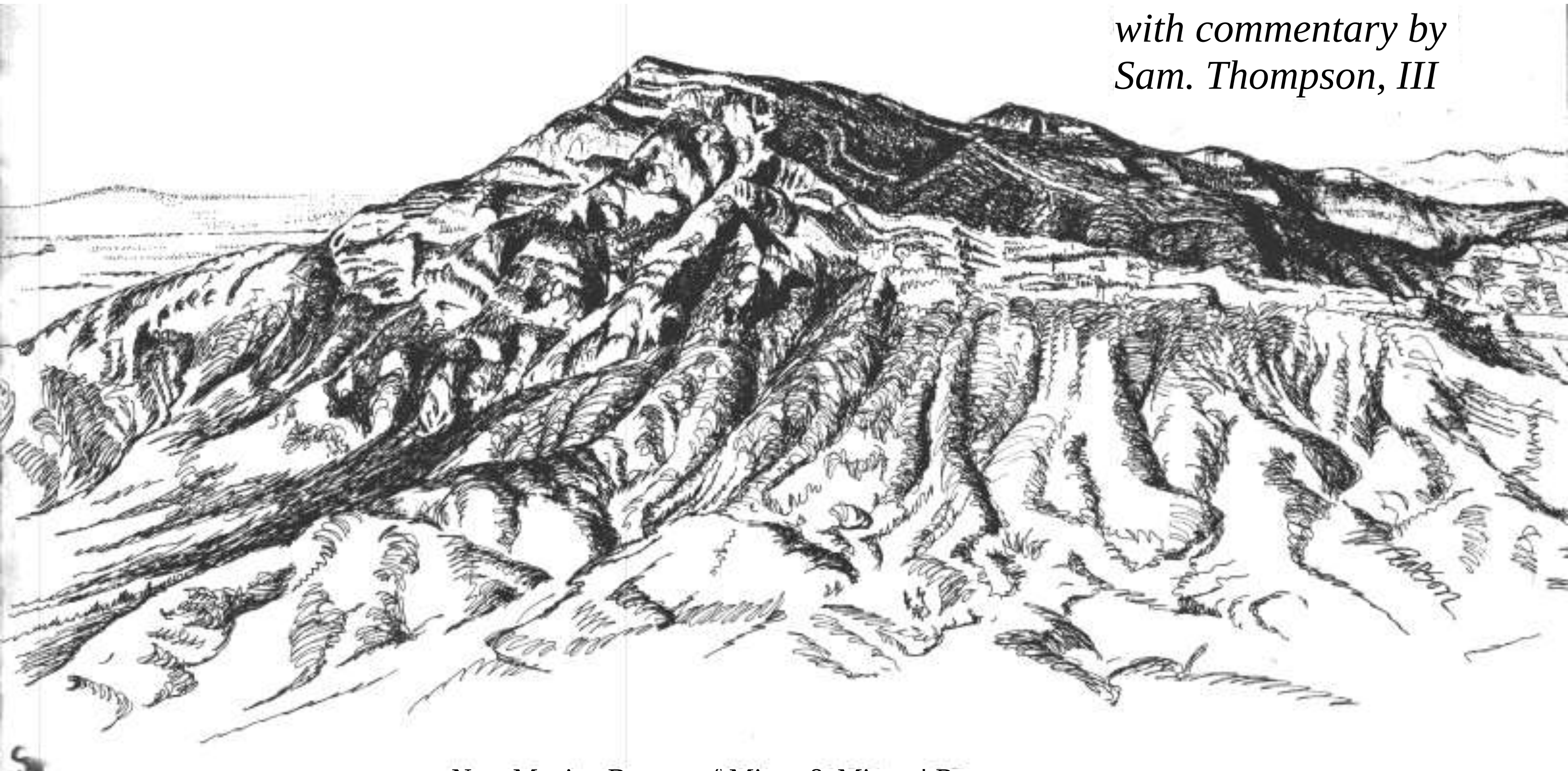
CIRCULAR 146 *1975*

Structural Geology of
Big Hatchet Peak Quadrangle,
Hidalgo County, New Mexico

by

Robert A. Zeller, Jr.

with commentary by
Sam. Thompson, III



New Mexico Bureau of Mines & Mineral Resources
A DIVISION OF
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Circular 146

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SOCORRO 1975

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Published by Authority of State of New Mexico, NMSA 1953 Sec. 63-1-4
Printed by University of New Mexico Printing Plant, November, 1975

Available from New Mexico Bureau of Mines & Mineral Resources, Socorro, NM 87801 Price $4.00

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FOREWORD

In 1965 the New Mexico Bureau of Mines and Mineral Resources published Memoir 16, "Stratigraphy of the Big Hatchet Mountains Area, New Mexico." That work by Robert . Zeller, Jr. established the fundamental stratigraphic column for southwesternmost New Mexico. On March 16, 1970 he died in an airplane crash (see memorial by Wengerd, 1970) before he could finish a companion project on the structural geology of the Big Hatchet Peak quadrangle.

In this circular we are presenting, with as few alterations as possible, Zeller's unfinished work on this area. His geologic map, the most important contribution, was nearly in final form. Those familiar with Zeller's high quality of detailed mapping will appreciate our reluctance to modify it even slightly, but some minor alterations were necessary. His structure sections were also in final form, but some irregularities in the topographic and stratigraphic surfaces appear uncontrolled and also possibly unnatural. Such irregularities cannot be modified without reconstructing entire sections. I believe Zeller intended to leave such random irregularities to avoid the definitely unnatural aspect of artificially smooth lines.

Zeller's original manuscript was written for a bulletin planned about 1960. He extracted the part on stratigraphy and polished it for Memoir 16. For the present circular, I used the unfinished part of the text on structural geology (completed through the discussion of the Hatchet Gap fault) and supplemented it with material from his dissertation (Zeller, 1958a, section on Tertiary—Quaternary deformation). Zeller would have wanted a thorough review of his text, the same as he requested prior to publication of Memoir 16. However, without his response to challenged statements and an opportunity for him to consider suggestions, we have rewritten less than a fifth of his original manuscript — and only where needed for clarity.

To Zeller's text, I have added the Abstract and the Introduction. Figs. 1 and 2 were taken from Memoir 16. I also added fig. 3 (structure index map) so that the lengthy descriptions and interpretations can be followed more easily. Zeller shows the names of the major folds and faults only on the structure sections (not on the geologic map).

In the commentary at the back, I have expressed personal views regarding some of Zeller's concepts and interpretations. For each point in the text indicated by a superscript number, a corresponding note is found in the commentary (beginning on p. 21). This procedure allows the user to read through Zeller's text without interruption; or, he may go to the commentary at any questionable point to consider other interpretations. In particular, comments No. 5 and No. 9 should be studied because they involve changes on Zeller's geologic map.

My comments were not placed in the text because they include the type of remarks generally made by a reviewer and need to be judged by the author. Nor could I assume the role of a junior author in publishing this report because my firsthand knowledge of the area is limited to a stratigraphic reconnaissance several years ago. Moreover, these remarks were residual considerations following the correction of the few errors in Zeller's text and the clarification of the more awkward constructions. Many of my comments clash with Zeller's expressed preferences. Others deal with omissions or questions that could have been answered best by Zeller himself. Hopefully, these points will be resolved by future field studies, but our main objective now is to make Zeller's work available without further delay.

Zeller's detailed map of the Big Hatchet Peak quadrangle is the first concentrated effort to cover the area completely. The precision of his work emphasizes the local complexities but tends to obscure the major structures having regional significance. His objectivity in showing only observed structural features on map is commendable; however, many fold axes and fault traces need to be extended with dashed or questioned lines to present a more comprehensive structural picture. Subsequent to Zeller's mapping, a great deal of data has been added to the regional framework; and new concepts, such as plate tectonics, have been developed. Because of these advances, the quadrangle may need to be remapped, perhaps on a smaller scale, so this key area can be better synthesized into the regional framework.

Zeller's work is an essential base for future geologic studies especially in the search for minerals and petroleum. Unfortunately, Bob died before he could polish this work to the same high standards of his Memoir 16. Every effort has been made to insure that this posthumous publication is a fair representation of the author's work. Any geologist who finds a discrepancy or new field evidence is encouraged to call it to our attention.

Socorro
August 18, 1975

Sam Thompson III
Petroleum Geologist
New Mexico Bureau of Mines
& Mineral Resources

ABSTRACT

In the Big Hatchet Peak quadrangle, field evidence indicates three general episodes of deformation. Prior to the deposition of Lower Cretaceous rocks, a deformation in the Precambrian was followed by epeirogenic movements during the Paleozoic and Mesozoic. Differential subsidence beginning in Desmoinesian time formed the Alamo Hueco basin; reefs developed on the margin between the basin and shelf. Only epeirogenic movements are indicated in the Lower Cretaceous sequence.

The episode of greatest structural deformation in the area occurred later than Early Cretaceous deposition and earlier than Tertiary deposition. This orogeny produced large folds, reverse, thrust, and overthrust faults, and probably some high-angle faults. Thrusting in the Big Hatchet Mountains was generally toward the west and southwest, but that in the Sierra Rica apparently was toward the northeast, similar to the general direction indicated in other areas of the region. The Tertiary—Recent deformation produced the Basin and Range topography. In addition to the normal faults bounding the ranges, broad open folds, two systems of high-angle faults, and minor thrust faults were formed.

INTRODUCTION

This report on the structural geology of the Big Hatchet Peak quadrangle is a supplement to the memoir on the stratigraphic geology published by Zeller (1965). Much of the discussion in the introduction to that work (p. 1-5) is pertinent here and should be reviewed.

Fig. 1 (page 5) is an index map which shows the location of the Big Hatchet Peak quadrangle in Hidalgo County, New Mexico, and the chief geographic features of the region. This oversized 15-minute quadrangle covers 296 square miles of typical basin-and-range country. The highest point is Big Hatchet Peak at 8366 ft above sea level, and the lowest point is at 4129 ft near Artesian Well in the Hachita Valley. The average elevation in the Big Hatchet Mountains is about 6000 ft, and that of the Sierra Rica (in the northeast part of the quadrangle) is about 5000 ft. The most prominent ridges and valleys in the ranges trend northwest and reflect structural control, but faults show little topographic expression. However, exposures of bedrock generally are good.

Continued on page 7

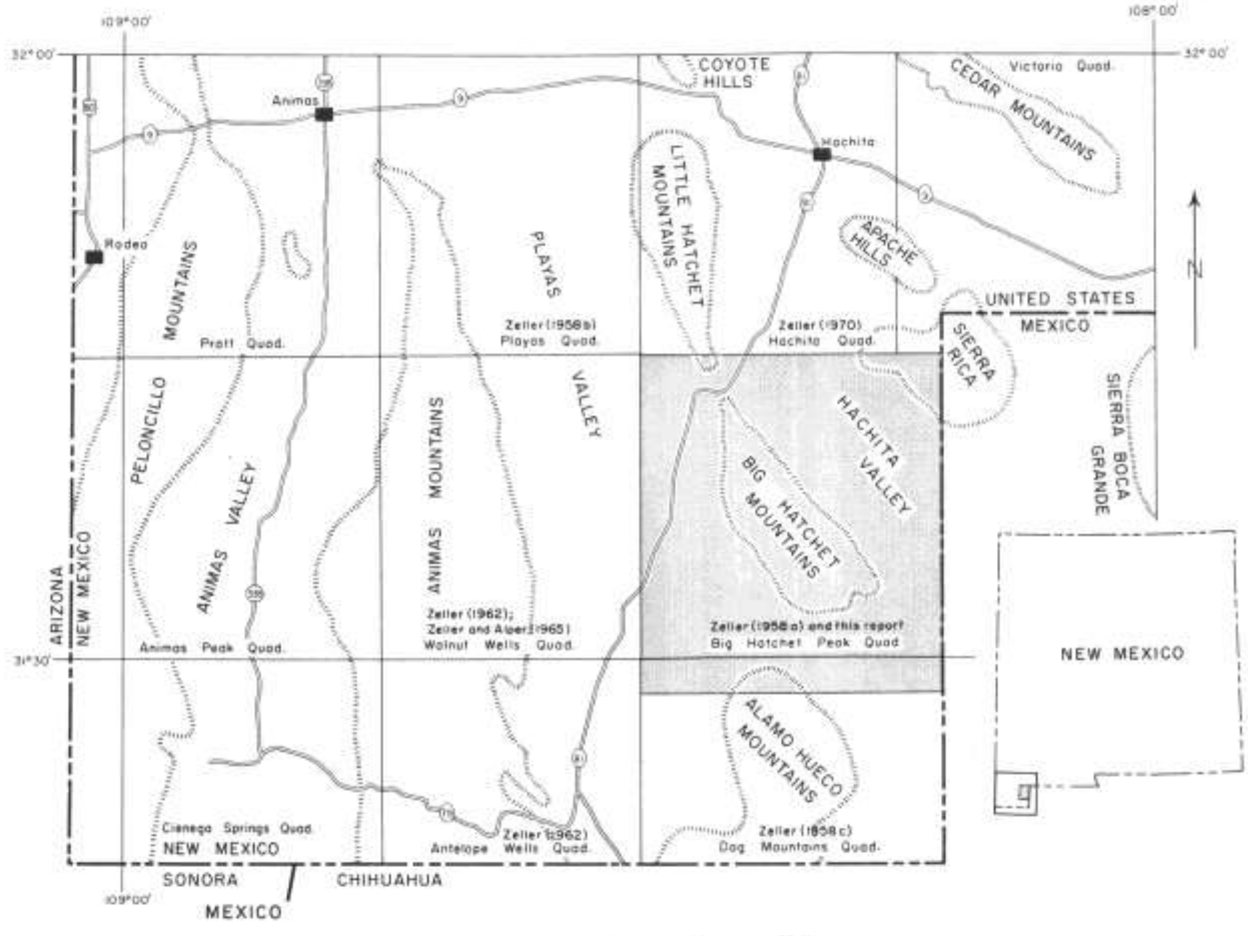

Figure 1—Index map of Big Hatchet Peak quadrangle area and the chief geographic features of the region (references show areas of field work done by Zeller and others)

