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TECTONICS OF THE CENTRAL DRAGOON MOUNTAINS: A NEW LOOK

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Abstract

Traditional interpretation of the structural geology of the central Dragoon Mountains holds that the predominant tectonic fabric resulted from compression-induced, low-angle tectonic transport via thrusting, the principal element of which is the Dragoon fault. Evidence based on new detailed mapping is presented that (1) establishes that intrusions previously mapped as Triassic-Jurassic have Precambrian ages and (2) invalidates the thrust fault hypothesis. The complex structural geometry consists of a large, northeast-vergent, northwest-trending, southeast-plunging fold pair named the Silver Cloud fold, which is parallel to the northwest-striking, high-angle normal fault named the Black Diamond fault. The Black Diamond fault had considerable pre-Cretaceous movement of southwest side down, which predates formation of the Silver Cloud fold. The Silver Cloud fold formed in response to northeast-directed compression between 72 and 52 m.y. ago. The Black Diamond fault considerably influenced the locality and geometry of the Silver Cloud fold. Relatively downthrown Paleozoic rocks southwest of the Black Diamond fault were compressed against an unyielding upthrown buttress of Precambrian crystalline rocks on the northeast resulting in the disproportionately large, disharmonic Silver Cloud fold. Implications of this structure for adjoining areas are also discussed.

Introduction

Traditional interpretation of the structural geology of the central Dragoon Mountains (Fig. 1) holds that the predominant tectonic fabric resulted from compression-induced, low-angle tectonic transport via thrusting of which the principal element is the Dragoon fault named by Cederstrom in 1946 and popularized by Gilluly (1956). We present new evidence based on detailed mapping that minimizes the importance of thrust fault tectonics and establishes a fold and high-angle normal-fault alternative to explain the complex structural geometry of the central Dragoon Mountains.

