DIFFERENTIAL VERTICAL UPLIFT — A MAJOR FACTOR IN THE STRUCTURAL EVOLUTION OF SOUTHEAST ARIZONA

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INTRODUCTION

Previous Work

With few exceptions geologists working in southeast Arizona (Fig. 1) have believed that the major Laramide[2] structural events were extensive overthrusting and concomitant crustal shortening and that the ranges were not defined until the major normal faulting of the Basin and Range orogeny. Four of the ranges, the Mustang Mountains (Bryant, 1951), northern Canelo Hills (Feth, 1947, 1948), Empire Mountains (Galbraith, 1949, 1959), and the Tucson Mountains (Brown, 1939) have been interpreted as overthrust blocks *in toto*. Major overthrusting has been reported in

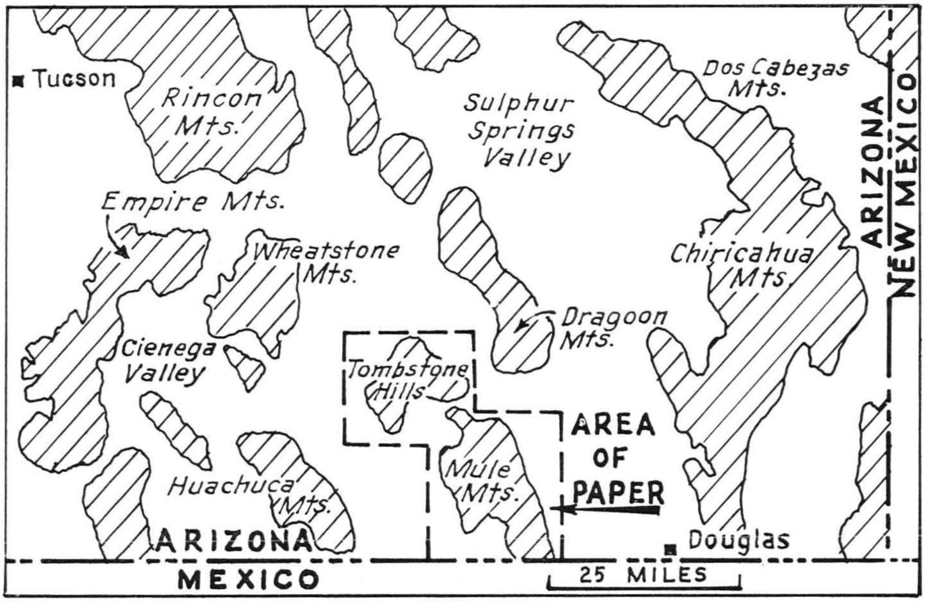

FIGURE 1. Index map of southeast Arizona.

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[1] This paper updates part of a Ph.D. dissertation at the University of Chicago (Jones, 1961).

[2] In this paper the term Laramide refers to the major orogeny and associated extrusive and intrusive igneous events which recent radiometric age determinations (Damon, et al., 1964, 1965) indicate was concentrated near the Cretaceous-Paleocene boundary.

nearly all ranges (e.g. Cooper and Silver, 1964; Gilluly, 1956; Moore et al, 1941; Sabins, 1957). In addition, presumed strike slip faults with a displacement measurable in miles have been mapped by Alberding (1938) in the Empire Mountains, Gilluly (1956) in the southern Dragoon Mountains, Sabins (1957) in the northern Chiricahua Mountains, Lutton (1958) in the Santa Rita Mountains, and Greybeal (1962) in the southern Whetstone Mountains. Although dissents have recently been registered against the interpretation of major overthrusting in several specific areas (e.g. Kinnison, 1959, Mayo, 1963, and McCoy, 1964, in the Tucson Mountains; Medhi, 1964, and Fair and Jenks, 1961, in the southern Santa Catalina Mountains; and McColly, 1961, in the southern Rincon Mountains), the overwhelming number of written reports remains strongly committed to the concept that the Laramide orogeny was dominated by severe compression and major overthrusting.

Objectives and Methods

In my opinion Laramide compression and overthrusting have been greatly overestimated in southeast Arizona. The primary objective of this paper is to suggest that the structural evolution of many of the ranges in southeast Arizona has been dominated by various effects of differential vertical uplift of the Precambrian, Jurassic, and Laramide granites. Admittedly, effects of strong local compression are myriad in southeast Arizona. I do not deny them, but only suggest that they are trees, not forest; it is argued in this paper that most of the local compressional effects originated from uplift of granites, high angle faulting, diapiric action, intrusion, and gravity sliding, and not from a major regional compressive stress system developed in the upper crust.

Most of the work which led to the conclusions herein presented consisted of a detailed literature review. However, detailed field work was done in several areas where mapor overthrusting and compression had been described by others.

Because of space limitations only two ranges are discussed, the Mule Mountains and the Tombstone Hills. However, the principles illustrated by these ranges are believed to have wide application in southeast Arizona. A detailed analysis and discussion of several other ranges will be presented in subsequent papers.

In the next section are summarized what I consider to be the major lines of evidence supporting the differential uplift hypothesis. The summary is brief and rather categorical; it is not intended to convince, but is intended to focus the reader's attention on the main points which I believe the subsequent discussion of the individual ranges will document.

Summary of Evidence

1) Most of the ranges are complexly deformed and intruded anticlines with granitic cores which range from Precambrian to Miocene in age.

2) Most of the ranges were originally well defined by vertical movements during either the Nevadan or Laramide orogenies and are not a new development of a Basin and Range orogeny.

3) The perpetuity of the anticlines in space and time is primarily due to intermittent uplift of the various granites in their cores.

4) Overthrusting has been overemphasized, primarily because of a failure to discriminate between large overthrusts and detached blocks which have moved down the flanks of the large anticlines under the influence of gravity. This conclusion is based on recognition of a possible source and an available declivity, and, in particular, on a study of the internal structure of the detached blocks which has commonly shown that the blocks moved down the range flank rather than out of the valley onto the uplifted mountain block.

5) The existence of tension[3] rather than regional compression in the upper crust during Laramide time is suggested by (a) the remarkable parallelism in space and time of the varying magnitudes of volcanic and intrusive activity and structural deformation, (b) the utilization by intrusion of many of the faults during or shortly after their formation, (c) the structural uniqueness of each range as indicated by the impossibility of projecting even gross structural trends from range to range, (d) gross disparities between the crustal shortening required on adjacent northeast-southwest regional cross sections if the overthrust hypothesis is adhered to, and (e) the large variety of trends of major structural features including directions of presumed overthrusting and strike slip faulting.

MULE MOUNTAINS

Introduction

The Mule Mountains serve as an apt vehicle to initiate the documentation of this paper's thesis: the importance of vertical movement in the structural history of southeast Arizona. Not only do they illustrate many aspects of the differential vertical movement hypothesis, but also, thanks to the excellent areal mapping of Ransome (1904), Gilluly (1956), Hayes and Landis (1964a), and the detailed work by many geologists in the Bisbee area, their surface geology is well known.

Present Structure

The Mule Mountains are a complex anticline with east and west flanks and north and south plunge defined in Cretaceous and older rocks (Figs.

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[3] In this paper tension refers to any compressive stress in the crust which is less than lithostatic.

2 and 3). Both the topographic expression and the gross structure within the range strike approximately N30°W. The axis of the Mule Mountains anticline is occupied by the Juniper Flat granite of Jurassic age which was intruded into Precambrian Pinal schist. No Basin and Range type faults are either known or suspected along the flanks of the range. Clearly, the gross structural features of the range make it difficult to escape the conclusion that the present Mule Mountains are a major anticline formed by a renewed upward movement of the Jurassic granite (Figs. 2 and 3). Unfortunately, it is not known whether the present anticline is a product of the Laramide or Basin and Range orogeny since the Lower Cretaceous strata are the youngest pre-Recent sedimentary or extrusive rocks preserved in the range. However, since the range is defind by anticlinal uplift, not by major normal faulting, a Laramid age is presumed.