Figure 2 —Summary of sedimentary rock formations in Big Hatchet Mountains area

Age			Rock units			Measured thicknesses (feet)	Lithology and remarks
TERTIARY							Basal unit consists of several hundred feet of limestone fanglomerate. This is overlain by thick sequence of volcanic tuffs and flows.
				Angular unconformity			
EARLY CRETACEOUS	Albian	Washita		Mojado Formation	Upper member	5195	Sandstone and shale. Thin to medium beds of strongly cross-laminated brown and gray sandstone are interbedded with thin units of shale. Lens-shaped sandstone masses probably represent channel fillings. Most of formation is of terrestrial origin. Calcareous fossiliferous marine beds are present in upper member and increase in number upward.
		Fredericksburg			Lower member		
				U-Bar Formation	Suprareef ls. mem.	3500	Limestone. Most of formation consists of medium and thin beds of bioclastic limestone alternating with thin gray shale beds. Lenses and thin beds of sandstone are found in lower part. Massive limestone near top of formation is a reef which ranges in thickness from 500 to 20 feet within the area.
					Reef ls. member		
		Trinity			Ls.-sh. member		
					Oyster ls. member		
	Aptian				Brown ls. member		
	?	?		Hell-to-Finish Formation		1274	"Red beds." Composed mostly of interbedded red arkose and sandstone, red and gray shale, and red siltstone. Basal bed is conglomerate composed of chert pebbles derived from Concha Limestone.
				Erosional unconformity			
PERMIAN	Leonard		Naco Group	Concha Limestone		1376	Limestone. Medium-bedded limestone characterized by abundance of purple chert nodules and silicified productid brachiopods. Upper beds often dolomitized. Pre-Cretaceous erosion removed varying amounts of upper beds.
	Leonard or Wolfcamp			Scherrer Formation		5-20	Quartz sandstone and limestone. Sandstone occurs as strata and lenses in limestone.
				Epitaph Dolomite		1480-1519	Dolomite. Medium-bedded light to dark gray dolomite with small knots of quartz. Lower part has a few lumpy limestone and dolomitic limestone beds. A red-weathered interval in lower part has red siltstone and, in one area, massive gypsum.
				Colina Limestone		355-505	Limestone. Thin-bedded limestone which is black on fresh fracture and which weathers light gray. Upper contact lies at different levels depending upon depth in section of Epitaph dolomitization.
				Earp Formation		997	Siltstone and claystone. Composed mainly of interbedded terrestrial brown-weathered cross-laminated siltstone and light gray claystone. Upper part contains marine limestone beds which increase in abundance upward.
				Local disconformity			
	Wolfcamp			Horquilla Limestone		3245-3530	Limestone. Lower third is medium-bedded bioclastic limestone which includes oolitic and crinoidal beds and some zones rich in gray chert nodules. Upper two-thirds is complicated by basin, reef, and shelf facies. The crest of the Big Hatchet Mountains in general follows the reefs; the basin lies southwest of the range; the shelf lies along the east side of the range. The reefs consist of massive bioclastic limestone with dolomitized areas. Basin deposits consist of dark shale and black thin-bedded limestone. The shelf beds consist of light-colored medium-bedded bioclastic limestone.
PENNSYLVANIAN	Virgil Missouri Des Moines Derry Morrow?						
?	?			*Erosional unconformity*			
MISSISSIPPIAN	Chester			Paradise Formation		318	Limestone. Thin-bedded yellowish-brown-weathered bioclastic and oolitic limestone rich in well-preserved fossils. Quartz sandstone beds and lenses near top have plant fossils. Pre-Horquilla erosion removed varying amounts of upper beds.
	Meramec			Escabrosa Limestone	Upper member	1261	Limestone. Lower member composed of thin-bedded limestone and a few shale beds. Middle member consists of rhythmic succession of thin limestone strata and nodular chert strata. Upper member composed largely of crinoidal limestone. Upper two members together usually form single cliff hundreds of feet high.
	Osage				Middle member		
	Kinderhook				Lower member		
?	?						
DEVONIAN				Percha Shale		280	Clay shale. Basal beds include a few strata of calcareous argillaceous siltstone and black shale. Upper beds include thin strata of nodular limestone. Bulk of formation is gray shale.
				Unconformity			
ORDOVICIAN	Cincinnatian			Montoya Dolomite	Cutter Member	385	Dolomite. Basal member consists of 10 to 20 feet of dolomitic quartz sandstone interbedded with dolomite. Aleman Member composed of rhythmic succession of dark gray dolomite strata and strata of black chert nodules.
					Aleman Member		
	Champlainian				Upham Member		
					Cable Canyon Mem.		
				Disconformity			
	Canadian			El Paso Formation	Bat Cave Member	916-1070	Limestone and dolomite. Sierrite Member composed of dolomite and dolomitic limestone; some strata rich in chert nodules and brown reticulated chert laminae. Bat Cave Member consists of bluish-gray-weathered bioclastic limestone. Uppermost beds dolomitized.
					Sierrite Member		
?	?						
LATE CAMBRIAN	Trempealeauian? Franconian Dresbachian?			Bliss Formation		192-327	Arenaceous rocks. Basal beds composed of arkose and boulder conglomerate. Middle beds consist of white orthoquartzite. Upper beds composed of dolomite with varying quantities of quartz sand. Thickness and lithology of units variable.
				Erosional unconformity			
PRECAMBRIAN							Coarsely crystalline porphyritic granite and quartzite.

Fig. 2 (page 6) is a stratigraphic summary of the sedimentary units exposed in the Big Hatchet Mountains (taken from fig. 2 of Zeller, 1965). Precambrian granite is the basement rock, but most of the thick Paleozoic sequence is composed of competent limestones and dolomites. The limestones, sandstones, and shales of the overlying Lower Cretaceous formations are generally less competent. Fig. 3 (page 8) is a structure index map which shows the names and locations of the major folds and faults discussed in the text.

The geologic map (in pocket) of the quadrangle was originally drawn on a scale of 1:31,250 (2":1 mile) then reduced to 1:48,000. In the field, data were plotted on aerial photographs of the U. S. Soil Conservation Service at a scale of 1:20,000 and were transferred later to the topographic base map. The structure sections (in pocket) also were originally drawn at 1:31,250 with no vertical exaggeration, and reduced here to match the scale of the geologic map.

GENERAL STATEMENT

The structural geology of the Big Hatchet Peak quadrangle is treated under three headings: Periods of deformation prior to Early Cretaceous deposition, deformation later than Early Cretaceous deposition and earlier than Tertiary deposition, and Tertiary—Recent deformation.'

The duration of periods of deformation may have been prolonged over considerable intervals of geologic time. Where thick sections of rocks were deposited during the extent of a period of deformation, as in the case of Tertiary deformation in the region, and where the involved rocks are widely exposed, the deformation is well documented. However, in most cases within the region deformation occurred during a period for which no rocks are preserved; that is, it occurred during the hiatus represented by an unconformity. Evidence of such a deformation is seen in the structures which affect rocks below the unconformity but not those above it. The time of such a hiatus is ordinarily sufficiently long so that the deformation cannot be closely dated, and all that can be determined are the maximum time limits of the hiatus and thus the limits of the period of deformation. For example, the deformation which most strongly affected the rocks exposed in the quadrangle occurred after deposition of the Lower Cretaceous section and before deposition of the Tertiary section. The exact bounding ages of this period of deformation are not known. Whether Upper Cretaceous rocks are present in the area and simply not exposed is not known, and also the age of the oldest rocks of the Tertiary section is not known. Thus deformation may have occurred during any part of a long interval of geologic time which may have embraced the Late Cretaceous and much of the Tertiary.

In this report periods of deformation are given general titles. To brand the above mentioned period of deformation as Laramide presupposes a known systematic time relationship with the Laramide orogeny of its type area, and as structural studies in the region have not advanced to the point of attempting such correlation the term is not here used. Instead, this period of deformation is designated by the cumbersome but accurate title "deformation later than Early Cretaceous deposition and earlier than Tertiary deposition." Titles used for the other periods of deformation in the area are similarly general and accurate. Evidence for some of the periods of deformation of the region are not found within the quadrangle, but to provide a more complete description of the structural events which affected the entire region they are nevertheless discussed.

The assignment of structures to their proper periods of deformation is often difficult and is sometimes not possible. In rare cases where an unconformity transects a structure in underlying rocks the evidence is clear. An example is the U-Bar Ridge syncline in which strongly folded Lower Cretaceous rocks are overlain unconformably by gently dipping Tertiary rocks. The various structures of the area which are not transected by unconformities must be dated by other means. sequence of structural events can be worked out using intersections of structures, and such a sequence may sometimes be dated by one of its latest structures being cut by an unconformity. In cases where structural intersections are not found, particular structures are sometimes assumed to have resulted from the same forces which produced nearly like structures of similar attitude, and they are then assigned to the same period of ←① deformation as the similar ones. As mentioned presently, this method is not always valid and it is best used in conjunction with other evidence. Intensity and types of deformation which are found to characterize certain periods of deformation are helpful in dating structures. For instance, during part of the orogeny which influenced Lower Cretaceous rocks and not Tertiary rocks, structures produced by crustal shortening through the action of compressive stresses are characteristic. Study of dated structures in the area show that only during this orogeny were strong folding and extensive thrust-faulting produced. Thus these structures, even though isolated, are immediately assignable to this period of deformation.

Another example of structures which characterize a particular period of deformation are the normal faults of the Basin and Range system which flank Big Hatchet Mountains and many other ranges of the area. These formed only during the latest period of deformation. High-angle northwest-trending faults in the area which are not cut by later structures cannot be dated with certainty because such faults are known to have occurred before and after thrusting in the Big Hatchet Mountains, and to have occurred during two distinct periods during the Tertiary in the Alamo-Hueco Mountains. Through cautious use of these techniques many of the structures of the quadrangle have been dated as to the periods of deformation in which they formed.