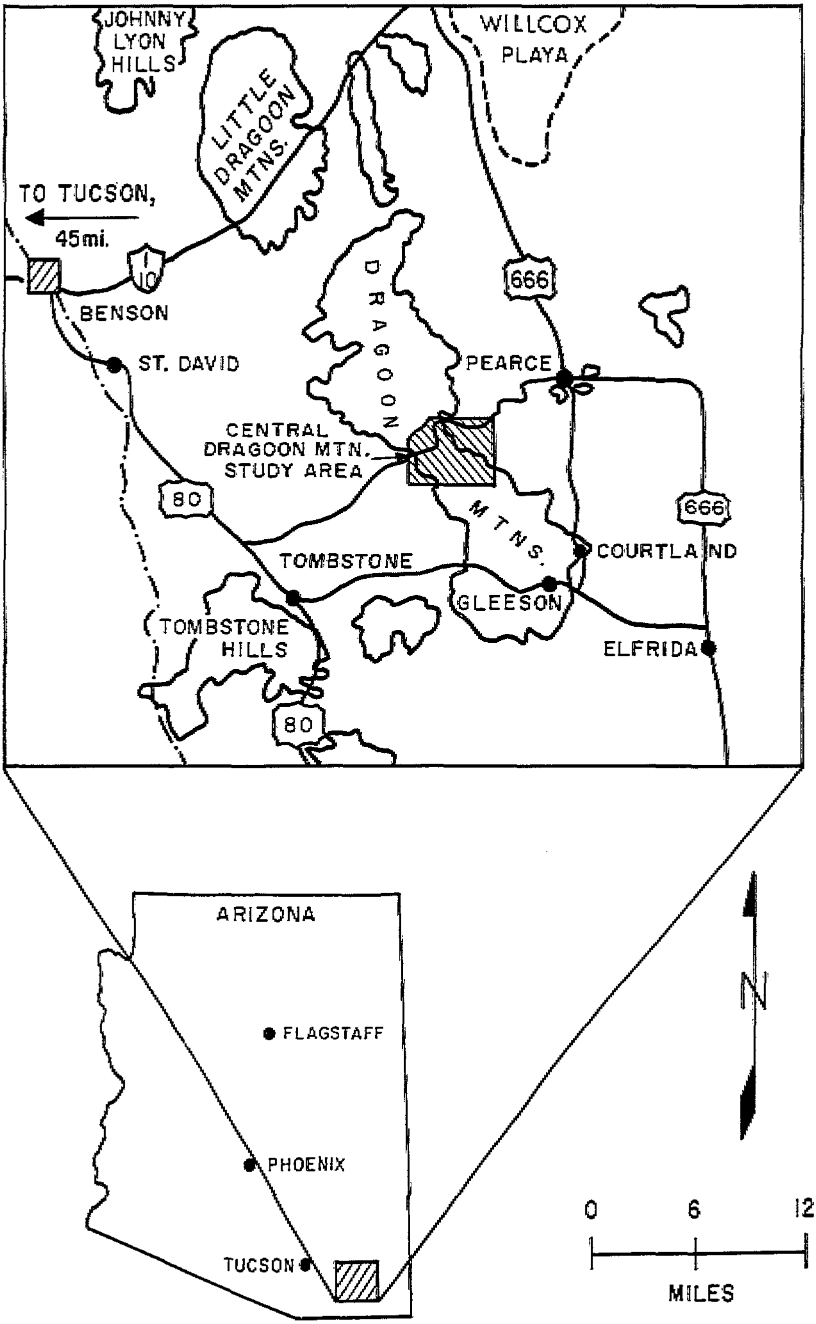

Figure I. Location map for the central Dragoon Mountains study area.

Preliminary mapping in the central Dragoon Mountains in the spring of 1975 disclosed problems with existing mapping interpretation. In an effort to gain insight into the complex structure of the central Dragoons, we mapped at a scale of 1 inch to 1,000 feet an area extending from the Middle Pass area southwest to the Dragoon Camp area, an area of about 16 square miles (Plate 3, in pocket). Our mapping units are essentially those skillfully defined by Gilluly and others (1954) and Gilluly (1956); only a summary description is provided in Table 1.

Our analysis has a six-part organization scheme. First, we will lay out the state of geologic knowledge for the Dragoon Mountains. Second, we will discuss the conflicts of our new mapping with existing maps (those of Gilluly, 1956, and Cederstrom, 1946). Third, using the constraints imposed by the new mapping, we will construct an alternative structural geometry. Fourth, we will place time constraints on the structural evolution of that geometry. Fifth, we will present a kinematic and dynamic interpretation for the spatial-temporal development of that structural geometry. Sixth, using the new interpretation, we will look briefly at its implications elsewhere in the Dragoon Mountains and vicinity and more generally for tectonic models in southern Arizona.

Previous Work

The first published geologic work in the Dragoon Mountains was —almost predictably—that of Ransome (1913) in the Courtland area about six miles southeast of the present study area. It was Ransome who first recognized the feature that in succeeding works would become known as the Courtland overthrust. Wilson (1927) described the low-angle faulting at Courtland and Gleeson in some detail, named the Courtland overthrust, and concluded that the thrusting postdated "mountain-making block faulting" in late Tertiary time after inception of the present-day physiography.

The central Dragoon Mountains were first studied briefly by Darton (1925), who noted a northwest-trending fold just south of the Stronghold Granite; that the Stronghold Granite intruded rocks up through the Lower Cretaceous Bisbee Group; and that easterly dipping Paleozoic rocks comprise the high ridge in the southern part of the area covered by this paper. No mention is made of any large-scale folding or high- or low-angle faulting (compare his Section C with Section D-D' of this paper). From 1932 to 1936, Cederstrom (1946) took the first detailed look at the structure of the central Dragoon Mountains. His principal observation was that the structure of this part of the Dragoon Mountains is fold dominated. Spatially, his cross sections E through H correspond quite closely with our sections A through D. Cederstrom recognized a steeply southwest-dipping fault in the southern part of his area that juxtaposed what he thought was right-side-up Cretaceous Bisbee Group against upper Paleozoic rocks. This he named the Dragoon fault and concluded that it was genetically related to the northwest-trending folding produced by southwest-northeast-directed compression. Also essential to Cederstrom's story is the presence of allochthonous masses of Bolsa Quartzite near Kelley's ranch and the Sentinel (section E), and on Black Diamond Peak (section F). These he believed to be upper plate remnants of a large continuous overthrust mass which preceded the folding and, hence, was deformed by it. This is the first mention of the folded thrust concept which has had considerable subsequent popularity. Cederstrom thought that the allochthonous masses of Bolsa Quartzite were later intruded by Stronghold Granite, which he interpreted to postdate the compressive deformation.

