus framed about the uplifts. When the basalt built up to a continuous layer under the miogeosyncline, the attenuation forces of regional direction became dominant, and an entirely new framework of deformation, discordant with the local uplifts, was created.

The nature of the block faulting and the cause of the attenuation westward point to a lateral shift of the crust to the Pacific basin in response to gravity.

It may be pointed out that the evolution of magmas and uplifts in the miogeosyncline differed from those in the shelf in several ways. The igneous rocks of the shelf are alkalic and calc-alkalic and poor in silica, whereas, those of the miogeosyncline are normal in alkalies and richer in silica. The high sodium and potassium content of many of the intrusive and extrusive rocks of the shelf is due presumably first, to a primary basalt rich in alkalies (olivine basalt) and second, to the melting and assimilation of crystalline rocks with high alkalic content. The high alkalic silicic magmas had considerable opportunity to differentiate in quiet hearths in the shelf province and to produce a variety of unusual rocks, such as shonkinite and nepheline syenite. The magmas of the miogeosyncline did not differentiate much but intruded and erupted in the form of the primary silicic magma as first formed. The basalt was evidently of the olivine variety, judging from the Quaternary basalts there, but the assimilated crystalline basement was low in the alkalies.

The volume of silicic magma was less in the shelf province and apparently was spotty in its development. The volcanic activity tended to be localized in centers. There the basaltic and silicic magma issued alternately to some extent. How nature managed this is not clear. In the miogeosyncline on the other hand, the melting of the crystalline basement became almost ubiquitous, and the magmas thus produced furnished almost all intrusive and extrusive melts. Only in the last dying stage of the magmatic activity was the deeper basalt tapped.

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