Under the heading for each period or periods of deformation the associated structural events are described in chronological order insofar as is possible, and certain important individual structures are discussed. Here the structural

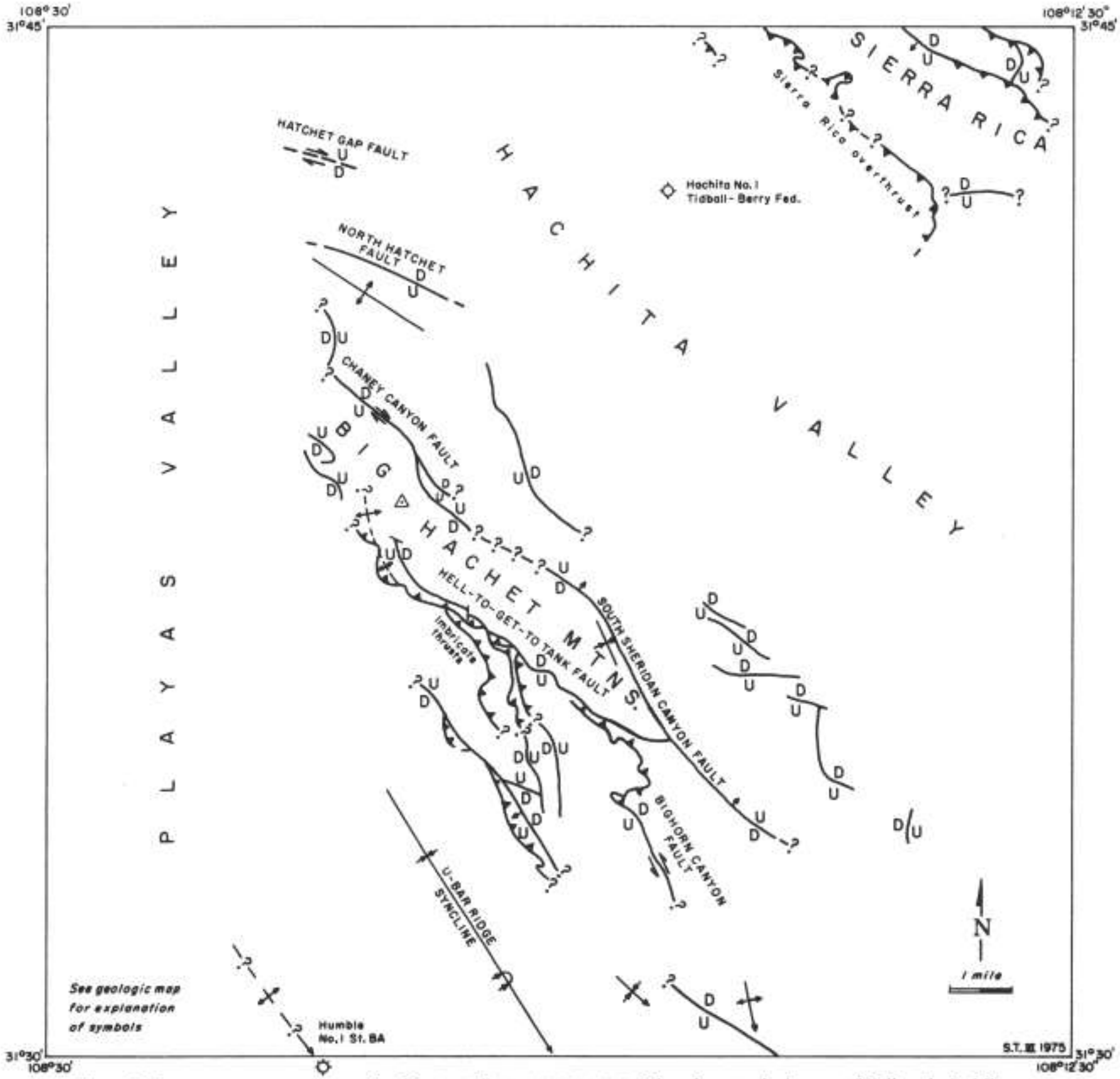

Figure 3—STRUCTURE INDEX MAP OF BIG HATCHET PEAK QUADRANGLE (taken from geologic map of Zeller; dashed lines and queries by Thompson)

geology is primarily treated descriptively, and a unified theory of its genesis is reserved until completion of continuing structural studies of the region. On the geologic map (in pocket) the structural geology is shown faithfully as observed in the field with a minimum of interpretation, and contacts are shown with symbols which indicate their reliability. The structure sections (in pocket) are of necessity largely interpretative. Most contacts on the geologic sections are shown as solid lines for clarity, but the reader should understand their interpretive nature. Those shown with dashed lines represent purely hypothetical structures for which there is little or no evidence. These sections were constructed from the completed geologic map.

Mapping of faults within the Big Hatchet Mountains is impeded by difficulties, one of which is that most faults have little topographic expression. more serious difficulty is that the mountains are dominated by exposures of the 3500-ft thick Horquilla Limestone which is not divisible into thinner units on the basis of lithology. Many faults which clearly separate different formations in one area may be traced into areas where Horquilla Limestone lies on each side of the fault trace. In a few cases such faults have been mapped for short distances in the Horquilla Limestone through use of the different fusulinid zones found on each side, but this technique, being extremely slow and tedious, was not used extensively. Therefore, the traces of many faults, even some having large displacements, are lost within the Horquilla Limestone and are indicated on the geologic map with "doubtful or probable" contacts?

PERIODS OF DEFORMATION PRIOR TO EARLY CRETACEOUS DEPOSITION

The earliest period of deformation recorded in the rocks of the quadrangle occurred in Precambrian time and is seen in Hatchet Gap (on the first hill north of the highway in sec. 1, T. 30 S., R. 16 W.) where Precambrian granite intruded quartzite (Zeller, 1965, p. 6). Details of this deformation are obscure because the quartzite is exposed only in an area of a few hundred square feet. Undoubtedly this orogeny is closely allied to Precambrian intrusion and deformation noted in the Burro Mountains northeast of Lords-burg, New Mexico, and to that seen in Precambrian exposures in some of the ranges of southeastern Arizona. Precambrian rocks in the area were beveled by deep erosion before deposition of Paleozoic rocks.

Throughout the Paleozoic section no notable angular unconformities are found, indicating that no orogenic deformation occurred in the area during the deposition of those rocks. Periods of epeirogenic uplift and depression during Paleozoic time produced several lithologic and faunal breaks. Notable erosional disconformities are found at the bases of the Bliss Formation, the Montoya Dolomite, the Percha Shale, the Horquilla Limestone, the Earp Formation and possibly the Scherrer Formation (Zeller, 1965). Detailed study of the faunal succession undoubtedly would reveal other hiatuses. Uplifts and depressions of the area with respect to sea level during the Paleozoic period were small in magnitude but influenced broad areas.[3] ←③ The lack of coarse terrigenous detritus in the rocks immediately above the disconformities in the Paleozoic section indicates that the source areas were not deeply dissected and therefore not highly uplifted. The clastic texture of the fossiliferous carbonate rocks tends to indicate shallow-water deposition; therefore, the area probably was not depressed very far below sea level in Paleozoic time.

The great areal extent of the erosional disconformities suggests that the uplifts were widespread, and the broad continuity of the strata suggests that the depressions were also widespread.

During middle or late Desmoinesian time, crustal unrest was initiated which continued until the end of Paleozoic deposition. The evidence for this is seen in the basin-reef-shelf relationships found in the later Paleozoic rocks. Reef formation in the Horquilla of the Big Hatchet Peak area evidently commenced with a monoclinal flexure which produced the shelf-to-basin profile and provided the environment for the reef margin (Zeller, 1965, p. 42-45). The mono-dine is indicated by a local angular unconformity at the base of the reefs on the peak. The deep Alamo Hueco basin formed in the southwestern part of the quadrangle and was filled during Wolfcampian time.

Differential vertical crustal movements, producing basin-reef-shelf relationships, continued into the latest Paleozoic time as indicated by massive reefs which the writer ←② has observed in the Permian Epitaph Dolomite and Concha Limestone in the Mustang Mountains of southeastern Arizona. The gypsum deposits in the Epitaph Dolomite of the Big Hatchet Mountains may be back-reef evaporites. Such relatively mild crustal 'distortion may have been the forerunner of the stronger period of deformation which followed deposition of the Paleozoic rocks.

Throughout much of the region of southeastern Arizona, southwestern New Mexico, western Texas, and adjoining parts of Mexico an angular unconformity lies at the base of the Cretaceous rocks (Zeller, 1965, p. 54-55; Zeller and Alper, 1965, p. 68-71). Its angularity is clear evidence of a period of deformation which influenced the region during the hiatus represented by the unconformity. In the Big Hatchet Peak quadrangle the umconformity has no detectable angularity, which may be due to a coincidental parallelism of the beds above and below in this particular area, or may indicate the deformation was weaker here. Because the unconformity is seen to be angular in all exposures around the Big Hatchet area, the former hypothesis is judged to be more likely.

DEFORMATION LATER THAN EARLY CRETACEOUS DEPOSITION AND EARLIER THAN TERTIARY DEPOSITION

Before proceeding with the discussion of the next period of strong deformation, it may be well to mention the mild vertical crustal movements that took place during deposition of the Lower Cretaceous rocks and which caused the formation of basins, produced environments under which reefs formed, and caused periodic local emergence above sea level. Evidences for these movements are seen in the stratigraphic record of the Lower Cretaceous rocks (Zeller, 1965, p. 55-75). These minor differential vertical movements perhaps were the early beginnings of the period of intense ④ deformation which was to follow.[4]

The episode of greatest structural deformation in the area involved Lower Cretaceous rocks and not Tertiary rocks. In the southern part of the quadrangle the Mojado Formation of late Early Cretaceous age is overlain with sharp angular unconformity by the Little Hat Top Fanglomerate, the basal formation of the Tertiary section. The age of the fanglomerate within the Tertiary is not known. Thus, in this area the orogeny occurred between late Early Cretaceous and an undetermined level of Tertiary time. The Little Hat Top Fanglomerate and overlying volcanic rocks are but little deformed in contrast to the older rocks.

This orogeny produced large folds, also reverse, thrust, and overthrust faults, and probably some high-angle faults. As deformation took place during a period for which no sedimentary rocks were deposited or preserved in the area, paleontologic dating of the structural events is impossible. Using the intersections of the various structures with one another, the relative order of structural events may be determined. The structures which are definitely assignable to this orogeny are all the result of compressive stresses; and the strikes of the faults and of the axial planes of the folds all trend northwest. Folds and the compressional faults are closely related, and in many cases these faults can be shown to have fractured folds. After continued compression, folds had reached certain stages of development beyond which such faulting was more favored than continued folding. The age of the folding, and also the compressional faulting, was between Early Cretaceous and Tertiary deposition. This is clearly shown in the manner in which the base of the Tertiary section truncates unconformably the folds in Cretaceous rocks.

In addition to the compressional structures, high-angle faults that formed both before and after thrusting are questionably assigned to this orogeny. Those high-angle faults which are overlain by thrust sheets may be assigned either to this orogeny or to the post-Paleozoic—pre-Cretaceous deformation. Some high-angle faults which followed folding and thrusting may be assigned to this orogeny and are discussed in this section, though some or all of them may have formed in Tertiary time. Intrusion of dikes and sills in the Sierra Rica occurred during this orogeny prior to reverse faulting. The various types of structures may have been formed at somewhat different times in different areas, so an exact chronological order cannot be based on these types. Nevertheless, structural events which probably and definitely are assignable to this orogeny are described in rough chronological order under the following headings: pre-thrust high-angle faults; folds; dikes and sills; reverse, thrust, and overthrust faults; and post-thrust high-angle faults.

Pre-Thrust High-Angle Faults

Evidence for early pre-thrust high-angle faulting is best seen near the head of Thompson Canyon (geologic map, SE% sec. 8, T. 31 S., R. 15 W.) where a prominent high-angle fault is overlain by a thrust fault and klippe. The high-angle fault strikes northwest, and has a nearly vertical dip. Some of the other high-angle faults of the area which neither cut nor are cut by thrust faults may belong to this period of faulting.

Although this fault was formed prior to the thrusting, there is no direct evidence to indicate whether it was formed before or after the folding. At least it probably was formed after the post-Paleozoic—pre-Cretaceous deformation, because no faults of that deformation have been identified in the vicinity, and because the northwest trend is characteristic of the later orogeny. Moreover, a restoration of the fault to its original attitude prior to the general eastward tilting of this part of the range shows that it was a reverse fault, which is in harmony with the compressive nature of this orogeny. If the tilting was related to the folding, then the fault would be older, but it may be related instead to the later Basin and Range faulting.