Table 1. Summary description of rock units mapped in the central Dragoon Mountains

Age	Rock Unit Name	Description
Quaternary	Alluvium (Qal)	Loosely consolidated sands and gravels.
	Colluvium (Qc)	Loosely consolidated hillwash.
Tertiary	Rhyolite porphyry (Tr)	Dikes of rhyolite porphyry containing phenocrysts of quartz, albite feldspar, and locally pyrite, set in a yellowish-white aphanitic groundmass; forms NW-trending ridges.
	Quartz latite (Tql)	Medium-grained porphyritic quartz latite containing embayed quartz phenocrysts, biotite, and plagioclase in a light-gray groundmass.
	Andesite (Ta)	Small sills and dikes of very fine grained, dark greenish-gray andesite.
	Granodiorite porphyry (qmp)	Medium to fine-grained biotite granodiorite porphyry near Black Diamond mine
Early Cretaceous	Bisbee Group	
	Undivided clastic sediments (Ks)	Slope-forming, interbedded, light-green arkosic sandstones, red shales and mudstones, and local intraformational limestone-bearing conglomerates; minimum thickness is 3,000 feet.
	Quartzite (Kq)	Cliff-forming, clean to arkosic quartzite with a few interbeds of green shale and mudstone; 100-300 feet thick; present in southern part of mapped area.
	Glance Conglomerate (Kg)	Mainly a cliff-forming limestone conglomerate containing angular to subrounded clasts of upper Paleozoic limestones and chert in a carbonate matrix; 100-200 feet thick.
	Glance Conglomerate—quartzite clast facies (Kgq)	Conglomerate predominantly containing quartzite clasts with subordinate limestone clasts. Half a mile ENE of Bennett this facies contains numerous volcanic clasts. Matrix is generally a coarse, poorly sorted arkose of granitic composition.
	Sandstone lens (Ksl)	Friable, pinkish-red to brown, medium-grained sandstone.
Permian	Naco Group	
	Colina Limestone (Pc)	Cliff-forming, dense, dark bluish-gray, micritic to sparry limestone; locally contains large *Omphalotrochus* gastropods and large foraminifera; about 300 feet thick.

Table 1. Summary description of rock units--Continued

Age	Rock Unit Name	Description
Permian	Naco Group--Con.	
	Earp Formation (IP-Pe)	Slope-forming, varicolored (mostly pinks and yellows), interbedded siltstones, shales, and micritic limestones; contains large (to 3/8") foraminifera; greater than 50% clastics; 400-500 feet thick.
Pennsylvanian	Horquilla Limestones (IPh)	Interbedded, pink to maroon shales and thin- to thick-bedded, light bluish-gray, sparry limestones containing small fusulinids; greater than 50% carbonates; generally a slope-former; 1,500 thick.
	Black Prince Limestone (IPb)	Cliff-forming, medium- to thick-bedded, white, sparry, crinoidal limestone; no fusulinids; basal unit is locally a 15-foot thick maroon shale or angular chert conglomerate; 150 feet thick.
Middle to Early Mississippian	Escabrosa Limestone (Me)	Cliff-forming, medium- to thick-bedded, bluish-gray, massive, crinoidal sparry limestone; middle units contain large zaphrentid corals; 500 to 600 feet thick.
Late Devonian	Martin Formation (Dm)	Slope-forming, gray-brown, fine- to medium-grained, limy sandstone, brown and gray shale, and brown, yellow, and dark-gray dolomite; middle units contain bryozoa and Atrypa brachiopods; 350 feet thick.
Middle Cambrian	Abrigo Formation (Ꞓa)	Slope-forming, gray-green, sandy and micaceous shale, bluish-gray, thin-bedded to laminated mottled limestones, and a few interbeds of edgewise conglomerate; pisolitic beds locally; 500-600 feet thick.
	Bolsa Quartzite (Ꞓb)	Cliff-forming, white to pinkish-gray, fine- to coarse-grained, medium-bedded, generally well-sorted, silica-cemented quartzite; 300 feet thick.
Precambrian	unnamed granite (quartz monzonite) (pꞒgr)	Slope-forming, light yellowish-brown, medium- to coarse-grained, biotite quartz monzonite; rapakivi feldspar textures and large (to 1"), porphyritic K-feldspars locally; biotite is altered to chlorite; commonly recrystallized and sheared.
	Pinal Schist (pꞒps)	Slope-forming, brownish-green muscovite-chlorite-quartz schists.