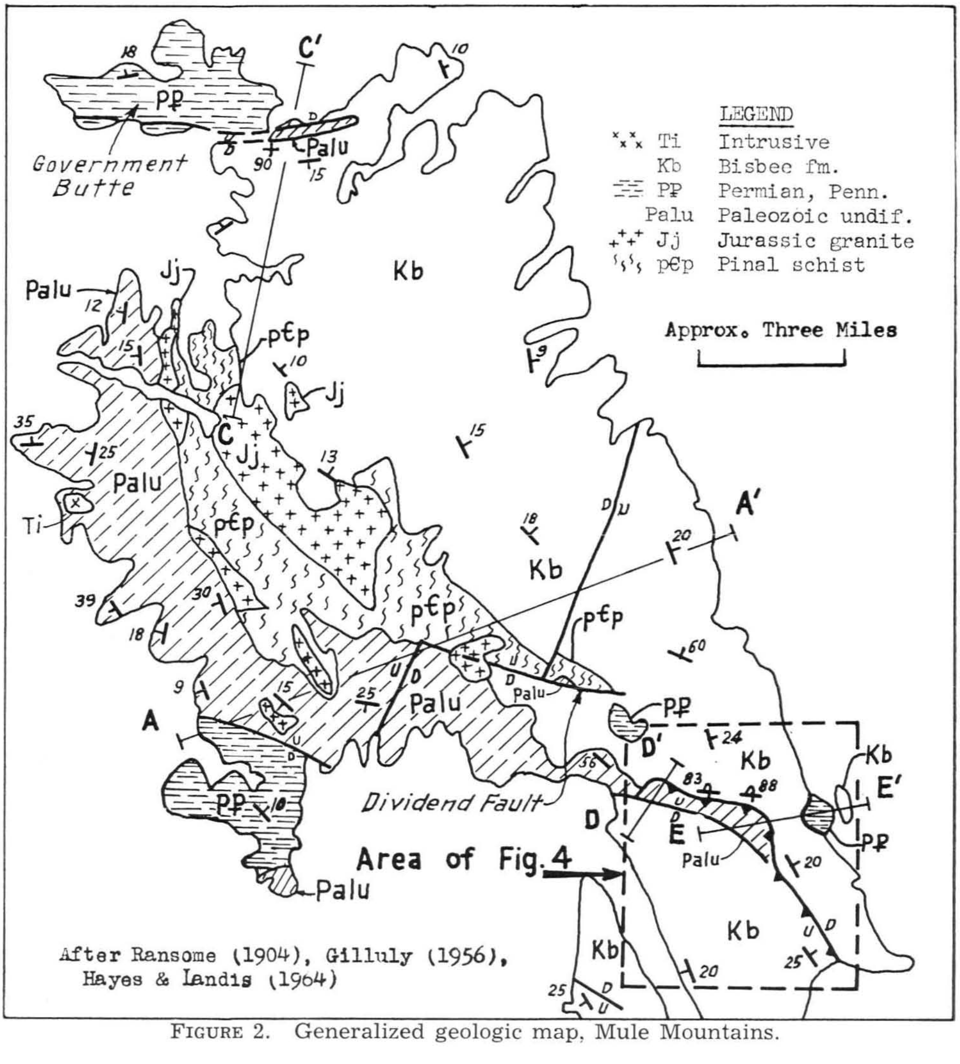


FIGURE 2. Generalized geologic map, Mule Mountains.

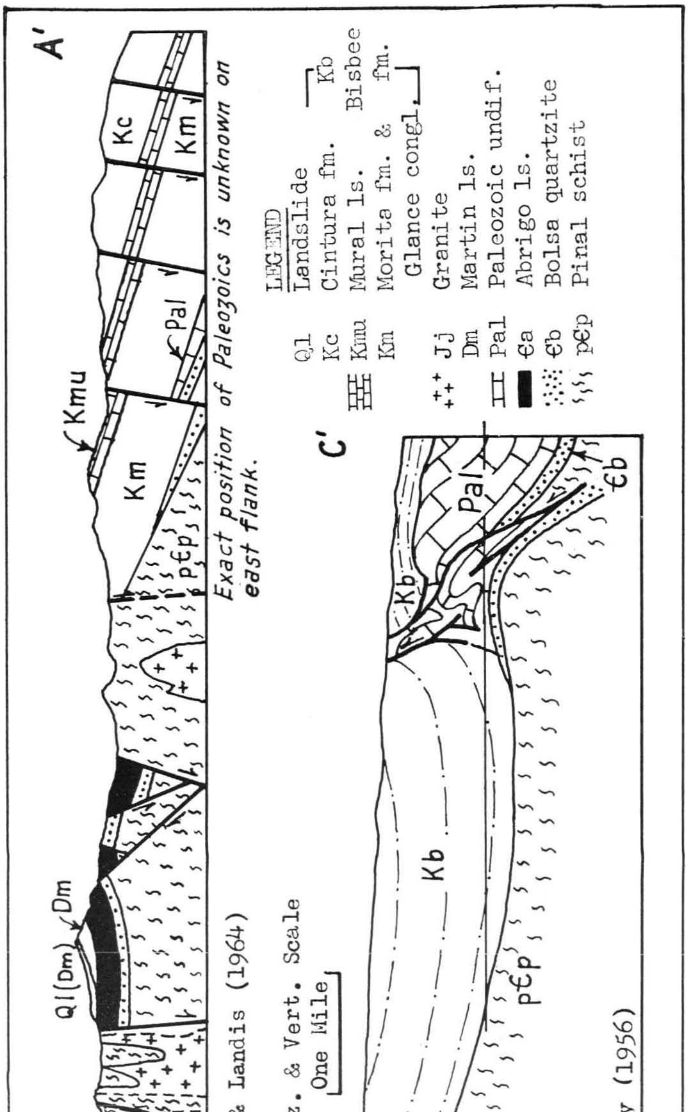


FIGURE 3. Structure sections, Mule Mountains.

Jurassic Deformation

In Jurassic time the Juniper Flat granite was emplaced in the core of an anticline whose position and trend must have been strikingly similar to the position and trend of the currently existing Laramide anticline. This conclusion is justified by the fact that Lower Cretaceous sediments rest with erosional contact on the granite near the crest of the present anticline, while Paleozoic rocks are now exposed on both the east and west flanks and the north and south plunges (Figs. 2 and 3). The exact position of the Paleozoic rocks under the Cretaceous on the east flank of the portion of the range north of the Dividend fault is unknown, but their presence is strongly suggested by: (1) their presence and westward truncation south of the Dividend fault (Fig. 2), (2) the remnants of Cambrian quartzite preserved on the east flank of the range immediately north of the Dividend fault (Fig. 2), and (3) the southeastward swing of the monocline associated with the diapiric structure at the north end of the range (Fig. 3b) which Gilluly (1956, p. 127) demonstrated was related to the truncated edges of the Paleozoic rocks.

Considerable compression was attributed to the Jurassic deformation by Wilson (1957) and Wilson and Moore (1959) who believed that the Juniper Flat granite was intruded along a westward trending strike slip fault. As the following discussion indicates, it is my opinion that the known pre-Cretaceous faults and the distribution of the granite forcibly argue that tension, not compression, existed in the upper crust in the Mule Mountains at the time of the intrusion of the granite. The most significant pre-Lower Cretaceous fault is the Dividend fault near Bisbee, the presumed strike slip fault of Wilson and Moore (Figs. 2 and 3a). The fault strikes N70°W, dips 60°S to vertical, and has a maximum several thousand feet of displacement consistently down to the south away from the main body of the granite. The normal fault interpretation suggested by the geometry of the Dividend fault is confirmed by the nature of the adjoining faults. For example, Ransome (1904) believed that the Dividend fault was a normal fault which terminated to the northwest against a northeast trending normal fault, an interpretation essentially substantiated by the recent mapping by Hayes and Landis (1964a). Moreover, significant strike slip movement on the Dividend fault would have been impossible without the development of types of subsidiary structures which do not exist. The only major faults genetically associated with the Dividend fault are a series of northeast trending normal fault which, in conjunction with the Dividend fault, controlled the emplacement of the Bisbee ore bodies (Ransome, 1904). Evidence from the mine workings at Bisbee confirms the normal fault designation (D. L. Bryant, Jr., geologist for Phelps Dodge, talk on G.S.A. field trip, April, 1959). Thus the field evidence indicates that the major fault developed during the pre-Lower Cretaceous deformation resulted from tension in the upper crust and not from compression.

The impression of tension and subsequent crustal extension given by the Dividend fault is confirmed by the considerable number of high angle reverse and normal faults of probable Jurassic age which parallel the main body of the Juniper Flat granite along its southwest flank (Fig. 3a). Many of the faults are intruded by granite porphyry associated with the Juniper Flat granite. Ransome (1904, p. 91) believed that the faulting and intrusion were essentially simultaneous since some of the faults experienced renewed movement after intrusion. The probable simultaneity of faulting and intrusion indicates that the faults were not sealed by compression at the time of their formation.

It is difficult for me to escape the conclusion that the dynamics of the pre-Lower Cretaceous deformation are dominated by a dilation of the near surface rocks as the Juniper Flat granite rose and domed the upper crust.