The fact that the fault surface itself shows no major folding is insufficient evidence to presume that the fault was later. In the first place, the traceable length of the fault is too short to preclude the possibility that it is folded where covered by the thrust sheet. In the second place, these massive limestones of the Horquilla are seldom folded. Perhaps the minor warpings of the fault surface indicate that it was formed prior to the folding, but these could also be attributed to initial irregularities (structure section *H-1?).*

Folds

Although folding may have begun before, during, or after the period of early high-angle faulting, folding certainly was in progress before compressional faulting when reverse, thrust, and overthrust faults were formed. Such compressional faults cut the folds and they show no significant signs of later folding, so thrusting probably followed closely after the formation of the folds. In fact, the same compressive stresses which were responsible for the folding probably continued to form the thrusts. Furthermore, the growth of the folds apparently was ended when the elastic limit was exceeded and they were broken by thrusts. The nature of the lithologic succession, with alternating competent and incompetent units, was an important factor in determining such a limit. The thick competent Horquilla Limestone is overlain with a series of thinner-bedded, less competent formations, and the gypsum of the Epitaph Dolomite may well have served an important role as a plastic lubricating medium which facilitated folding and subsequent thrusting.

Thus, folds probably developed to a particular critical stage at which time folding ceased as thrusting took over. Most probably, folds of different areas reached the critical stage at different times, so that while folding was still in progress in one place, thrusting may have commenced in another. Evidence for this relationship between folding and compressional faulting is seen in the southwestern part of the Big Hatchet Mountains where an anticline was broken by a system of imbricate thrust faults (structure sections *G-G', H-H' , I-I', J-J',* and *K-K').*[5] This relationship may also be seen in the U-Bar Ridge syncline where the northeast flank was overturned by apparently the same compressive stresses which later caused a thrust sheet to override that limb (structure section *L-L').* The Bighorn Canyon fault, which is primarily a thrust fault, cuts rocks which were folded before thrusting. Overthrust faults in the northwestern part of the Sierra Rica cut a homoclinal section of rocks, but here the genetic relationship between the faults and folding is not as clear as in the Big Hatchet Mountains.

The folds in this quadrangle are long, broad, and mostly open with dips averaging between 20 and 30 degrees. The fold axes trend northwest-southeast, and the general direction of plunge is toward the southeast. Later faulting has obscured details of the folds so that their reconstruction is difficult. Folds closely associated with thrust faults are locally overturned, as the U-Bar Ridge syncline and the anticline northwest of and on strike with the northwestern limit of the imbricate thrust zone. The general nature of the folds may be seen in the geologic structure sections.

The most outstanding fold of the quadrangle, U-Bar Ridge syncline, is named for U-Bar Ridge. It owes its unique horseshoe shape to the superior erosional resistance of the massive reef limestone near the top of the U-Bar Formation which was folded with the syncline. The western limb dips about 45 degrees and the dip of its northeastern limb progressively increases southeastward from the prow (or northwesternmost part) of the ridge until it becomes vertical and finally overturned. The reef limestone reaches its maximum thickness of about 500 ft at the prow of the ridge, and this point is also at the highest elevation of the ridge. Southeastward the reef progressively diminishes in thickness to about 100 ft, and the ridge becomes ever lower to the point where it is covered by alluvium. Southwest of the U-Bar Ridge syncline (beyond the limits of the quadrangle) is a complementary anticline which may also be traced through exposures of the same reef limestone (reconnaissance geologic map of Dog Mountains quadrangle, Zeller, 1958, upon which the formation is shown as "Lower Cretaceous Limestone"). The axis of this anticline also trends southeastward, but the axial area of the structure is broad, flattened, and undulating. It was upon the northeastern flank of this structure that Humble Oil & Refining Company drilled a deep well (Zeller, 1965, p. 116-119).[6]

Rocks in the southern end of the Big Hatchet Mountains generally dip southwestward and probably represent the limb of a very large syncline of which the smaller U-Bar Ridge syncline is the axial part (structure section *L-L').* In the southeasternmost part of the range, principally in sections 33 and 34, T. 31 S., R. 14 W., these southwestern dips become progressively less steep. Probably an anticlinal axis lies a short distance toward the northeast under cover of valley fill. This inferred anticline is broken by a hypothetical Basin and Range fault, as shown at the east end of structure section *L-L'.*

Near the center of the Big Hatchet Mountains, a syn- ⑤ clinal basin elongated in a northwest direction extends from the vicinity of Sheridan Wells on the southeast to possibly as far northwestward as the area east of Big Hatchet Peak. This fold is so broken by faults that it is difficult to trace or reconstruct. As discussed previously, there is an anticline along the southwestern edge of the range which has been greatly deformed by the system of imbricate thrust faults and high-angle faults. At the northern end of the range the rocks are folded into a rather sharp anticline which is also severely fractured by later faults. The axes of folds within the Big Hatchet Mountains are so indefinite that they are mapped for only short distances, but where determinable they are seen to trend northwestward.

In the Sierra Rica the rocks dip southwestward in a homocline, except for those in the overthrust sheets exposed on the northwestern part of the sierra and those involved in small local structures. This area apparently represents the southwestern limb of a large anticline which has its northeastern limb in the Apache Hills. The northern and northeasterly dips of the Paleozoic rocks of the overthrust sheets indicate that folds are present under Hachita Valley from whence they evidently were thrusted. hypothetical interpretation of such folds is shown on geologic structure sections *B-B'* and *C-C'.*[7] Beneath the valley fill, the folding ⑦ may be much more complicated by faulting than is shown. Also the overthrusts may have moved greater or lesser distances. Thus the reader is cautioned not to attach undue weight to this simplified interpretation.

Field studies in the quadrangle and in neighboring areas lead to the impression that the Paleozoic rocks yielded to stresses more readily through large-scale faulting and large-scale relatively mild folding than through small-scale more intense folding, and that the Cretaceous rocks yielded to similar stresses more commonly through small-scale tighter folding. This impression is supported by the evidence of the large faulted folds in the Paleozoic exposures in the Big Hatchet Mountains in contrast to the smaller, tighter, little-faulted folds in the Cretaceous exposures south and southwest of the Big Hatchet Mountains. In the Little Hatchet Mountains (and elsewhere in the vicinity) folds seem to be more dominant than large faults in the Cretaceous rocks. If indeed this impression is valid, it might be explained by the greater competence of the massive carbonate formations of the Paleozoic section which would be expected to fracture more readily than to fold. The Lower Cretaceous section is composed of thin beds, including a fair amount of shale, and would therefore ⑥ be less competent and more readily folded than faulted.

Dikes and Sills

Dikes and sills of latite porphyry are numerous in the Sierra Rica where they have been intruded into Cretaceous rocks. They are assignable to the orogeny which deformed Lower Cretaceous rocks but not Tertiary rocks, a fact which is adequately demonstrated by the gently-dipping remnant ⑧→ of a Tertiary andesite flow[8] which lies with angular unconformity upon steeply dipping Mojado Formation with sills of the latite porphyry on the peak in NW 1/4 NW 1/4 sec. 3, T. 30 S., R. 14 W. The largest latite porphyry sill, which trends diagonally across the northeastern corner of the Big Hatchet Peak quadrangle, is bounded along sections of its northeastern side by a reverse and thrust fault. Evidently the fault occurred after intrusion of the sill (structure section *B-B')*. Lack of latite porphyry within the overthrust sheets in the northwestern part of the Sierra Rica is due to the fact that the overthrust sheets originated in a distant area where no such intrusions occurred. The latite porphyry is thought to be closely related to monzonite and quartz monzonite intrusive masses and to mineralization in the Sierra Rica, the Apache Hills, and the Little Hatchet Mountains. By the same token, the weak mineralization found in the Big Hatchet Mountains is probably related to this period of igneous activity.

In the Big Hatchet Mountains a very few thin hypabyssal bodies of basic composition were noted. One body was found in the El Paso Formation of the Mescal Canyon section, a system of lit-par-lit sills was found at the top of the Percha Shale in two places, one body was noted in the lower part of the Horquilla Limestone in the Bugle Ridge section, one was found several hundred feet above the base of the U-Bar Ridge section, and another was found within about 300 ft of the top of the same section. All these dikes and sills are too small in outcrop area to be mapped, and the fact that they were found only in studied stratigraphic sections is an indication of how inconspicous they are. These basic hypabyssal bodies may have originated during the same igneous phase.

Reverse, Thrust, and Overthrust Faults

As used in this report the following distinctions are made between the faults in which the hanging wall apparently moved upwards with respect to the footwall, and which evidently are due to compressive stresses: reverse faults have a present dip greater than 45 degrees; thrust faults have a present dip less than 45 degrees; and overthrust faults are those thrust faults which have had demonstrable movements ⑨→ of the order of miles.[9] In the quadrangle reverse and thrust faults are found in the Big Hatchet Mountains which have predominantly easterly dips, and reverse, thrust, and overthrust faults having southwesterly dips are found in the Sierra Rica. Because of differences in the faults of the two areas, they are treated under different headings.

Reverse and Thrust Faults in the Big Hatchet Mountains

⑩→ In the Big Hatchet Mountains thrust and reverse faults are restricted to the southwestern part of the range. The fault surfaces are highly irregular due to original distortion, and although low-attitude thrusts are the most common, these same thrusts locally steepen into reverse faults. The average strike of the faults is northwest and their general dip is about 20 degrees toward the northeast. Drag folds and the overturning of anticlines and synclines indicate that thrusting was toward the west to southwest. Several of the more important thrusts are described below.

Imbricate thrust system — The most outstanding area of thrusting is on the southwestern slopes of the range centered about sec. 21, T. 31 S., R. *15* W., where four thin thrust plates are piled upon one another forming a classic example of imbricate thrust structure (structure sections *G-G' , H-11' , I-I', J-J' , K-K')*. Beds in the basal part of the largest thrust sheet are overturned southwestward, and drag folds in the beds immediately below the fault surface are also overturned in a southwestward direction. Hence, the evidence is clear that movement of the thrust sheets was in a general southwestward direction with respect to the footwall blocks. The lower thrusts are the oldest, and they are each cut by progressively higher ones. To the northwest the highest and youngest thrust of the series extends nearly two miles beyond the point where it cuts the older thrusts, and its trace is lost under alluvium in a narrow canyon (NW 1/4 sec. 7, T. 31 S., R. 15 W.). On the northwest side of this narrow canyon, along strike with the thrust, there is an anticline sharply overturned toward the southwest. On the southeast end of the area of imbricate structure two thrusts which have cut the others trail off and finally die out along the flank of an anticline (sec. 28, T. 31 S., R. 15 W.). The total length of this imbricate thrust system is about 5 3/4 miles.

This thrust system is of local extent and the movements on the thrusts were relatively small. Evidently compressive forces acting in a northeast-southwest direction formed a large anticline which broke high on its southwest limb, and the continuation of the same forces caused the thrust system to form. The breaking of the anticline to form the thrusts was facilitated by the massiveness of the thick Horquilla Limestone and the weakness of younger formations which acted as gliding lubricants. The oldest fault of the system apparently initially fractured the gypsum beds of the Epitaph Dolomite, and in moving forward the underlying gypsum was squeezed into a thick, highly contorted mass. Higher thrusts of the system probably likewise cut through the same gypsum beds, but erosion has removed traces of any such beds associated with the higher faults. The exposed portions of the higher faults show they have overridden the Earp Formation, which is also comparatively weak. Thus, it seems that the response of this area to thrusting instead of continued folding was largely due to the tendency for the competent Horquilla Limestone to override the incompetent beds of younger formations. Probably the absence of this set of conditions at the north end of the Big Hatchet Mountains, in the Little Hatchet Mountains, and in certain other nearby areas explains the absence of thrusting in those areas.[10]

In the case of one of the thrusts, the trace of its fault surface may be followed along a cliff face to a point where it merges with a bedding-plane joint and beyond which point it cannot be distinguished from the bedding surface. The great displacement of the fault probably does not decrease abruptly at this point, so beyond it continues as a bedding-plane thrust. There is no fault gouge or breccia or deformation of beds above or below the bedding-plane fault, and it truly has a "knife blade" contact.[11]

Bighorn Canyon thrust — Other thrust faults in the southwestern part of the range also had displacements of the same order of magnitude and probably were formed through conditions similar to those of the imbricate thrust system. Of these, the one which is here called the Bighorn Canyon thrust, is the most remarkable. The trace of this fault extends the length of Bighorn Canyon, passes northwestward over the mountain into Mine Canyon, passes (near the mouth of Mine Canyon) northeastward over a ridge into South Sheridan Canyon, where it turns northwestward to follow the south side of this canyon, and finally is lost near Sheridan Canyon where Horquilla Limestone lies on both sides (NE% sec. 27, T. 31 S., R. 15 W.).

The sinuous map pattern of the structure was worked out accurately. The southern part is a tear fault with left-lateral movement. Farther north the fault becomes a thrust with a very irregular fault surface. The most outstanding irregularity is on the ridge northwest of the mouth of Mine Canyon where the fault changes attitude from gently dipping to vertical over a horizontal distance of about 100 ft. Marker beds in the hanging wall and footwall were traced carefully to eliminate the possibility that the vertical portion was a later high-angle fault which offset the thrust."

The hanging-wall block may have moved northwestward about 1 1/2 miles as suggested by the offset of formational contacts. In Bighorn Canyon the fault is a high-angle tear, and northward it becomes a thrust where it overrode the soft Earp Formation. North of the mouth of Mine Canyon the attitude of the fault becomes vertical, which was probably due to the hanging-wall block encountering the massive thick Horquilla Limestone as it traveled forward. Evidently the original irregularities of this fault surface were controlled to a great extent by the relative competence of the beds over which it rode.

In order for the fault surface to have become vertical and for the hanging-wall block to have been lifted vertically at this point rather than to have cut through the competent Horquilla Limestone, the confining pressure of overlying formations must not have been great. This observation tends to indicate that the thrust occurred near the surface and that the overlying rocks were not thick.

The southern part of the Bighorn Canyon fault cuts an earlier thrust. The latter probably had a similar history, but its more easterly dip indicates movement to the west-northwest. It has thrust Concha Limestone upon Epitaph Dolomite and is shown on structure section *L-L'*.

Thrust and reverse faults at Horquilla-Earp contact - In this southwestern part of the range, minor thrust and reverse faults are found on many of the contacts between the Horquilla Limestone and the Earp Formation. In these cases, the competent Horquilla has been thrust over the incompetent Earp. The South Sheridan Canyon fault is a high-angle reverse fault which lies along the northeast side of South Sheridan Canyon and extends northwestward to form the northeast side of the Sheridan Wells topographic basin. In places, as in the area northeast of Hale Tank, it fails to follow the formational contact and passes through ←⑪ Horquilla Limestone. The maximum stratigraphic throw of the fault is about 1000 ft where most of the Earp Formation has been cut out (structure section *L-L')*.

Another such fault bounds the northwest side of the Sheridan Wells basin. Its northeastern part is poorly exposed, but it apparently has a high dip. Near Sheridan Mine the fault surface is nearly horizontal, and farther northwest it dips gently to the northeast. Its trace cannot be followed beyond the point where Horquilla Limestone lies on both sides. The northeastern end of the fault apparently terminates against the South Sheridan Canyon fault. This part of the fault, which bounds the northwestern side of Sheridan Wells basin, is unusual in that its dip is toward the northwest and north (structure section *J-J')* in contrast to the northeasterly dips of other thrusts in the area. However, this anomalous direction of dip is confined to a small area where there was little movement. Study of the map relationships between the Horquilla in the hanging wall and the Earp in the footwall show the thrust portion of the fault need not have moved more than 1/8 mile. The apparently anomalous dip direction may be due to the tendency for the competent Horquilla to override the incompetent Earp toward the southeast in the Sheridan Wells basin, or it may be a result of only a local irregularity of the fault surface. ←⑫

Thrust fault northeast of U-Bar Ridge — At the southwestern base of the Big Hatchet mountain mass (in the hills which lie northeast of U-Bar Ridge) Concha Limestone is thrust over the Hell-to-finish Formation (structure section *L-L')*. The stratigraphic throw is only about 2000 ft, so the movement of the thrust probably is relatively small. Its northwest and southeast ends are truncated by later high-angle faults. When the northeastern limb of the U-Bar Ridge syncline was overturned, the fold evidently fractured and the thrust sheet rode southwestward over the limb of the fold. Massive competent limestones of the Concha were thrust over incompetent shale and thin sandstone beds of the Hellto-finish Formation. The relationship of this thrust fault to the overturned fold indicates the fold formed first and probably ceased development when the thrust ruptured it and absorbed the continued stresses. Beds in the base of the thrust sheet exposed in SW% sec. 3, T. 32 S., R. 15 W., were overturned through more than 360 degrees." ←⑬

Reverse, Thrust, and Overthrust Faults in the Sierra Rica

In the Sierra Rica, reverse, thrust, and overthrust faults dip southwestward in contrast to the easterly dips of the reverse and thrust faults in the Big Hatchet Mountains. For the purposes of discussion the faults are divided into two groups — reverse and thrust faults, and overthrust faults.

Reverse and thrust faults — Two faults of these types are found in the northeastern corner of the quadrangle. The northeasternmost fault lies completely within the U-Bar Formation and evidently has small displacement. The other fault has a greater displacement and probably extends beyond both the northern and eastern boundaries of the quadrangle, though its southeastern end is concealed where it would project beyond the quadrangle boundary into Mexico. The strike of the fault parallels that of the bedding, and its southwestern dip is steep enough along the northwestern part for the fault to be classed as a reverse fault, and gentle enough along the southeastern part for the fault to be classed as a thrust fault. Along most of the northwestern part, where the fault has placed the U-Bar Formation upon the Mojado Formation, the trace is easily mapped (geologic map and structure section *B-B')*. A prominent sill of latite porphyry lies immediately behind the leading edge of the upper plate. Although the sill appears to parallel the fault over nearly all of its length, in places the fault presumably cuts the sill. About a mile within the eastern boundary of the quadrangle, this thrust fault cuts a dike of latite porphyry (probably intruded along an earlier high-angle fault). Southeast of this intersection the contact of the thrust fault is somewhat indefinite because the Mojado Formation is cut out and U-Bar Formation lies on both sides. However, the fault is known to continue because these U-Bar beds are duplicated as they are to the northwest. Although the exact position of the fault becomes questionable, its trace is extended along strike to follow the northeastern side of the latite porphyry sill.

In the northwestern foothills of the Sierra Rica in NW 1/4 sec. 32, T. 29 S., R. 14 W., a reverse fault lies in the hanging wall block of the Sierra Rica overthrust fault. The reverse fault strikes west-northwest, dips steeply southwestward, and has placed the lower Paleozoic rocks of its southern block upon the upper Paleozoic rocks of its northern block (structure section *A-A')*. The fault passes northwestward into the Hachita quadrangle, and southeastward it is cut off by the Sierra Rica overthrust fault.

Overthrust faults — The westernmost tiny hill of the Sierra Rica in NW 1/4 sec. 31, T. 29 S., R. 14 W., consists of El Paso Formation which is separated from its sister hill of Horquilla Limestone to the east by an overthrust fault that apparently has a low dip to the southwest (gentleness and direction of dip is inferred from the curved trace on the map). This fault is judged to be an overthrust because its stratigraphic throw is about 3000 ft, and because it is parallel and near to the Sierra Rica overthrust. ⑭ It is shown in section *A-A'*, and its hypothetical trace under Hachita Valley is shown on sections *B-B'* and *C-C'*.

The most prominent overthrust fault of the quadrangle lies along the southwestern side of the Sierra Rica and is here named the Sierra Rica overthrust fault. Within the limits of the quadrangle it has placed El Paso Formation, Montoya Dolomite, Escabrosa Limestone, Paradise Formation, and Horquilla Limestone upon Mojado Formation. The maximum stratigraphic throw is about 18,000 ft. This overthrust may be traced for over four miles in the Big Hatchet Peak quadrangle and for about three miles into the Hachita quadrangle to the north. The extremities and much of the fault trace are concealed by alluvium. The strike of the fault generally is northwest, but major and minor irregularities of the original fault surface produce variations of strike, which in combination with topography produce a sinuous map pattern. The fault has a low dip toward the southwest, but the irregularities of the fault surface produce frequent variation in angle and direction of dip. There is no doubt that the movement of the fault was of the order of several miles so it is properly classed as an overthrust (structure sections *A-A'*, *B-B'*, and *C-C')*.

The Sierra Rica overthrust fault passes northwestward into the Hachita quadrangle and is buried under alluvium, but it reappears to the northeast as a klippe on Doyle Peak hi secs. 21 and 22, T. 29 S., R. 14 W. The overthrust sheet (on the upper half of the peak) consists of low-dipping Horquilla Limestone, and the footwall block consists of steeply dipping Mojado Formation. The fault has an easterly dip on Doyle Peak, which is shown on structure section *C-C'*. In the northern part of the Big Hatchet Peak quadrangle three similar but smaller klippen are found, one of Horquilla Limestone, one of El Paso Formation, and the other of both Horquilla Limestone and El Paso Formation separated by an earlier fault. These klippen also rest upon steeply dipping Mojado Formation.

The fault may be traced southeastward beneath the pediment on the southwest side of the Sierra Rica and through a series of isolated exposures of Paleozoic rocks lying in contact with the Mojado Formation. The Paleozoic rocks west of the fault are mostly concealed by Tertiary volcanic rocks. A small exposure of Mojado Formation in NW% sec. 15, T. 30 S., R. 14 W., probably represents a fenster. On the other hand, the Tertiary rocks may conceal more complex faulting between this exposure and those of the Paleozoic rocks.

In the southern part of the range, both the strike of the overthrust and the strike of the adjacent Mojado Formation change from southeast to south. This parallelism suggests that the fault may have been involved in later folding which also affected the Mojado Formation. Such folding need not have been strong and may have occurred during Tertiary time. In this southern area an east-west high-angle fault has offset the U-Bar—Mojado contact, and although the fault cannot be traced to the overthrust, its displacement is great enough that the fault probably extends that far. Since the trace of the overthrust is not offset, this high-angle fault must be cut by the overthrust and therefore must be older.[14]

The direction of movement of the Sierra Rica overthrust is thought to have been toward the northeast, as is shown in structure sections *A-A'*, *B-B'*, and *C-C*. This belief is based on the fact that the present general dip of the fault is toward the southwest, but this evidence is not conclusive because of the great initial irregularities of the fault surface (its eastern dip on Doyle Peak), and because of the possibility that post-overthrust tilting of the area may have reversed the direction of the original general dip. Overthrust faults elsewhere in the region, such as in the northern Animas Mountains (Zeller, 1958b), commonly dip westward or southwestward. This fact tends to support a general westward or southwestward dip for the overthrusts of the region and thus a probable thrusting from that quarter. No overturned folds or drag folds associated with the Sierra Rica overthrust fault were recognized to aid in establishing its direction of movement. Assuming that the present southwestern dip of the overthrust continues under Hachita Valley, the displacement of the fault is probably too great for it to disappear before reaching the Big Hatchet Mountains. Therefore the fault must either pass beneath the Big Hatchet Mountains or must steepen and disappear under Hachita Valley. The probable southwestern direction of dip and movement of this overthrust is opposed to the easterly directions of dip and movement of the reverse and thrust faults in the Big Hatchet Mountains.

In the northwestern part of the Sierra Rica in NW% sec. 32, T. 29 S., R. 14 W., granite is exposed over an area of only a few hundred square feet in an arroyo. It is designated as Precambrian because of its similarity to the Precambrian granite of the Hatchet Gap area and its lack of similarity with younger granites exposed in the region. The exposure appears to be a fenster in the Sierra Rica overthrust sheet, but it may either represent a horse, or a small exposure of an underlying overthrust sheet which is generally covered by the Sierra Rica overthrust sheet. If the granite is part of an underlying overthrust sheet, the stratigraphic throw of the concealed overthrust fault is greater than 18,000 ft. This latter hypothesis was assumed in the construction of structure sections *A-A'* , *B-B'* , and C-C'.

Post-Thrust High-Angle Faults

In the Big Hatchet Mountains the Hell-to-get-to Tank fault, which is named for the earth stock tank (NE% sec. 21, T. 31 S., R. 15 W.) through which it passes, is a northwest-trending high-angle fault which cuts at least two thrust faults near the tank (geologic map and structure sections *H-H'* , , , and *K-K').* Its trace has several large bends. Its dip, as estimated from the fault's trace upon the topography, varies a few degrees to either side of vertical. The maximum stratigraphic throw is about 2000 ft. Southeast of the tank the fault is dashed through an area of Horquilla Limestone on inconclusive evidence and is joined with a high-angle fault. The latter traverses South Sheridan Canyon, and lies on strike with and has similar movement to the Hell-to-get-to Tank fault. This southeastern end of the fault terminates against the South Sheridan Canyon reverse fault.

If indeed the northwestern and southeastern parts are truly a single Hell-to-get-to Tank fault, a sequence of structures may be deduced. The northwestern portion cuts a thrust which in turn cuts a high-angle fault near the head of Thompson Canyon. Thus a pre- and a post-thrust period of high-angle faulting are evident. The southeastern portion which terminates against the South Sheridan Canyon fault suggests that there are two post-thrust periods of high-angle faulting. However, all three periods of high-angle faulting and the thrusting may have been formed during the same general orogeny which deformed Lower Cretaceous rocks but not Tertiary rocks.