Lower Cretaceous Time

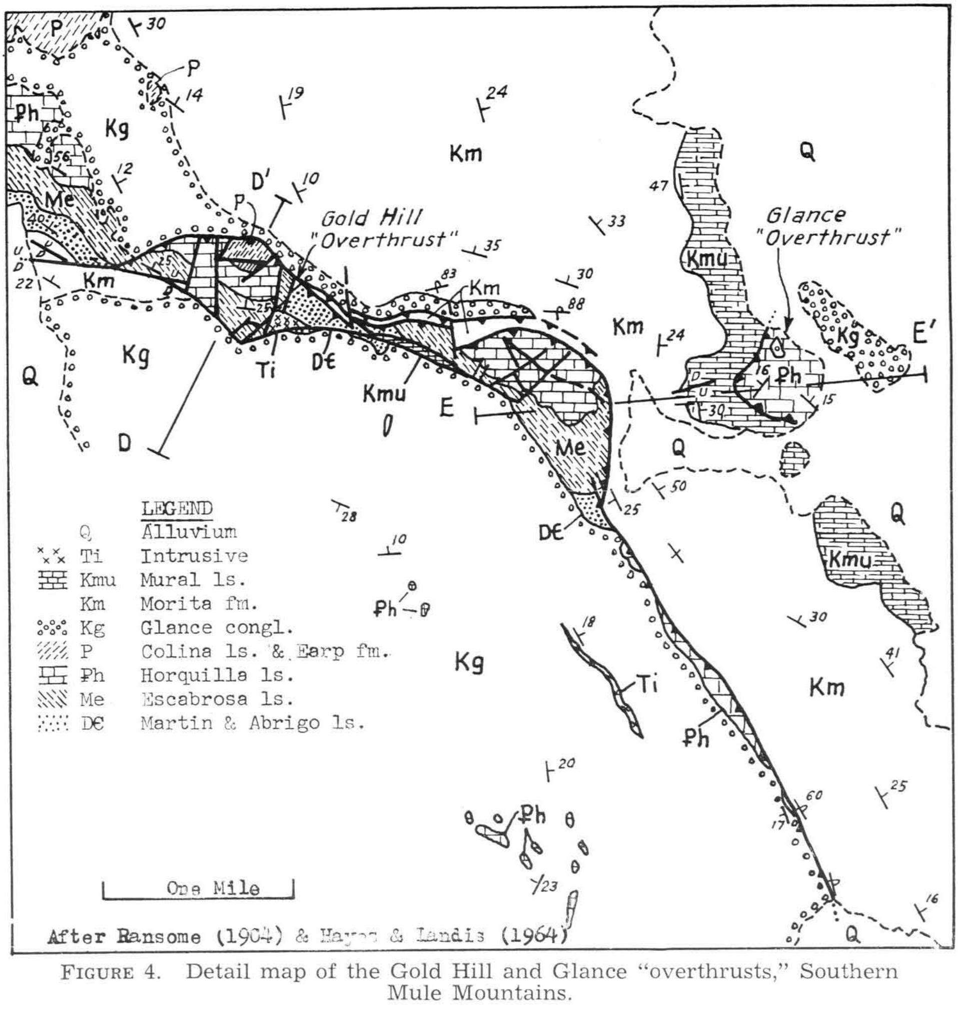
The thickness and facies variations in the Lower Cretaceous rocks demonstrate that the gross anticlinal nature of the Mule Mountains area persisted well into Lower Cretaceous time. Near the crest of the present range the basal Lower Cretaceous Glance conglomerate is locally absent (Gilluly, 1956; Hayes and Landis, 1964a), suggesting that the crest of the present Laramide anticline was one of the last areas within the range to be buried by Lower Cretaceous deposits. Down the north plunge of the present range, the depositional thickness of the Lower Cretaceous rocks increases in the same area where the presence of Paleozoic rocks indicates the pre-Lower Cretaceous anticline also plunged north (Fig. 3b; Gilluly, 1956, p. 122). Similarly, south of the Dividend fault, down the south plunge of the present anticline, the Lower Cretaceous Glance conglomerate greatly thickens.

Laramide Deformation

As noted previously, the present anticlinal structure is presumed to be a product of the Laramide orogeny although the accuracy of that presumption is not critical to the thesis of this paper since the Mule Mountains were already an anticline in Jurassic time. The damping effect of the massive Juniper Flat granite north of the Dividend fault probably caused the parts of the range north and south of the fault to deform somewhat differently in Laramide time although both parts preserved their basic anticlinal configuration. North of the Dividend fault in the main body of the range, renewed uplift of the Juniper Flat granite was accompanied by minor normal faulting which included renewed movement on the Dividend fault; no Laramide compressional structures have been reported. South of the Dividend fault a broad relatively flat topped anticline is well defined in Cretaceous rocks. The westward truncation of the Paleozoic rocks by the Glance conglomerate on the east flank (Fig. 4) clearly shows that the east flank of the Laramide anticline coincided, at least in part, with the east flank of a Pre-Cretaceous anticline. What happens under the west flank of the Laramide anticline is not known; however, the presence of only Horquilla limestone as windows in the Glance conglomerate in the broad crestal area of the Laramide anticline (Fig. 4) encourages the supposition that the crestal area, and perhaps the west flank, of the Laramide and Purassic anticlines are, like the east flanks, superimposed.

The argument for strong Laramide compression in the Mule Mountains rests almost entirely on the interpretation of two possible thrust faults which Ransome mapped in the Paleozoic and Cretaceous rocks south of the Dividend fault (Fig. 4).

Six miles southeast of Bisbee the approximate crest of the range is occupied by a structurally high block defined on the east by a reverse fault termed the Gold Hill thrust by Ransome (Fig. 4). Although both Ransome



After Ransome (1904) & Hayes & Landis (1964)

FIGURE 4. Detail map of the Gold Hill and Glance "overthrusts," Southern Mule Mountains.

(1904) and Hayes and Landis (1964a) believed that the fault was a thrust with a minimum of two miles of horizontal movement, it is suggested here that vertical movement was more important in the formation of the Gold Hill fault block than has hitherto been recognized. When combined with the steep dip of the fault where exposed (Ransome, 1904, p. 103), the fact that the varying strikes of the footwall structures rather faithfully reflect the changes in strike of the erosional outline of the hanging wall block (Fig. 4), suggests we are dealing with vertical uplift accompanied by some lateral spreading away from the centers of uplift. This concept is consistent with the large number of normal faults which fragment the hanging wall block of the Gold Hill fault but which are conspicuous by their virtual absence in the footwall block. It is suggested that we are dealing with a complicated natural example of structures which Sanford (1959) formed experimentally by vertical movement alone. Sanford showed experimentally and theoretically that the vertical faults bounding a horst at depth tend to flatten as they approach the surface. In Sanford's experiments the doming at the surface was accompanied by minor normal faulting and by a tendency of the hanging wall block of the flattened boundary fault to move over the footwall block. By analogy with Sanford's work it is argued here that the Gold Hill "overthrust block" is a complex horst, shattered by small normal faults, and bounded by a high angle reverse fault on one side and by a normal fault on the other. A suggested sequence of events is diagrammatically sketched in Figs. 5a-5d. The indicated sequence is consistent with the following facts:

1) The fault dips steeply wherever the dip can be observed (Ransome, 1904, p. 103), particularly at the northwest termination of the fault where (Ransome, 1904, p. 101) the fault has . . . "a rather steep dip to the south," and 1000 feet southeast of Gold Hill where the fault strikes N45°W and dips 50° to the southwest (Ransome, 1904, Pl. I).

2) The linear southeastern extension of the fault in an area of uniform stratigraphic displacement and very little topographic relief indicates a steep dip here also (see Ransome, 1904, Pl. I).

3) Plowing rather than overriding by the east edge of the uplifted block occurred (Ransome, 1904, p. 103).

4) Widespread normal faulting was virtually restricted to the uplifted block.

5) Normal faulting and thrusting appear to be genetically related.

6) The strata in the hanging wall block at Gold Hill flatten to the east (Ransome, 1904, Pl. XXII).

7) The decollement within or at the base of the Glance conglomerate is clearly indicated by the isoclinal fold in the Glance in the footwall of the Gold Hill fault (Ransome, 1904).

8) The original high angle fault formed in the area of greatest curvature of the Paleozoic strata on the east flank of the pre-Cretaceous anticline (Fig. 5a).

9) If the Paleozoic strata northwest of the northwest termination of the Gold Hill fault were uplifted and tilted to the southwest and the Glance conglomerate removed, the various Paleozoic formations would project directly into their counterparts on the other side of the fault without any horizontal offset (Fig. 4).

10) No low angle "overthrusting" exists along the southwestern extension of the fault where the west dip of the strata in the hanging wall of the fault (Fig. 4) precluded any gravity sliding.

11) The broad, flat topped, nearly symmetrical configuration of the major anticline in the southern Mule Mountains (Rigs. 2, 4) suggests control by vertical uplift rather than shortening by thrusting.

12) The uplifted block contains the largest, albeit small, Tertiary (?) intrusive in the southern Mule Mountains.

Gravity controlled movement to the northeast was undoubtedly facilitated by the fact that the marly, shaley member of the Devonian Martin limestone and an upper marly member of the Cambrian Abrigo limestone were juxtaposed across at least part of the Gold Hill fault with the contact of the Glance conglomerate and the underlying Paleozoic rocks (see, e.g., Fig. 5b; Ransome, 1904, Pl. I). The low shearing strength of the Martin in the Bisbee area is well demonstrated by: (a) the large landslide shown on Fig. 3a, (b) the widespread structurally disconformable contact between the Escabosa and Martin three miles southwest of Bisbee (Hayes and Landis, 1964a), and, (c) possibly, by the abnormally thin section of Martin measured by Hayes and Landis (1964b) two miles northwest of Gold Hill at Black Gap where the steep northeast dip of the Martin and the proximity to a high angle fault suggests the thin section is due to the same type of internal shearing which, when combined with slightly greater vertical uplift, gave rise to the more spectacular results developed two miles to the southeast at Gold Hill.