Besides the pre- and post-thrust periods of high-angle faulting, two later periods of high-angle faulting, and the whole period of Basin and Range faulting are indicated. Most of the high-angle faults in the Big Hatchet Mountains cannot be dated precisely and may belong to any of the systems of high-angle faults. Problems in dating occur because all of these faults have similar attitudes, because many are not cut by later datable faults, and because no mappable Tertiary rocks are preserved in the range to aid in dating faults.

However, some high-angle faults formed before Tertiary deposition can be distinguished provisionally from those which formed after the start of Tertiary deposition based on the order of magnitude of fault displacement as estimated from the stratigraphic throw. The prominent northwest-trending, high-angle faults of the Big Hatchet Mountains have displacements of the order of thousands of feet, and those which cut Tertiary rocks in the Alamo Hueco Mountains to the south (Zeller, 1958c) have displacements that seldom exceed several hundreds of feet. This observation leads to the hypothesis that the faults of large displacements which are confined to exposures of pre-Tertiary rocks probably formed prior to Tertiary deposition. Accordingly, high-angle faults in the Big Hatchet Mountains of large displacements are assumed to have formed during the period of strong orogeny which preceded Tertiary deposition, but similar faults of small displacement may have developed either before or after this orogeny. It should be understood that dating faults by the magnitude of their displacements is not conclusive, and was used only as a guide in this work.

Some of the high-angle faults in the quadrangle may have had early origins and subsequent rejuvenated movements during later periods of deformation. Though this hypothesis is not strongly supported by any good evidence, it is suggested by the parallelism of attitudes of the high-angle faults of different systems, and by the fact that those in older rocks frequently have greater displacements than those in Tertiary rocks. This last fact probably is largely a result of the stronger deformation which affected the older rocks, but it could be due in part to a series of movements along the faults. The cumulative effects of all movements would be reflected in the faults exposed in older rocks, and only the latest movements would be reflected in the faults displacing younger rocks. In either case, high-angle faults of large displacement in the Big Hatchet Mountains can be assigned to the earlier orogeny even though they may have had later recurrent movements.

Though some high-angle faults in the range may have formed during Tertiary deformation, there is sufficient evidence to disprove any possibility that they belong to the system of late normal faults of the Basin and Range type. The high-angle faults strike northwest and have dips ranging from about 80 degrees to vertical, whereas the normal faults have a more northerly strike, ranging from north-northwest to north, and have dips ranging from 45 degrees to about 70 degrees. No intersections of normal and high-angle faults are exposed, but indirect evidence shows that the normal faults cut at least one of the high-angle faults. The high-angle fault along the northeastern side of Chaney Canyon called the Chaney Canyon fault, if projected northwestward under alluvium, would intersect the projected extension of the north-striking normal fault exposed in sec. 24 and 25, T. 30

S., R. 16 W. The north-south trend of the mountain front in this area is probably the result of a parallel normal fault which is buried under alluvium, and its strike would contrast sharply with the northwest strike of the Chaney Canyon fault. The fact that this trend of the mountain front extends without offset both to the north and to the south of the projected intersection of the two faults indicates that the Chaney Canyon fault is cut by the normal fault.

Three of the high-angle faults which are assigned to the post-thrust period of faulting (because of their parallelism with the Hell-to-get-to Tank fault and their large stratigraphic throws) are of particular interest and are described separately. They are 1) the Chaney Canyon fault, 2) the North Hatchet fault, which is so named because it lies on the northernmost peak of the Big Hatchet Mountain mass, and 3) the Hatchet Gap fault, which lies on the north side of the first hill south of the highway in Hatchet Gap.

Chaney Canyon Fault

The Chaney Canyon fault strikes northwest and has a near-vertical dip. Its northwestern end is lost under alluvium, and its southeastern end is lost where Horquilla Limestone is found on both sides. It can be traced with certainty for only
⑮ two miles.

This fault is unusual in that its apparent movement was great on one end and small on the other. The strati-graphic throw of the fault at its northern end where Precambrian granite rests against middle Horquilla Limestone is about 4500 ft. Southeastward along the fault progressively younger formations lie adjacent to the fault in the southwest block whereas the Horquilla Limestone lies along the entire length of the fault in the northeast block. The southeastern part of the fault lies within the Horquilla Limestone and was mapped by the use of fusulinid zones. The southeastern end of the fault is lost where its stratigraphic throw decreases nearly to zero and the fusulinid zones on both sides are the same. Thus, the stratigraphic throw diminishes from 4500 ft to practically zero over a distance of two miles.

Explanation of the mechanics of movement of the fault is made difficult by the lack of drag folds and mullion structure. However, three types of movement along the fault are considered as possibilities: pivotal, hinge, and strike-slip.

The possibility of pivotal movement depends upon the possibility that the Chaney Canyon and South Sheridan Canyon faults are coextensive. At least they are on strike with each other. If they do join, the opposite directions of displacement would constitute a pivotal movement. The southwest side of the Chaney Canyon fault moved relatively upwards whereas the southwest side of the South Sheridan Canyon fault moved relatively downwards. These two faults were not joined by tracing across the Thompson Canyon area because the Horquilla Limestone is found on both sides, and tracing of the faults is nearly impossible. Also, across this
⑯ area the displacements would decrease to zero at the pivot
point, and would be increasingly difficult to map. On the other hand, following this hypothesis the stratigraphic throw of the fault would he expected to increase progressively away from the pivot point. This is not the case in the South Sheridan Canyon fault where the stratigraphic throw remains nearly constant and relatively small throughout most of its length. Therefore, this hypothesis of pivotal movement is considered to be the least acceptable of the three.

The second hypothesis, that the Chaney Canyon fault had hinge movement, is supported by the decrease in stratigraphic throw, to the southeast from 4500 ft to nearly zero. Though this explanation is possible, it seems incredible that a fault with such a large vertical displacement could disappear over a horizontal distance of only two miles.

The third hypothesis, that the movement of the fault was chiefly strike-slip, is more strongly supported by the evidence than the others and is the one which is favored. In the Chaney Canyon area, the strike of the lower Paleozoic formations on the southwest side of the fault is about 15 degrees more westerly than the strike of the Horquilla Limestone on the northeast side. This more westerly strike is the same as that found in the lower Paleozoic formations about 1 1/2 miles to the north. Therefore it seems likely that the lower Paleozoic formations of Chaney Canyon are the extensions of those in the area to the north, and that they have been offset by right-lateral movement of the fault of approximately 4 miles to the southeast.[15] Another supporting point is that the reefs of the Horquilla Limestone on the northeast side of the fault are much thinner than the corresponding reefs on the southwest side. Because the reefs are thicker toward the basin margin, the movement would appear to be right-lateral. Also in support of this hypothesis is the anomalous lithology of the Bliss Formation between Mescal Canyon (on the northeast side of the range) and Chaney Canyon. These exposures of the formation are less than 2 miles apart at present, but assuming 4 miles of right-lateral movement of the Chaney Canyon fault, they originally would have been separated by about 5 or 6 miles. Such greater original distance between them would aid in explaining their lithologic differences.

According to this hypothesis, the Chaney Canyon and South Sheridan faults should join in the Thompson Canyon area. The fact that they are not joined on the geologic map has already been explained, and should not detract from this idea. In South Sheridan Canyon, any lateral movement of the fault could not exceed one mile. However, the difference of right-lateral movement between that here and the four miles at the northwest end could be explained if the southwestern block here had been shortened by more intense folding and faulting than the northeastern block. Such shortening could have been produced by the convergence of thrust fault on the northwest side of Sheridan Wells basin and the Bighorn Canyon thrust. According to this hypothesis the thrusting and late high-angle faulting would be closely associated and would result from the same stresses. The folding of the structural basin in the Sheridan Wells area also tends to shorten the southwestern block.[16]

North Hatchet Fault

The North Hatchet fault traverses the northernmost peak of the Big Hatchet Mountain mass in SW 1/4 sec. 18, T. 30 S., R. 15 W. Its strike is about west-northwest, which is slightly west of the average strikes of large high-angle faults to the south. Its dip is within a few degrees of vertical, and the stratigraphic throw ranges from 500 ft, where middle or upper Escabrosa Limestone lies against upper Paradise Formation, to about 3300 ft where Bliss Formation lies against lower Horquilla Limestone. Its trace is very straight and is exposed for a distance of 2 1/4 miles (geologic map and structure section *D-D')*, and it cuts several earlier small faults. The fault lies about a half mile northeast of the axis of a large anticline which trends northwestward.

The horse [block caught between the walls of a fault] of Precambrian granite (at the northwestern end of the exposure of the fault) is an indication of lateral movement. Unidirectional vertical movement of the fault could not have brought the granite to its present position. The granite may have been emplaced by an earlier fault which was parallel to and very close to the North Hatchet fault, but such a coincidence is unlikely. Also unlikely would be great vertical movement of the fault in two different directions with the remnant of granite left behind after the first movement. However, a component of right-lateral movement, in which the northeastern block shifted southeastward with respect to the other block, would account for the Precambrian horse most satisfactorily. The westernmost formation exposed along the southwestern side of the fault is northeastward-dipping Montoya Dolomite; thus the Precambrian granite originally lay to the west. The Horquilla Limestone northeast of the fault dips northeastward and northwestward, and is thought to represent part of the northeastern limb of the large anticline whose axis lies a short distance south of the fault. This would require lateral movement of the fault of the the order of several miles. Such would be in concordance with the direction and magnitude of lateral movement which is thought to have occurred on the Chaney Canyon fault."

Hatchet Gap Fault

Only a few hundred feet of the Hatchet Gap fault is exposed low on the north side of the hill south of the highway in Hatchet Gap (NE% sec. 12, T. 30 S., R. 16W.) It strikes west-northwest (parallel to the North Hatchet fault) and judging from its straight trace on the hill, the dip is nearly vertical. Precambrian granite close to the contact with Bliss Formation lies on the northeast side of the fault, and Horquilla Limestone lies on the southwest side. The Horquilla Limestone adjacent to the fault has fusulinids which were identified by John W. Skinner and Garner L. Wilde as primitive forms of *Fusulinella* sp. of Derryan age, and it is rich in black chert. By comparison to the measured sections of Horquilla Limestone, these beds are seen to be about 600 ft above the base of the formation. Thus, the stratigraphic throw of the fault is approximately 4000 ft. In all characteristics this fault is comparable to the large northwest-trending high-angle faults of the Big Hatchet Mountains which formed prior to the start of Tertiary deposition.

The fault may have had a component of right-lateral movement as probably did the Chaney Canyon and North Hatchet faults, but there is no conclusive evidence of such movement. The pre-fault geology of the area to the northwest of the present exposures (from which rocks would have been carried by such movement) is too speculative to warrant a definite assertion that the section of Precambrian granite and overlying Bliss Formation was carried to its present position from the northwest. Though not conclusive, the anomalous lithology of the Bliss Formation in the Mesca Canyon area with respect to that of the formation in Hatche Gap favors lateral movement of the fault. The lithology of the Bliss Formation in the two areas 5 miles apart is so different that it is difficult to explain over such a short distance. Both the North Hatchet and the Hatchet Gap faults lie between the two exposures, and if right-lateral movement occurred on both faults, the present exposures would have originally been farther apart by roughly the sum of the lateral components of movement of each fault. With wider original separation of the Hatchet Gap and Mescal Canyon Sections, explanation of differing lithologies in the Bliss would be simplified, and the hypothesis of lateral movement on the faults would be supported.[18] ←⑱

Lasky (1947, p. 50-51) mapped the Hatchet Gap fault and interpreted it as either a thrust or a fault related to a thrust. His interpretations were based upon a steep dip to the south observed at one point along the fault and upon the belief that the fault had a stratigraphic throw of the order of 25,000 ft. The observed southerly dip is evidently of only local extent because of the straight trace of the fault upon the hill. The large magnitude of the stratigraphic throw was derived from the mistaken belief that the granite north of the fault is of Tertiary age instead of Precambrian age, and that the sandstone in Hatchet Gap is an unidentified sandstone of the Cretaceous section instead of the Bliss Formation.

←⑰

TERTIARY—RECENT DEFORMATION[19] ←⑲

The last period of deformation in the region started during Tertiary time, continued into Recent time, and is still somewhat active. Although this deformation is minor compared to that of the post-early Cretaceous—pre-Tertiary volcanic period, its effects upon the present topography are profound. It produced the uplift of the mountains and the depression of the valleys along normal faults commonly called Basin and Range faults. Besides the normal faults, it has produced broad open folds, two systems of high-angle faults, and minor thrust faults.

Two lines of evidence indicate that this period of deformation started during the deposition of the Tertiary volcanic rocks. In the Alamo Hueco and Animas Mountains several angular unconformities are found within the volcanic rocks. Some of these unconformities are of only local extent and are due to deposition of tuffs upon irregular erosional surfaces. However, two of the unconformities are widespread. The most notable one occurs at the base of andesite flows thought to be of late Tertiary age.[20] ←⑳ The flows were deposited upon a very irregular surface, but the gross difference of attitude between the older volcanic rocks and the andesite cannot be entirely explained by irregularities of the pre-andesite surface.

Another bit of evidence is the presence of well-rounded boulders of Paleozoic limestone in conglomerates ㉑ → interbedded with the Tertiary volcanic rocks.[21] The high concentration of these boulders in the conglomerate beds (and their lack of metamorphism) rules out the possibility that they were brought to the surface by volcanic eruptions. The conglomerates are found several thousand feet above ㉓ → the base of the Tertiary volcanic succession. Therefore, the area from which they were derived could not have been a residual high from the earlier period of deformation, for such a high area would have been mantled with the thick pile of volcanic rocks and would thus produce only volcanic ㉒ → detritus.[22] The source areas of the limestone were ancestral mountains which were uplifted during the early stages of deposition of the volcanic rocks.

Folds

Deformation during the post-early Cretaceous—pre-Tertiary volcanic period was so intense that the effects of later low intensity folding are not noted in the older rocks. However, in areas where Tertiary rocks are found, the effects of the later folding may be seen. Folds are common in the Tertiary volcanic ranges of the region, such as the Alamo Hueco, Animas, and Peloncillo Mountains. But within the Big Hatchet Peak quadrangle, they are found only in the two small areas of Tertiary rocks: along the southern border, and on the southwest side of the Sierra Rica.

Except where beds are locally steepened near faults, the dips of beds in these folds average 10 degrees or less. The folds are long and broad and strike generally north. In the high elevations of some of the ranges, older Tertiary formations are exposed at the edges of the ranges and younger Tertiary formations are exposed near the crests. The resulting pattern on geologic maps of the area gives a false illusion that the mountains are synclinal.

In the hills northwest of Mengus Camp (sec. 26, T. 32 S., R. 14 W.) the Tertiary rocks are folded into a broad low anticline which plunges southeastward. Along the southern border of the quadrangle, the Little Hat Top Fanglomerate dips gently southward under the Tertiary volcanic rocks of the Alamo Hueco Mountains.

High-Angle Faults

Two systems of high-angle faults are found in the Tertiary rocks of nearby ranges. The predominant faults belong to a system in which the faults strike northwest and north-northwest. Some of these parallel the high-angle faults of the post-early Cretaceous—pre-Tertiary volcanic period of deformation, and some of the high-angle faults of the Big Hatchet Mountains may belong to this later system. This system is very well developed in the Alamo Hueco Mountains.

The other system is characterized by west-striking high-angle faults of generally large displacements. Such faults are seen in the Animas and Peloncillo Mountains, but none belonging to this system are found in the Big Hatchet Peak quadrangle.

Thrust Faults

Within the Tertiary volcanic rocks of the Alamo Hueco and Animas Mountains, the writer has found low-angle thrust faults having movements of from several hundred feet to about one mile." These cut the northwest-trending high-angle faults. No such thrusts were found in the Big Hatchet Peak quadrangle.

Normal Faults

Throughout this region, physiographic evidence shows that the mountain ranges are flanked by normal faults which were responsible for the uplift of the mountains with respect to the valleys. In the Big Hatchet Mountains, direct observation as well as physiographic evidence support this contention.

On some spurs along the northeast and west flanks of the range, such normal faults are found. Their strikes vary from north to nearly northwest, but in general the strikes are more northerly than those of the earlier high-angle faults. Their dips range from 45 degrees to about 70 degrees. On the east side of the range the faults dip eastward, and on the west side they dip westward, so the total effect of movement of the faults uplifted the mountain mass with respect to the valleys.

The normal fault a half mile south of the mouth of Chaney Canyon (sec. 36, T. 30 S., R. 16 W.) is curiously exposed so that the hanging wall is nearly eroded away. Movement was very small, perhaps on the order of 100 yards, and the fault surface is concave upwards.

Although some of the normal faults are exposed, the largest ones are concealed by the alluvial fans. In order to explain some gross irregularities of the borders of the mountain, the presence of intersecting scallop-shaped normal faults along each side of the range are postulated. This hypothesis is strengthened by the concave surface noted on the normal fault south of the mouth of Chaney Canyon, and it is further supported by data (unfortunately confidential) from magnetometer surveys in the area.

Late normal faults are not seen in the Sierra Rica. A broad pediment lies off the southwest side; it indicates that this area has been stable for a long period of time. In Mormon Well (SW^{1}% sec. 1, T. 31 S., R. 14 W. in the center of Hachita Valley) bedrock was encountered at 454 ft, a fact which shows the pediment surface extends to the present center of the valley. Also, the exposure of Escabrosa Limestone near the Hatchet Ranch shows that the alluvial cover is shallow. Therefore, if any normal faults exist on the west side of the Sierra Rica, they must be west of the present center of the valley.

Uplift of the Big Hatchet Mountain Block

The Big Hatchet Mountains lie near the middle of a long north-northwest trending range which can be traced for about 80 miles. From north to south it includes some low hills south of Separ, New Mexico, the Brockman Hills, the Coyote Hills, the Little Hatchet Mountains, the Big Hatchet Mountains, the Alamo Hueco Mountains, the Dog Mountains, and a group of unnamed hills northeast of Janos, Chihuahua. This entire range has been uplifted with respect to the valleys by late normal faults. The northern and southern parts of the range have been uplifted only slightly. The center part, which includes the north end of the Big Hatchet Mountains and south end of the Little Hatchet Mountains, has been uplifted greatly. Thus the range has been arched upward along its length. The amount of uplift is proportional to the depth of erosion of the stratigraphic succession, so progressively older rocks are exposed toward the center of the range where Precambrian granite crops out.

As the Big Hatchet Mountain block rose with respect to the valleys, the block was tilted toward the east, as indicated by physiographic evidence. The west side of the mountain is very steep and has up to 4000 ft of relief. The alluvial fans on the west side have steep slopes and have been rejuvenated, suggesting recent movement of the normal faults. Therefore, the west side of the range probably has moved upward a great distance in relatively recent time. However, the east side probably has not risen as much, judging by the lower relief and the normal alluvial fans of lower gradients on this side of the range. Thus, as the west side moved higher than the east side, the block was tilted eastward.

Physiographic evidence also shows that Playas Valley tilted eastward as it sank with respect to the Big Hatchet Mountain block. Downward movement of the west side of the valley adjacent to the Animas Mountains was small as is indicated by normal alluvial fans and bedrock exposures several miles east of the mountain front. However, the east side of the valley adjacent to the Big Hatchet Mountains moved downward as the mountain block moved upward. This is shown by the unusually small alluvial fans on the west side of the Big Hatchet Mountains. One would normally expect great alluvial fans to have developed along the mountain front as a result of the high uplift, but apparently depression of the east side of the Playas Valley nearly kept pace with uplift of the mountain block so that the fans were buried as they formed. The small fans on the east side of Playas Valley enabled the larger fans on the west side to displace the drainage from the center of the valley to the east side. The drainage now lies about two miles from the Big Hatchet Mountains and eight miles from the Animas Mountains. Therefore, as the east side of the valley moved downward more than the west side, the valley was tilted eastward.

Commentary and References follow

COMMENTARY

by Sam Thompson III

In the Foreword, I explained the purpose and use of this Commentary. Here, each note is numbered in accordance with the superscript which appears on the designated page of Zeller's text.

Note 1, p. 7:

Abbreviated headings could be: pre-Laramide, Laramide, and post-Laramide (or Basin and Range) deformations. At the time Zeller wrote this draft there may have been some cause to avoid the specific term Laramide. However, many geologists then, and most now, use it with little reservation.

Zeller had planned to have four headings, splitting the Tertiary—Recent deformation into "deformation during deposition of Tertiary rocks" and "deformation after deposition of Tertiary rocks." Unfortunately, he did not complete this part of his manuscript, so the Tertiary—Recent section from his 1958 dissertation was used.

Note 2, p. 9:

Although in some ways it is commendable that Zeller's geologic map (in pocket) is constructed with a "minimum of interpretation," I would prefer that the interpretation be more comprehensive. Rather than leave loose ends of faults and folds, they could be dashed or questioned where inferred to complete the structural picture. Apparently he was reluctant to use the fracture traces on aerial photographs to extend faults of large displacement into the Horquilla. Did he map faults only where they displace formation contacts (or fusulinid zones)?

Note 3, p. 9:

Zeller did not consider the possibility that the relative changes of sea level in Paleozoic time may be a result of glacio- or tectono-eustasy. Subsequent workers have offered evidence in support of eustatic changes affecting various parts of the region, especially in Pennsylvanian-Permian time. However, his concept of regional epeirogenic uplifts and depressions may explain provincial changes which do not correlate with the eustatic ones.

Note 4, p. 10:

If the title of this section was simply "Laramide Deformation," and that of the previous section was "Pre-Laramide Deformations," this first paragraph would fit properly under the previous one. Here it is somewhat awkward, discussing the indicated deformations during deposition of the Lower Cretaceous rocks. Moreover, evidence of a basin in the Big Hatchet area is scant. The fact that the reefs are so widespread regionally suggests that they are local developments on a broad, shallow marine shelf, and are not confined to a basin margin (in contrast to the reefs at the margin of the Alamo Hueco Basin in Pennsylvanian-Wolfcampian time). Thus I doubt that there were even mild differential vertical movements during Early Cretaceous time in this area. The regional stratigraphic relationships suggest that there may have been broad epeirogenic movements which produced provincial changes of sea level, or mild effects of global-tectonic movements which produced eustatic changes.

Zeller suggests that these very mild, Early Cretaceous movements were the early beginnings of the intense (Laramide) deformation. However, he also stated the same for the Late Paleozoic epeirogenies, and did not discuss what happened during the Triassic-Jurassic hiatus. I doubt that a plot of deformational intensity with time would show a gradual increase from Late Paleozoic to Late Cretaceous. Thus I see the Laramide orogeny in this region as a pronounced deformation in Late Cretaceous-Early Tertiary time, with no forerunners in the Early Cretaceous or earlier, other than in a general concept of continuously fluctuating diastrophism.

Note 5, p. 11:

The anticline broken by the imbricate thrusts was not shown too well on Zeller's work maps and cross sections. He mapped only a short segment of the axis in the NW1/4 sec. 7, T. 31 S., R. 15 W., which I extended questionably to the line of *G-G'* and across the alluvium to the line of *H-H'*. On both these sections the crestal part of the anticline is in the upper plate of the thrust sheet, and the western limb is broken. As I see it, the crestal part is eroded away where the imbricate thrusts are mapped in the re-entrant into the mountains at sections *I-I'* and Zeller shows a large anticline in the lower plate on these two sections. His statement that the anticline is seen on the series of sections from *G-G to K-K'* suggests that he considered the anticlines in the lower and upper plates to be the same structure. If the axis had been plunging steeply southeastward, I can see how this may be possible. However, the southeasternmost segment of the anticline is mapped by Zeller in SW% sec. 22, T. 31 S., R. 15 W. again in the upper plate of the thrust. Thus I see the anticlinal segments at and *K-K'* as possibly the same structure in the upper plate, and the segments at I-I' **and** *J-J'* as a different one in the lower plate.

Note 6, p. 11:

Unfortunately Zeller did not draw a cross section to show the relationship of this complementary anticline to the U-Bar Ridge syncline, and the subsurface structure of the Humble well. The two reverse faults I describe in the well (Zeller, 1965, p. 116) may have regional significance. In my current project on the petroleum geology of southwestern New Mexico, I plan to have a regional structure section through this well.

Note 7, p. 11:

Zeller's interpretation of the structure beneath the Hachita Valley fill on sections *B-B* and *C-C* is incomplete. Although there is no control in the blank areas, at least his best guess would have been better than no interpretation at all. Again, I hope to fill this gap in my regional studies.