The suggested origin of the Gold Hill fault requires elongation of 1000-1500 feet of the outcrop width of the Glance conglomerate west of Gold Hill by means of near bedding plane faulting. Bedding plane faulting is ubiquitous in the southern Mule Mountains but no workers have explicitly commented on its presence or absence in the critical area. Unfortunately at the time of my field work I was not aware of the critical nature of the Glance exposures southwest of Gold Hill and they were not looked at in detail. Probably the poor and scattered exposures preclude obtaining sufficient information to either confirm or refute the hypothesis offered here. Pending further work or additional information the hypothesized extension is believed to be consistent with, albeit not proven by, the following: (a) the flat to gentle dip within the broad area of Glance southwest of Gold Hill (Figs. 2, 4, 5) is parallel to the hypothesized faulting (Fig. 5), (b) beds of grit and shale are present in the Glance near Gold Hill (Ransome, 1904, p. 60) suggesting a facility for bedding plane faulting near Gold Hill which is not shared by the more massive Glance of other areas.

The Glance "overthrust" occurs on the east flank of the range and consists of a block of Pennsylvanian Horquilla limestone and Lower Cretaceous Glance conglomerate about half a square mile in areal extent which rests on Lower Cretaceous rocks along an eastward dipping fault contact. Although Ransome (1904) interpreted this block as an erosional remnant of a westward moving low-angle thrust, it was pointed out in an earlier paper (Jones, 1963) that the internal structures within the limestones of the "overthrust" block clearly indicated that the block was emplaced from

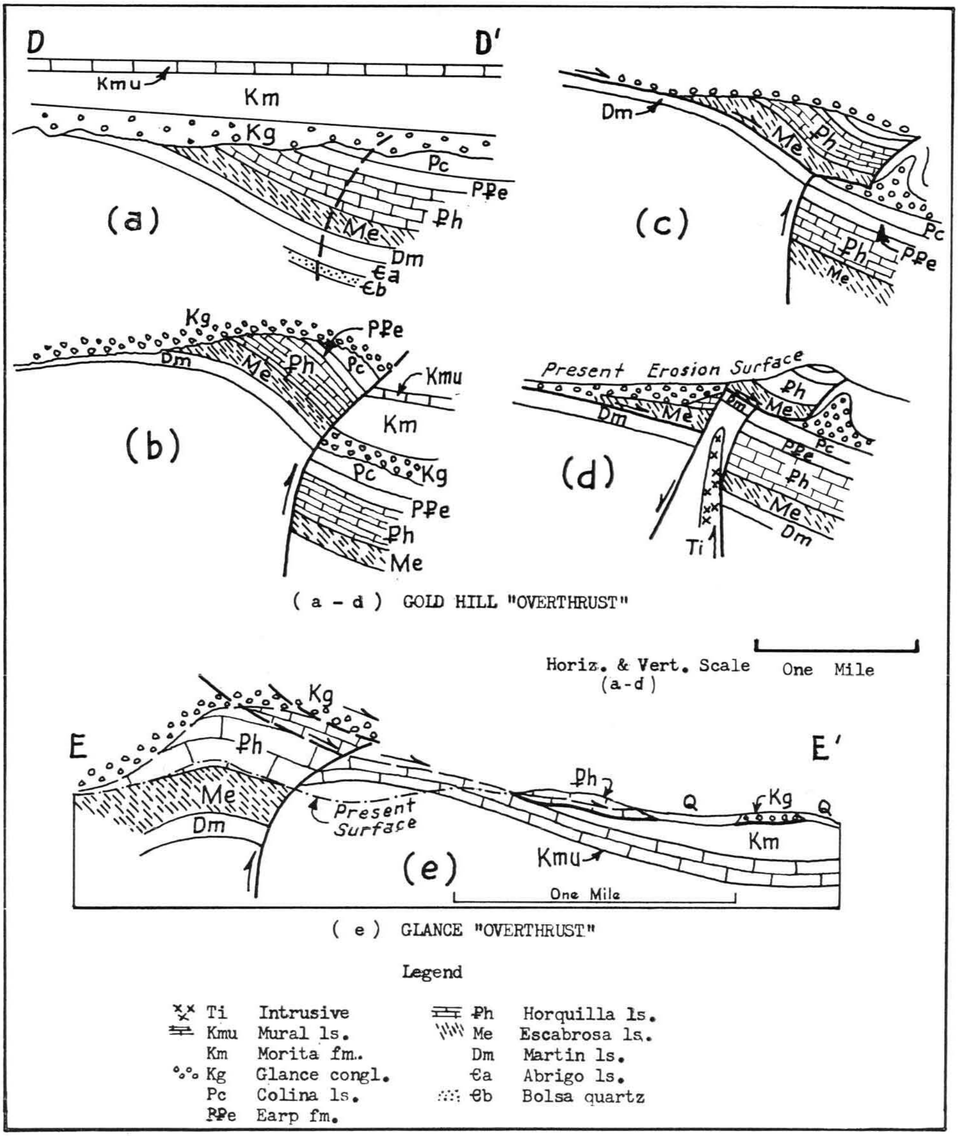


FIGURE 5. Cross sections illustrating the formation of the Gold Hill and Glance "overthrusts."

the west, not the east. The direction of emplacement plus certain other features to be discussed shortly were used to suggest the detached block was emplaced by gravity sliding from the crest of the anticline to the west. Although the recent map of Hayes and Landis (1964a) agrees with the concept of emplacement from the west, they have interpreted the detached block as a klippe once tectonically attached to the Gold Hill fault block exposed one mile to the west. On the other hand Ransome (1904, p. 103) argued that the steep dip of the Gold Hill fault wherever exposed and the "plowing action" in front of the fault indicated that the Gold Hill fault never moved much farther east than its present position. I side with Ransome here, to whose arguments I add the evidence previously adduced in the discussion of the origin of the Gold Hill fault. In particular, the substantial changes in strike of both the trace of the Gold Hill fault and the structures in the hanging and footwalls of the fault forcibly argue that the Glance block at its present location could never have been tectonically attached to the Gold Hill fault. For such tectonic continuity to have existed, the north trending segment of the Gold Hill fault west of the Glance block must have been tectonically separated from the easterly trending portion of the fault further northwest. Despite abundant minor faulting the required tectonic break does not exist (Fig. 4).

Figure 5e indicates the suggested mode of origin of the Glance "overthrust" block. The reconstruction on Fig. 5e clearly shows that a source and a slope were definitely available. Stratigraphically, the Horquilla limestone and Glance conglomerate are exactly the rocks which the reconstruction shows would have been in the most favorable position to slide. Furthermore, it is undoubtedly significant that the detached block occurs directly east of the only place along the Gold Hill fault to the west where the amount of uplift and the structure in both the hanging and footwall blocks were favorable for the development of a detached slideblock. Of interest is the fact that the fault surface underlying the block clearly cuts up section to the west in the direction of the origin of the block (Fig. 5e). This relationship is to be expected in slides, is not found in most overthrusts, and is also not found along the Gold Hill fault to the west (Ransome, 1904; Hayes and Landis, 1964a). In addition, the small grabens and minor east dipping normal faults observed by myself in the detached block of Horquilla limestone are structures to be expected in a slide block moving eastward under a small overburden rather than in the leading edge of an eastward moving thrust plate.

Two additional comments about the cross section are warranted. If the source area has been mapped correctly and the contact between the Glance and Escabrosa is not faulted, the aggregate width of the slide block is slightly greater than can be reasonably postulated in the source area unless the Glance and Horquilla slid separately. Unfortunately the contact between the two is covered by a low alluviated area; however, the mere presence of the cover suggests a brecciated easily erodable structural contact, rather than a depositional one, since the contact between the two massive resistant units is not an area of differential erosion in the Mule Mountains. A rapid westward truncation of the Horquilla is necessary to reconstruct an acceptable source area. The rate of truncation shown on Fig. 5e is large, but it is less than the westward truncation of 1600′ of Horquilla and Earp within 2500′ horizontally which is well documented three miles along strike to the northwest (Fig. 4).

In summary, it is concluded that neither the Gold Hill nor the Glance "overthrusts" reported by previous workers demonstrate significant Laramide compression in the Mule Mountains.

Government Butte

Government Butte is an east-west trending anticlinal range of hills lying between the Tombstone Hills and the north end of the Mule Mountains. At the east end of the anticline a sliver of Paleozoic rocks has essentially been intruded into the overlying Cretaceous rocks (Fig. 3b). The sliver is bounded by a north dipping reverse fault on its south side and by a north dipping normal fault on the north. The two faults join and mutually terminate at the extreme east end of Government Butte. Gilluly (1956, p. 127) believed that the two faults formed simultaneously and that the structure was essentially a diapir. The reverse drag in the Cretaceous strata (Fig. 3b) suggests that during the formation of the north flank of the structure no compression existed at the structural level now exposed. Farther west within the Government Butte structure are additional east-west striking normal and reverse faults whose parallelism Gilluly (1956, p. 128) interpreted as suggesting a genetic relationship. The structure at the east end of Government Butte is of particular interest because, like the Gold Hill horst discussed above, it may be a documented small scale example of a type of structure which was important in the formation of the main ranges in southeast Arizona. As will be shown in a subsequent paper, parts of the Huachuca, Swisshelm, northern Chiricahua, and Dragoon Mountains are characterized by genetically related, simultaneously formed, high angle reverse and normal faults which are sub-parallel but trend into each other from opposite sides of the ranges.