Note 8, p. 12:

The age of this Tertiary andesite flow which unconformably overlies the Mojado in the Sierra Rica could help date this "deformation later than Early Cretaceous deposition and earlier than Tertiary deposition" more precisely. If these andesites correlate with the Hidalgo Volcanics as revised by Zeller (1970, p. 10), they probably were deposited in Early Tertiary time. A radiometric age of these or correlative andesites would provide a critical limit to the youngest age of the deformation in this area.

Note 9, p. 12:

Zeller's definitions of reverse, thrust, and overthrust faults are clear, but could cause confusion if not understood. Following Billings and others, I prefer to use reverse as a general 'term for apparent movement, and thrust as the general term for actual movement, on those faults along which the hanging wall has moved upward relative to the footwall. I also make a distinction between high- and low-angle reverse or thrust faults, with the division at 45 degrees original dip (rather than the present dip as per Zeller). If the hanging wall is the active element, a high-angle thrust may be termed an upthrust and a low-angle thrust an overthrust.

Owing to the mechanical advantage of underthrusting, I suspect that at least some of Zeller's overthrusts are actually underthrusts. Possibly some of his thrusts may be low-angle reverse faults with mostly strike-slip movement. His restricted use of reverse fault leaves him without a general term equivalent to my preferred usuage.

Zeller showed very few dips of fault surfaces on his preliminary maps. I have added some arrows to show at least the dip directions indicated on the cross sections. Otherwise, there is no way to distinguish his normal from his reverse faults with the "U/D" symbol alone. We changed his "T" symbol for thrusts to the sawtooth symbol (barbs on upper plate). This change was difficult in those areas which had no cross sections, and may not be completely correct, but the "T" symbols were too hard to see in the complex structure.

Note 10, p. 12:

Here Zeller attempts to explain the absence of thrusting in the Little Hatchet Mountains. At the time he wrote this manuscript and at least until 1964, he stated (personal communication) that he had seen no evidence for thrusts along Lasky's contacts which he had walked out in reconnaissance traverses. (Many geologists believed thrusts must be present to explain the obvious duplications in Lasky's stratigraphic column.) After detailed mapping (Zeller, 1970) he shows several thrusts. This example, based on the experience of one of the best field geologists we have had in southwestern New Mexico, shows how difficult it is to spot some of the major thrusts in reconnaissance work.

Note 11, p. 13:

Unfortunately, Zeller did not identify this thrust which passes into a bedding plane thrust. Probably it is one of the imbricate system on the southwest side of the mountains.

Note 12, p. 13:

Unfortunately again, Zeller did not give a precise location of this abrupt change in fault attitude from gently dipping to vertical. Probably it is in the NE 1/4 sec. 25, T. 31 S., R. 15 W. If it occurs where the trace of the fault bends from NW to NE, then the NE part could be a tear fault along the thrust. If so, we should show no barbs along this part of the upper plate. Zeller put very few "T's" along his thrusts; thus we are never quite sure where our change to the barb symbol overextends his observations.

Note 13, p. 13:

What is the evidence that beds "in the base of the thrust sheet" were overturned "through more than 360 degrees"? Are these beds in the base of the upper plate (Concha Limestone) or are they beneath the fault surface (Hell-to-finish Formation)?

Note 14, p. 14:

The east-west high-angle fault which offsets the U-Bar-Mojado contact is terminated with a "?" on the west. If indeed Zeller believed that its displacement is so large that it probably continues to the Sierra Rica overthrust, he should have mapped it with a questionable trace to show a more comprehensive picture. Even so, the fact that it would appear to have terminated against the thrust is not conclusive evidence that the high-angle fault "must be cut by the overthrust and therefore must be older." The throw could decrease to the west such that the overthrust is not noticeably offset, or the high-angle fault could have developed only within the incompetent Mojado and may not have had sufficient force to displace the Paleozoic rocks in the upper plate of the overthrust.

In my opinion it is more likely that the east-west fault terminates westward against a north-south fault covered by the narrow strip of alluvium. This relationship would explain the fact that he could not find the trace of the fault in the Mojado exposures to the west. Moreover, such a north-south fault would be a strike fault and would be hard to detect in the Mojado exposures to the north.

Note 15, p. 16:

Although some strikes in the lower Paleozoic rocks to the north are parallel to the more westerly ones in the Chaney Canyon area, others are parallel to the more northerly ones in the Horquilla on the downthrown side of the fault. On the map, the strikes on both sides are so variable that I cannot accept this line of Zeller's reasoning. Moreover, the lower Paleozoic rocks to the north are separated from the Chaney Canyon fault by other faults and folds. Even if they were adjacent to the fault, I would be very reluctant to use such evidence in determinations of strike-slip movement.

Note 16, p. 16:

The nearly vertical dips of the Chaney Canyon and South Sheridan Canyon faults also suggest strike-slip movement, as this is a common characteristic of wrench faults.

Note 17, p. 17:

The Precambrian horse is anomalous; whether it and the other horses deserve such special structural significance is doubtful. I disagree with Zeller's arguments against the horse being emplaced by vertical movements, but I also consider his argument for lateral movement to be reasonable. Moreover, the apparent curve in strike from northwest to north up to the North Hatchet fault, as seen in the Lower Paleozoic rocks on the south side, suggests right-lateral drag. However, in such complex structure, movements probably were vertical, lateral and oblique at various times, and the small fault blocks could have been emplaced in any type of movement or a combination of them. Thus, the horses may not indicate one particular interpretation.

Note 18, p. 17:

On Plate 2 of Zeller (1965) the lithology of the Bliss in the Chaney Canyon Section is an arkose, but in the Mescal and Hatchet Gap Sections it is mostly sandy dolomite. Thus his argument for lateral movement along the Chaney Canyon fault based on the contrast between arkose and sandy dolomite may have some merit. However, I question his use of this same line of reasoning when two sandy dolomites are involved. In fact, any lateral change in the Bliss would not be too surprising to me, considering its origin as a nonmarine to shallow marine elastic deposit upon an irregular basement surface. Furthermore, many workers would include the sandy dolomites in the overlying El Paso, so Zeller's correlations of anomalous facies in his Bliss may not be valid.

Note 19, p. 17:

Note that this final section was taken from the dissertation of Zeller (1958a). His hand-written text of about 1960 ended with the previous section. In his outline he had planned to separate this last part into two sections — one on "Deformation during deposition of Tertiary rocks," and the final on "Deformation after deposition of Tertiary rocks."

Note 20, p. 17:

Zeller's marginal note says: "Refer to Dog Mountains Quadrangle map." This unit of andesite flows in the Alamo Hueco Mountains is shown in the legend of Zeller (1958c) as Ta. Around sec. 4, T. 34 S., R. 15 W., it covers two high-angle faults and no doubt rests unconformably on the older units of Um, Tic, and Tvu which were displaced by the faulting. Thus there is at least one period of faulting during the time that his Tertiary volcanic rocks were deposited, but I know of no radiometric determinations in this area which would definitely date these rocks.

Note 21, p. 18:

Zeller's marginal note says: "Refer to Walnut Wells Report." Apparently this reference is to Zeller and Alper (1965, p. 74). but the limestone conglomerates discussed there are near the base of the Tertiary volcanic section, not several thousand feet above it. The OK-Bar conglomerate, which is in that position and is overlain by more volcanic rocks, appears to be made almost entirely of volcanic detritus and contains no limestone boulders (Zeller and Alper, 1965, p. 57-58).

Note 22, p. 18:

Zeller's marginal note: "Check for concurrence with Walnut Wells report.????" In the discussion by Zeller and Alper (1965, p. 73-78) on "Deformation during Tertiary deposition," the only discussion on limestone conglomerates (p. 75) concerns the boulders in the Oak Creek Tuff near the base of the volcanic sequence. Thus his arguments for uplift of ancestral mountains (with limestones) during deposition of the volcanic rocks, and against a residual high, may not have been necessary and may have been deleted or at least modified if Zeller had been able to finish this text himself.

Note 23, p. 18:

Zeller's marginal note: "Refer to Dog Mountains map." Around the Dog Spring Ranch (sec. 13, T. 34 S., R. 14 W.) on Zeller (1958c) he maps a thrust between a coarse-grained quartz latite (Tic) and an older volcanic unit (Tvu).

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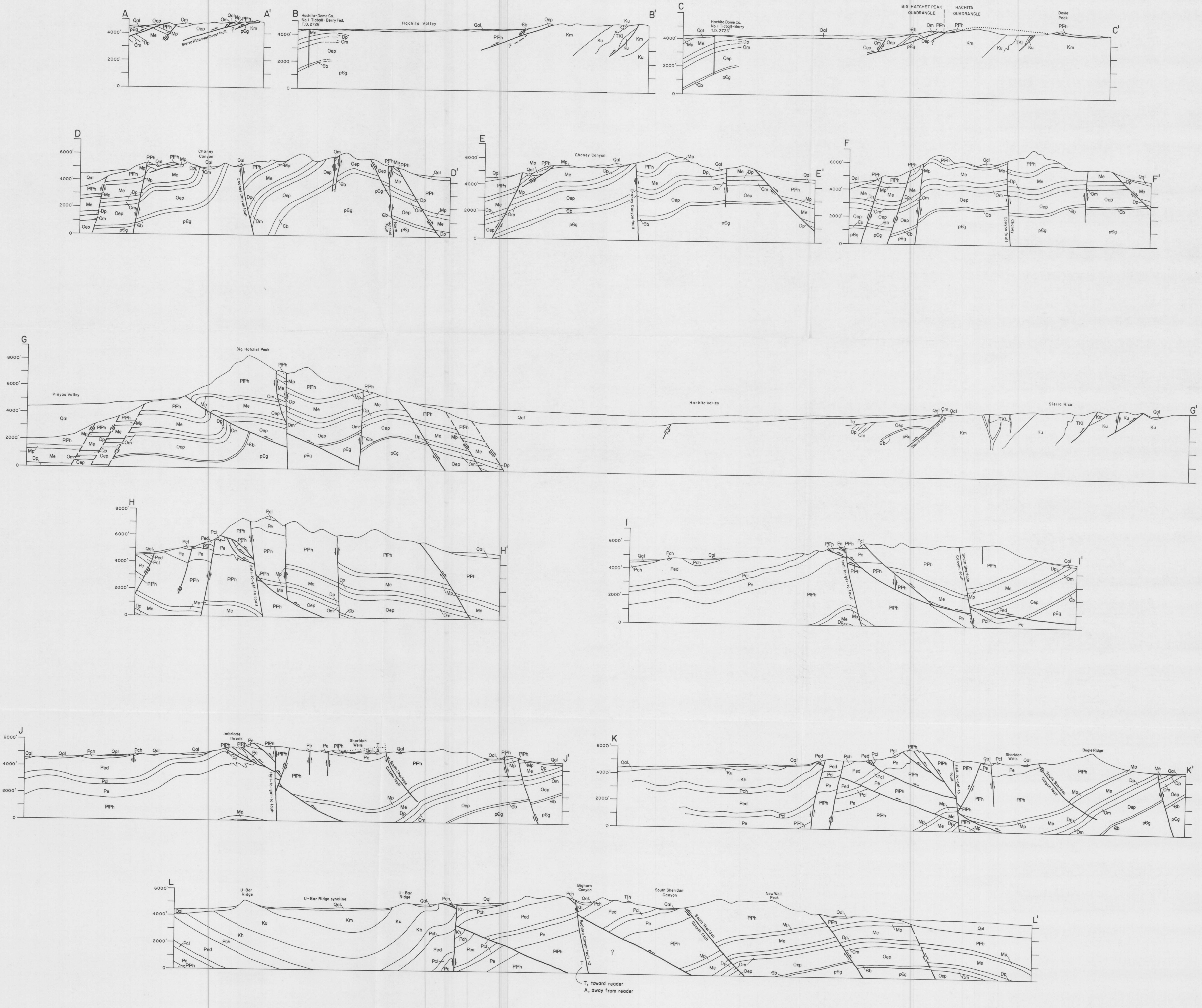

STRUCTURE SECTIONS OF BIG HATCHET PEAK QUADRANGLE, NEW MEXICO

by Robert A. Zeller, Jr., 1960-61

SCALE 1:48,000

1 0 1 MILE

Geology by Robert A. Zeller, Jr.; revised by Sam Thompson III, 1975
Cartography by Robert A. Zeller, Jr. and Neila M. Pearson