Vulcanism, Intrusion and Structural History

No extrusive volcanic rocks are present in the Mule Mountains although some of the small rhyolite porphyry intrusives of Tertiary age may represent volcanic necks. A dearth of both extrusive and intrusive igneous rocks of Laramide and Tertiary age is unusual in the ranges of southeast Arizona, and, in fact, the Mule and Whetstone Mountains stand alone in this respect. The two ranges share another characteristic: they are the least structurally complex of the southeast Arizona ranges. In my opinion, the combination of the dearth of extrusive and intrusive igneous activity and the minimal structural complexity are genetically related and are as important to an understanding of structural history in southeast Arizona as the more usual combination of extensive and intensive vulcanism, intrusion, and deformation.

A full discussion of the possible dynamics and significance of these inter-relationships is beyond the scope of this paper; however, one comment is offered. The contrast between the situation in southeast Arizona and the lack of correlation in space and time between major overthrusting and major intrusions in the western United States in Phanerozic time which Gilluly (1965) pointed out suggests that in southeast Arizona we are dealing with significantly different dynamics than those found in areas of major overthrusting.

Summary

In every period for which evidence is available from Jurassic time to the present, an anticlinal structure of varying degrees of complexity has existed at the site of the Mule Mountains. The anticlines had a core of Jurassic granite which was intermittently uplifted. No significant overthrusting or major conpressional structures are known in the range.

TOMBSTONE HILLS

General

The detailed work of Butler, Wilson and Rasor (1938) in the Tombstone mining district and the areal mapping of Gilluly (1956) clearly show that the structural history of the Tombstone Hills is both complicated and obscure. Although the final word on their structural evolution is certainly not included here, Gilluly's (1956, p. 128-133) belief in the dominance of severe compression and major overthrusting in the structural evolution of the Tombstone Hills is, in my opinion, based on substantially incorrect interpretations. In the succeeding paragraphs several lines of evidence are pointed out which strongly suggest that the importance of tension and vertical movements has not previously been given adequate consideration.

Some of the evidence minimizing compression effects is contained in two of Gilluly's cross sections which are reproduced here with a generalized map (Figs. 6 and 7). Considering Gilluly's conclusions concerning compression and overthrusting, it can only be termed extraordinary that 16 out of the 17 faults shown on these sections show dip displacement characteristic of normal faults. The section in Fig. 7a shows a lengthening of 2000′ at the base of the Cambrian over the 7½ mile length from the east end of the section to the footwall of the Ajax Hill fault. Although most of the normal faults cannot be dated, the largest of them, the Ajax Hill fault, has frozen contacts with a Cretaceous intrusive, displaces Lower Cretaceous strata, and therefore must be Laramide in age. The two sections also show that folding in the Paleozoic rocks is minor and is usually related to underlying intrusive rocks (Figs. 6 and 7). Furthermore, evidence of low angle overthrusting is conspicuously inconspicuous. The gross structural impression of crustal distention yielded by cross section FF′ of Fig. 7a is amplified in the discussion of specific areas given below.

Major Overthrusting

The most important concept which Gilluly (1956) adduced to support the concept of major crustal shortening and overthrusting is the low angle overthrust that he believed once covered much of the western part of the Tombstone Hills. Gilluly's belief in the major thrust was a direct result of the following three interpretations: (1) three small klippen of Paleozoic rocks were once connected as part of a major eastward moving thrust sheet; (2) the Uncle Sam porphyry was intruded along a thrust plane; and (3) the

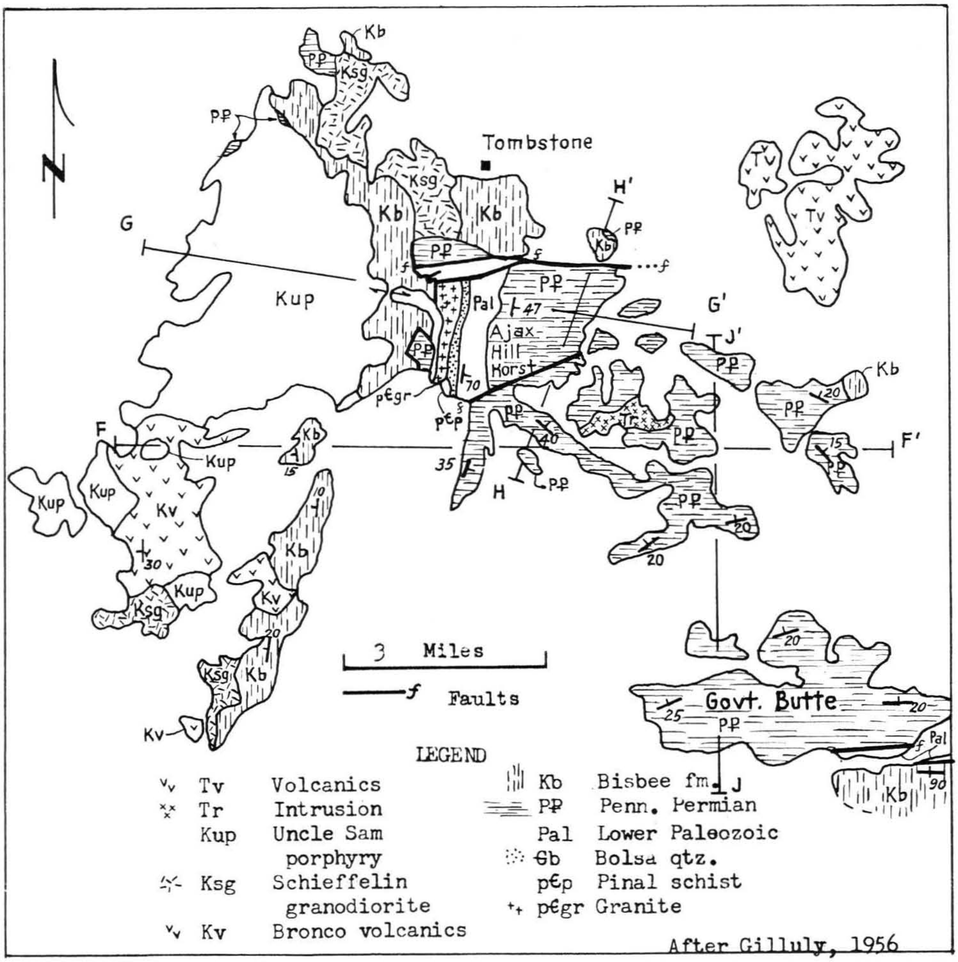
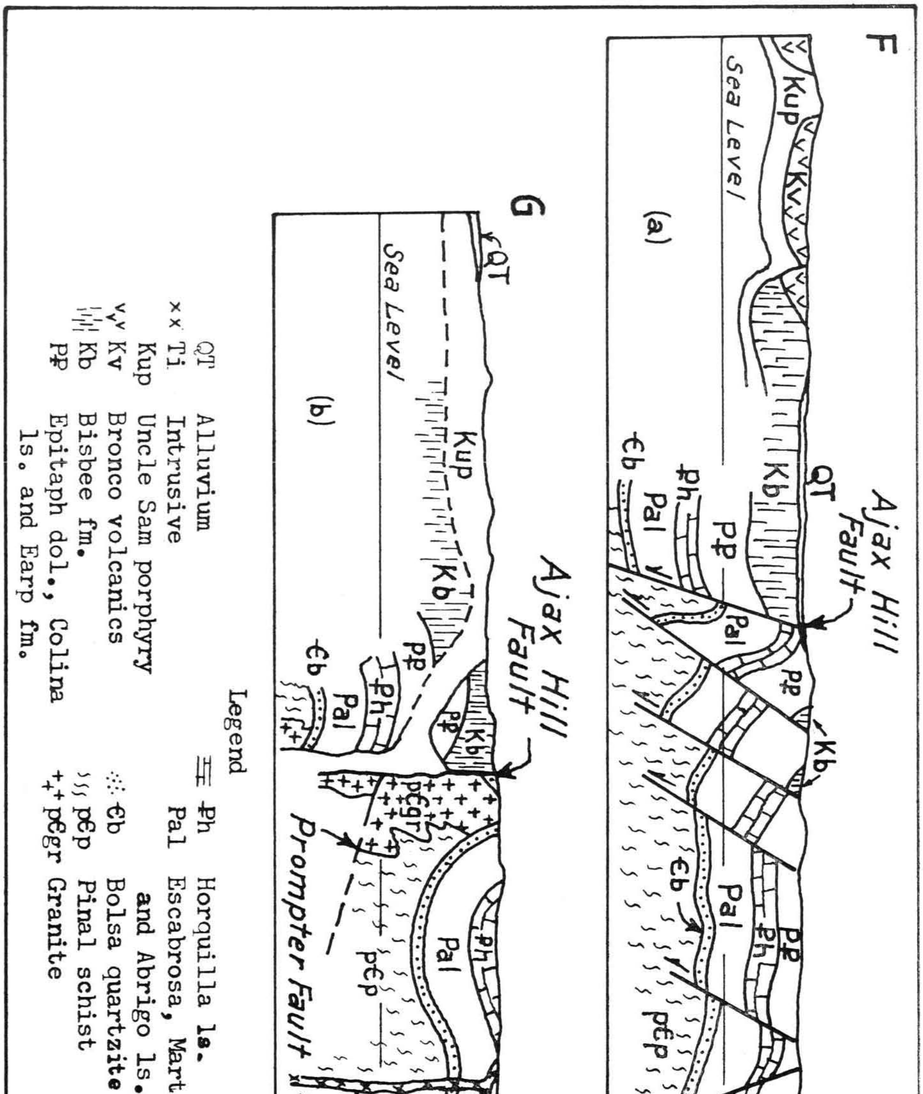


FIGURE 6. Generalized geologic map, Tombstone Hills.



From Gilluly (1956)

FIGURE 7. East-west structure sections, Tombstone Hills.

Ajax Hill horst was a compressional structure "formed . . . owing to partial shearing off of the basement ahead of the thrust and squeezing up of the block to the east" (Gilluly, 1956, p. 132). In my opinion the major thrust envisioned by Gilluly does not exist. The following three sections of the paper are keyed by subject to Gilluly's three lines of argument and present a detailed discussion of the basis for my disagreement.

Klippen and Their Significance

The single most important piece of evidence bearing on the existence of the conjectural overthrust is the large block of Permian Colina limestone and Epitaph dolomite and a smaller block of Epitaph that rest on Bisbee rocks immediately west of the Ajax Hill horst. Figs. 6, 7, 8 indicate that if the klippen came from the west, as believed by Gilluly, extensive overthrusting is strongly suggested. Conversely, if the klippen came from the east, a sliding origin must be preferred. Evidence suggesting an easterly origin by sliding can be conveniently grouped into two categories: (a) regional structural relationships, and (b) structures within, and adjacent to, the klippen.

> (a) The geologic setting is perfect for sliding (Figs. 618). An inspection of Figs 7b and 8 clearly shows that replacing the eroded strata on top of the Ajax Hill horst demonstrates that the development of the Ajax Hill fault could have created a westward dipping slope of any desired magnitude for the Permian rocks to slide down. In addition, the Paleozoic rocks on the west flank of the Ajax Hill horst would have been dipping in the right direction to facilitate sliding. Moreover, the massive Permian carbonates and the overlying but since eroded Cretaceous rocks are precisely the rocks to be expected in a slide block off of Ajax Hill anticline.
>
> The regional relations do not favor thrusting. An inspection of Gilluly's cross sections (e.g. Fig. 7, this paper) demonstrates that if thrusting from the west is invoked the klippen must have originated west of the west end of the cross sections in a covered area many miles to the west of the klippen. An inspection of the map (Fig. 6) does not make things any easier. If one is inclined to special pleading, it is possible to believe the source area of the thrust is buried under the Uncle Sam porphyry. However, Gilluly's cross sections do not suggest this, and the fact is that no convincing evidence of major thrusting exists west of the klippen under consideration.
>
> (b) There are several structural features within or adjacent to the klippen which are inconsistent with thrusting from the west, but which have a straightforward explanation in terms of gravity sliding from the east (Fig. 8). Gilluly (1956) mapped two normal faults within the larger klippe that down drop the west side of the block but probably do not cut the underlying Cretaceous rocks and do not displace

the fault contact at the base of the klippe (Fig. 8). As a consequence, different Permian rocks overlie the surface of the "overthrust" in each of the small blocks defined by the normal faults. The most reasonable interpretation of these relationships is that the normal faulting occurred prior to the final emplacement of the klippe. Clearly, west dipping

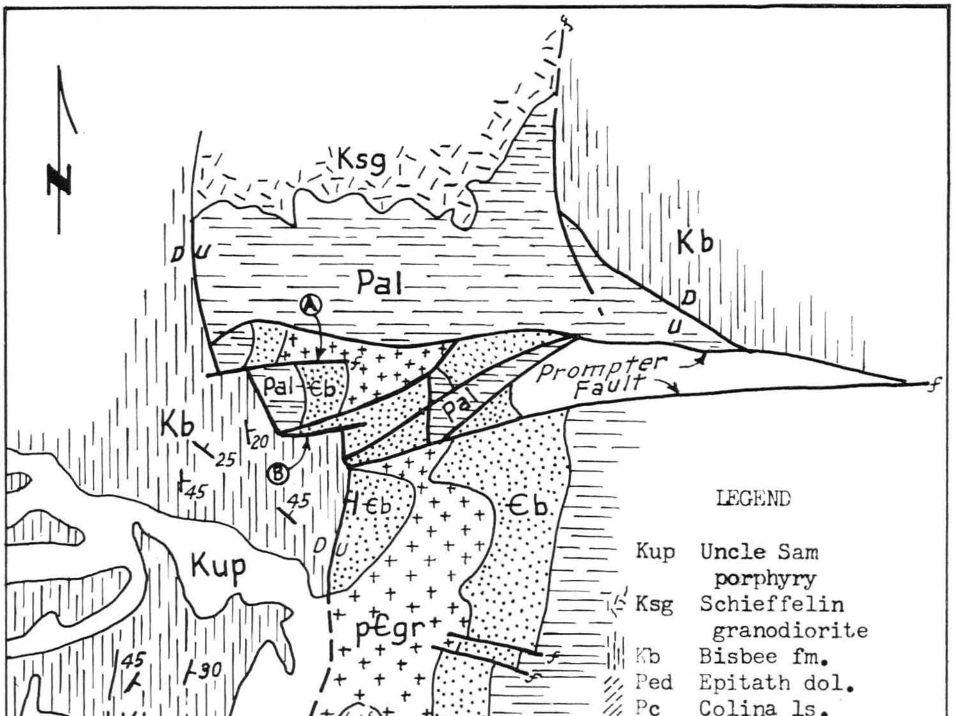


FIGURE 8. Semi-detailed map of the Ajax Hill area.

normal faulting is more likely to occur in a block moving westward under the influence of gravity than in the thin frontal edge of an eastward moving thrust sheet.

The massive limestone and dolomite strata of the larger klippe exhibit very few internal structures. Probably the most significant is a shearing out of approximately 30-40 feet of strata near the base of the west corner of the klippe. At this location the upper beds strike N5°W and dip 10° E. Below them are poorly exposed strata that strike N50°W and dip 30° N. The lower beds appear to bend into conformity with the overlying beds as the intersection of the two sequences is approached. This relationship is interpreted as an overriding and cutting out, from east to west, of the lower beds by the upper ones. In addition, two small faulted folds within the larger klippe suggest that the klippe was emplaced from east to west. Despite an intensive search, no internal structures were found which indicate, or suggest, an emplacement of the klippe from the west. In particular, the block has no internal structures consistent with Gilluly's (1956, p. 132) interpretation that the block was the leading edge of a thrust which formed the Ajax Hill horst by . . . "partial shearing off of the basement ahead of the thrust and squeezing up of the block to the east."

At the base of the klippen the younger Permian rocks are generally exposed to the west rather than to the east. Although this relationship would be expected in the leading edge of a westward moving gravity slide, most thrusts cut up, not down, section in their direction of motion. Moreover, it is difficult to understand why, after a thrust has cut across massive competent carbonates to within several hundred feet of the less competent Cretaceous strata, it should cut back deeper into the competent carbonates once again.

Although the Cretaceous rocks in the vicinity of the klippen are too poorly exposed or too deformed to permit determining the direction of overriding by study of small scale internal structures, a plot of all available strikes and dips in the Cretaceous rocks adjacent to the klippen shows a definite tendency for the strike of the Cretaceous rocks to parallel the erosional edges — and possibly the original outline — of the klippen (Fig. 8). The fact that the Cretaceous rocks directly adjacent to the larger klippe are much more structurally disturbed than those farther removed suggests that the semi-parallelism of strike of the Cretaceous and the erosional edge of the klippe may in part be a result of the plowing action of a westerly moving block. However, Gilluly's map and sections (Figs. 6, 7, this paper) suggest that the major reason for the change in dip of the Cretaceous rocks from east and southeast along the northern and western part of the slideblock to southwest near the southern part of the block is the southward decrease in displacement on the Ajax Hill fault. If, as postulated, the Ajax Hill horst and fault controlled the emplacement of the klippe, the structure of the Cretaceous strata adjacent to the fault can be interpreted as providing a structural low for the block to slide into and be preserved.

In the northwestern part of the Tombstone Hills, north of Three Brothers Hill, a small sliver of Colina limestone rests on Bisbee rocks along a westerly dipping fault contact (Fig. 6). Gilluly interpreted this block as a remnant of his major thrust. It could be, but unfortunately the block is small and is surrounded on three sides by a large mass of Uncle Sam porphyry which was emplaced after the block of Colina reached its present structural position. Thus, in my opinion, neither the local significance of the block nor its importance in understanding the major deformation in the Tombstone Hills can be reliably interpreted.

Mode of Intrusion of the Uncle Sam Porphyry

Gilluly (1945) devoted a whole paper to the mode of intrusion of the Uncle Sam porphyry. An emplacement along a thrust plane was argued for on the basis of: (a) the fine grained nature of the intrusive, implying solidification near the surface, (b) the abundant and varied inclusions, requiring a convenient source for same, and (c) the demonstrable fact that locally the porphyry intrudes fault planes (e.g. Ajax Hill fault) and is sill like in form.

Although the emplacement of the Uncle Sam porphyry was clearly locally controlled by faults, it is readily apparent from Gilluly's maps, cross sections (e.g. Fig. 7, this paper), and discussion that where the actual contact relationships can be established the Uncle Sam porphyry cuts across bedding planes, is sill like in both the Bisbee formation and Bronco volcanics, and follows the Bronco-Bisbee unconformity as often, or more often, than it appears along known fault planes. As noted by Gilluly (1956, p. 131), the Bronco volcanics and the surface underlying the presumed thrust fault remnants have a similar west dip. However, it is obvious that the known erosion surface at the base of the Bronco volcanics (Gilluly, 1956, p. 130) has a similar dip, and, if such a dipping surface is deemed necessary to explain the distribution and mode of emplacement of the Uncle Sam porphyry, the known erosion surface should qualify at least as well as the conjectural thrust. In addition, the fact that inclusions of Precambrian and Paleozoic rocks are far more abundant to the east than to the west in the presumed source area of the thrust (Gilluly, 1945, p. 653), is a strong suggestion that the Uncle Sam porphyry obtained many of its inclusions from the area near Ajax Hill, either along the Ajax Hill normal fault or from the pre-Bronco erosion surface developed around the Ajax Hill horst. It is extremely interesting that in his abstract Gilluly (1945, p. 643) describes the emplacement of the Uncle Sam porphyry as follows: ". . . the intrusive is roughly laccolithic in form and has extended laterally along either a thrust or erosional surface." This statement is extraordinary in that the above reference to possible emplacement along an erosion surface is the only time that possibility is mentioned in either of his two papers.

In my opinion a great deal more evidence must be forthcoming before the mode of intrusion of the Uncle Sam porphyry can be considered to demonstrate large scale overthrusting in the Tombstone Hills.

Ajax Hill Horst

The Ajax Hill horst is a north-south trending anticlinal uplift which has Precambrian schist and granite in its core and whose west flank has been down faulted as much as 7000′ along the Ajax Hill fault. Clearly it is the major structural feature of the Tombstone Hills (Figs. 6 through 8). Not only do the map and structure sections demonstrate that the Ajax Hill horst was the dominant Laramide structure, but they also show that the present structural and topographic highs in the Tombstone Hills were also the areas of maximum Laramide uplift (Figs. 6 and 7).

Although the Ajax Hill fault has a west dip in the area of greatest displacement (Butler, et al, 1938, p. 31) and Gilluly (1956, p. 102) interpreted the fault as a normal fault, Gilluly (1956, p. 102 and 132) also believed that the Ajax Hill fault was a compressional feature and was formed during the same epoch as the presumed thrust. Part of the argument for compression and shortening is the 3000′ of shortening over the uplifted area of the Ajax Hill horst (Fig. 7b; Gilluly, 1956, p. 132). However, this figure makes the implicit assumption of no compensating extension in the footwall block. The 7000′± of throw on the fault requires an average west dip of 67° to account for the necessary 3000′ of extension. The 67° dip is slightly less than the observed surface dip but the mild discrepancy can be easily accounted for two other factors. First, the Uncle Sam porphyry intruded along the fault locally reaches 1000′ in thickness and may in part reflect extension independent of that accomplished by the fault. Second, and most important, the "reverse drag" into the fault of the Cretaceous rocks in the footwall of the fault strongly suggests, by analogy with the Gulf Coast where excellent well and seismic control is available, that the Ajax Hill fault is concave upward and flattens at depth. On the Gulf Coast the dip into the fault is necessary to fill the space created when the deeper beds pull apart along a fault surface which is concave upward. That this phenomenon is not restricted to non-lithified rocks has recently been well documented by Hamblin (1965) who, by means of vertical exposures in the north side of the Grand Canyon, clearly demonstrated that the reverse drag so characteristic of the major normal faults of the southwestern margin of the Colorado Plateau is caused by the flattening of the dip of the faults at depth.

Gilluly (1956, p. 132) interpreted the east-west trending Prompter fault on the north flank of the Ajax Hill horst as a transcurrent fault formed when the main body of the Ajax Hill was sheared off and squeezed up ahead of the major thrust he postulated in the area (Fig. 8). My lack of belief in the thrust obviously requires a close look at the Prompter fault. Butler et al (1938) termed the Prompter fault a reverse fault. Such a conclusion appears reasonable since the fault dips steeply south, the north side is always downthrown, and the strata in the footwall generally strike parallel to the fault and are often vertical to overturned. Gilluly's case for transcurrent movement was based on the apparent westerly offset along the north side of various branches of the fault. Although the geologic map (Fig. 8) shows such offsets, the details of the offsetting faults argue for the primacy of vertical, not horizontal, movement. The major offsetting is along faults A and B (Fig. 8), but neither of these faults could have had significant horizontal movement without extending eastward into one of the main branches of the Prompter fault. Such extensions are not shown on either Gilluly's or Butler's map and they were not found in the field by myself (Fig. 8). Clearly, if the faults are correctly mapped, the east-west and north-south faults in the critical area must have developed simultaneously by differential vertical movement. A further difficulty in associating the Prompter fault and the "thrust" is the fact that many dikes related to the Schieffelin granodiorite of post Ajax Hill horst and of post "thrust" age are cut off by the Prompter fault (Butler et al, 1938). Obviously this latter movement had no genetic relationship to the presumed thrusting and transcurrent faulting.

The Precambrian granite which Gilluly mapped in the core of the Ajax Hill horst is a major statistical oddity since all of Gilluly's cross sections clearly show that he shares my belief that schist constitutes over 98% of the Precambrian basement in the area he mapped in central Cochise County. Gilluly's sections also indicate he believed that the Ajax Hill fault, the largest fault in the Tombstone Hills, cuts right through the middle of the granite. Despite the lack of direct evidence, this is probably an unrealistic interpretation. Everywhere in southeast Arizona where the nature of the Precambrian rocks is known on both sides of large faults, granite has been upfaulted with respect to schist (e.g., Whetstone and Dos Cabezas Mountains and Johnny Lyon Hills). A similar interpretation is offered here for the Ajax Hill fault and associated Precambrian granite.

Laramide Orogeny — An Intimate Association of Deformation, Vulcanism and Intrusion

If Gilluly (1956, p. 103) is correct in his belief that the Uncle Sam porphyry is older than the Schieffelin granodiorite, the emplacement of the Schieffelin was probably the last major event in the complicated history of the Tombstone Hills. The dating of the Schieffelin granodiorite as latest Cretaceous (72 m.y.) by Creasey and Kistler (1962) severely limits the time span available for the sequence of major orogenic, extrusive and intrusive igneous events in the Tombstone Hills. Conforming to the sequence of events ascribed to by Gilluly (1956, pp. 131-133; 160), the latest Cretaceous age of the Schieffelin now makes it necessary to compress the following sequence of major events into what was left of Cretaceous time after deposition of the Lower Cretaceous Bisbee formation. (1) N-S compression, (2) a major unconformity involving "a considerable interval of time" 'Gilluly, 1956, p. 131) at the base of the Bronco volcanics, (3) extrusion of 6000′+ of the Bronco volcanics, (4) E-W to NW-SE compression and the major deformation of the Tombstone Hills, (5) intrusion and quick quenching of the Uncle Sam porphyry, (6) extrusion of a thick sequence of andesites, and (7) intrusion and slow cooling of the Schieffelin granodiorite at the same crustal level as the Uncle Sam porphyry. This concentration of activity invites two conclusions, stated and discussed below.

1) There is not enough time for two major, orthogonal, compressional episodes. Gilluly fully recognized the problem involved in having the direction of major compressional stress rotate nearly 90° in a short period of time. By considering the last major event, the emplacement of the Schieffelin granodiorite, as probably mid-Tertiary in age, and by tentatively concluding, "as a matter of convenience rather than demonstration" (Gilluly, 1956, p. 132), that both a long period of erosion and the deposition of the Bronco volcanics intervened between the two proposed compressional episodes, Gilluly was able to sufficiently stretch out the period of time between the presumed N-S and E-W periods of compression to make them both appear possible. At the time of Gilluly's work, his conclusions were fully consistent with the available dating. Now, however, the late Cretaceous age of the Schieffelin granodiorite puts a severe strain on the reasonableness of two major orthogonal compressional episodes. There was probably not enough time. It is suggested here that neither of the presumed compressional episodes was as strong or as distinct as Gilluly suggested. Earlier in this article several lines of evidence were presented which severely limit the amount of E-W compression which can be demonstrated in the Tombstone Hills. In my opinion, N-S shortening is equally difficult to demonstrate. The cross section in Fig. 9a trends N15°E across the Ajax Hill horst and the east end of the Tombstone syncline. By including the offset shown on the normal fault at the left of the section, net shortening across the entire section, including the major compressional structures of Gilluly and Butler et al, — the Ajax Hill horst, the Prompter reverse fault and the compressed Tombstone syncline — is zero. (The "thrust" at the upper right hand corner of the section is not included in the measurements because a field of inspection of the small severely brecciated block of Colina indicated it could be reasonably interpreted as a slideblock which moved into its present position from the hanging wall of the Prompter fault.) The cross section in Fig. 9b trends N-S across Government Butte and Earp Hill. In a cross section of this type, where the thrusts and folds involving the shortening do not extend beyond either end of the section, geometrical

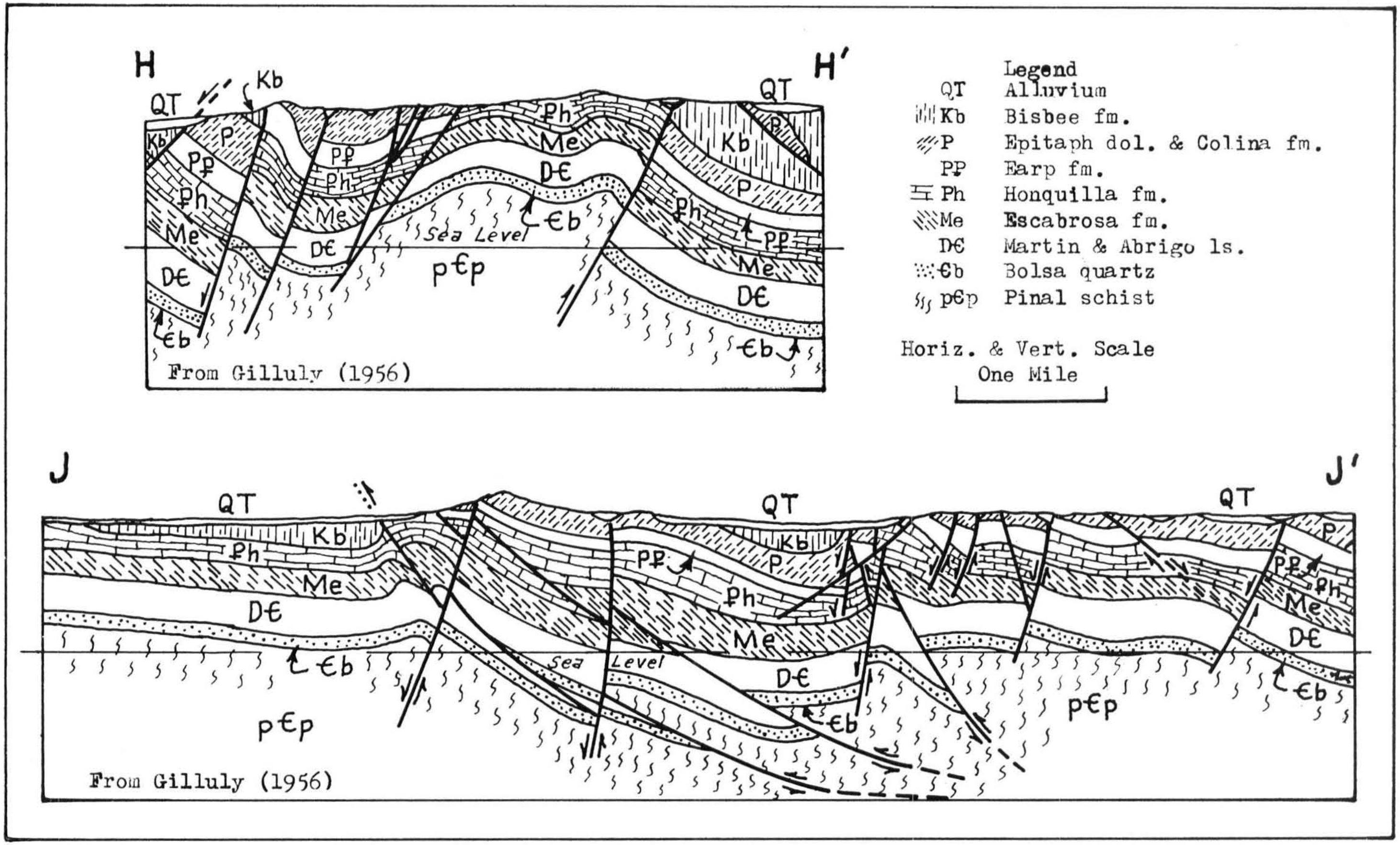


FIGURE 9. North-south structure sections, Tombstone Hills.

considerations dictate that the shortening must be the same for all horizons no matter what combination of folding, faulting or flowage effects the shortening. Such does not appear to be the case with Fig. 9b. The best controlled part of the section must be the surface and here 11 out of 15 faults are normal faults and the uppermost formations down to the Earp show no demonstrable shortening. The shortening of the older formations increases progressively downward until, at the depth of the Bolsa quartzite, a shortening of some 8000′ is indicated. One has the choice of believing the pronounced shortening inferred at depth or the minimal shortening indicated near the surface. My preference is obvious.

In summary, it is argued here that Gilluly's sections indicate neither N-S nor E-W shortening, and, as a consequence, the problem of timing of compressional episodes caused by the late Cretaceous age of the Schieffelin granodiorite does not exist.

2) The close temporal and spatial association of deformation, vulcanism and intrusion in the Tombstone Hills must imply a genetic relationship between all three. It is suggested here that in Laramide time rising magmas (a) broadly domed the area of the Tombstone Hills causing local compressional features of diverse trends but primarily causing normal faulting, (b) pushed up the Precambrian granite, (c) permitted access to the surface of various extrusive rocks, and (d) concluded their active rise by intruding some of the faults and then solidifying in the near surface rocks. The three types of activity probably peaked in the following sequence: deformation, vulcanism, and intrusion, as would be anticipated if rising magma was the prime mover. However, it cannot be stressed too highly that all three forms of activity strongly overlapped and had major fluctuations in intensity.

Basin and Range Orogeny

Gilluly (1956, p. 158) believed that the Tombstone Hills are typical fault block mountains whose boundary faults are obscure only because the "faulting ceased long enough ago (early Pleistocene?) to allow later erosion to reduce the fault relief and for younger gravel to bury the faults." An alternative interpretation is that the faults are obscure because they are small in number and significance. In my opinion it cannot be pure coincidence that the Ajax Hill horst was clearly the area of maximum uplift in Laramide time and is just as clearly the area of greatest uplift today. Tertiary uplift of the large block welded together by the various intrusions undoubtedly rejuvenated the Tombstone Hills as indicated by the normal faults cutting "Gila" gravels mentioned by Gilluly, the renewed movement on the Prompter reverse fault which offsets Tertiary(?) dikes (Butler, et al, 1938), and perhaps some of the westward tilt of the Bronco volcanics. However, it is clear that this later uplift only accentuated an uplift which was present as a result of Laramide deformation.

Although most of the normal faults within the Tombstone Hills cannot be dated more precisely than post Permian or post Lower Cretaceous, it is very unlikely that many of them are of Basin and Range age. The most important, the Ajax Hill fault, is clearly a Laramide structure. In the southern Tombstone Hills many of the normal faults are parallel to and genetically related to minor thrust faults of presumed Laramide age. In the area southeast of the Ajax Hill horst at least two normal faults are cut off by a rhyolite porphyry intrusion 63 m.y. in age (Creasey and Kistler, 1962). To the north the numerous normal faults and dikes indicated by Butler and Wilson (1938) to be older than the Schieffelin granodiorite attest to the intimate association of normal faulting and the Laramide deformation.

During much of early Tertiary time the center of the Tombstone Hills may have been a "fossil" high buried beneath a thick accumulation of volcanic rocks. As noted by Gilluly (1956, p. 88) the presently preserved thickness of 6000′ of the Bronco volcanics is a strong presumption that the Bronco volcanics once completely covered the area of the Tombstone Hills. Gilluly also suggested that the textural differences between the Schieffelin granodiorite and the Uncle Sam porphyry implied that, since the two intrusives were emplaced at the same crustal level, the Schieffelin cooled slower and, therefore, was possibly overlain by an additional volcanic series which has subsequently been eroded away. Other periods of extensive volcanic cover may have existed if the 3000′+ of the S.O. volcanics of probable mid-Tertiary age extended much farther west than their present outcrop in the synclinal area east of the Tombstone Hills, and if flows associated with the volcanic necks and sills of probable Paleocene age in the southern Tombstone Hills and northern Mule Mountains covered the area. Such a volcanic cover would account for the fact that relatively little erosion of the pre-Tertiary sedimentary rocks has occurred in the Tombstone Hills in post Cretaceous time.

Summary

The structural development of the Tombstone Hills is more reasonably interpreted in terms of complications developed over the top of rising Laramide magmas than as a product of two orthogonal major compressions followed by blocking out of the range by Basin and Range faults.

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