Gilluly (1941, 1956) concluded as Cederstrom had that the structure of the central Dragoon Mountains was produced by east-northeast-directed compression but emphasized the presence of large thrusts:

> The northward-trending faults seem to involve "structural ungluing" of the Paleozoic and Mesozoic rocks from the basement, with repetition of thin thrust slices at and near the base of the Comanche. Presumably, the piling-up of these thrust slices raised the cover of Comanche rocks into a high anticline, with a syncline to the east. After this anticline had risen high enough to override the eastern syncline, the high-angle Dragoon thrust broke through it and overturned the western limb of the syncline along the eastern side of the present Dragoon Mountains. The travel involved in this high-angle thrust is not known, but apparently it need not have been very great, perhaps a few miles (Gilluly, 1956, p. 122).

Incorporated in the quotation is the clear implication that folding is the <u>result</u> of thrusting. The key structural element of thrusting for Gilluly in the central Dragoon Mountains is the Dragoon fault:

> The most conspicuous structural feature of the segment of the Dragoon Mountains here considered [the area of this report between Middle Pass and South Pass] is the Dragoon fault. This is a high-angle reverse fault whose displacement seems to increase markedly toward the south. It is clearly seen on plate 5 as marking the eastern boundary of the block of intrusive rocks and rocks of Paleozoic age that constitutes the main divide of the mountains, separating it from the large area of Bisbee formation in the eastern foothills (Gilluly, 1956, p. 143).

The position of the Dragoon fault on Gilluly's plate 5 is nearly identical to Cederstrom's placement of the Dragoon fault trace southwest of Silver Cloud Peak.* However, Gilluly shows the Bisbee Group northeast of the Dragoon fault to be overturned (a point with which we agree). The thrust-fault emphasis of Gilluly is clearly seen in cross section (Fig. 2). Gilluly adopts Cederstrom's folded overthrust concept, although he changes its placement considerably. For example, Gilluly argues that the allochthonous Bolsa Quartzite of Cederstrom on Black Diamond Peak is in reality resting unconformably on Precambrian granite (a point with which we also agree). For Gilluly, the overthrust on Black Diamond Peak is drawn between the Precambrian basement and the Bisbee Group (Fig. 2, section VII). Gilluly also adds allochthonous Escabrosa Limestone capping Silver Cloud Peak (Fig. 2, section VII). The effect of the thrust fault geometry (see especially section VI, Fig. 2) is parleyed into this final conclusion by Gilluly (1956, p. 160):

> It seems that any reasonable reconstruction of the rocks to depth on the basis of their present attitudes and distribution requires that the observed crust was shortened by several miles. There is a strong suggestion that much of the surficial faulting took place while the bedded rocks were being stripped off the basement. Much faulting took place, and I infer that it was in this way that the Bisbee rocks along the east side of the Dragoon Mountains were sufficiently uplifted to allow them to overfold into a recumbent syncline. Over this southward-plunging syncline the Dragoon thrust was able to ride along a zone of transcurrent faulting.

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*Place names used in this paper are adapted from Cederstrom (1946) and the Pearce 15-minute quadrangle map. Gilluly (1956) refers in his text to Silver Cloud Peak as Black Diamond Peak.

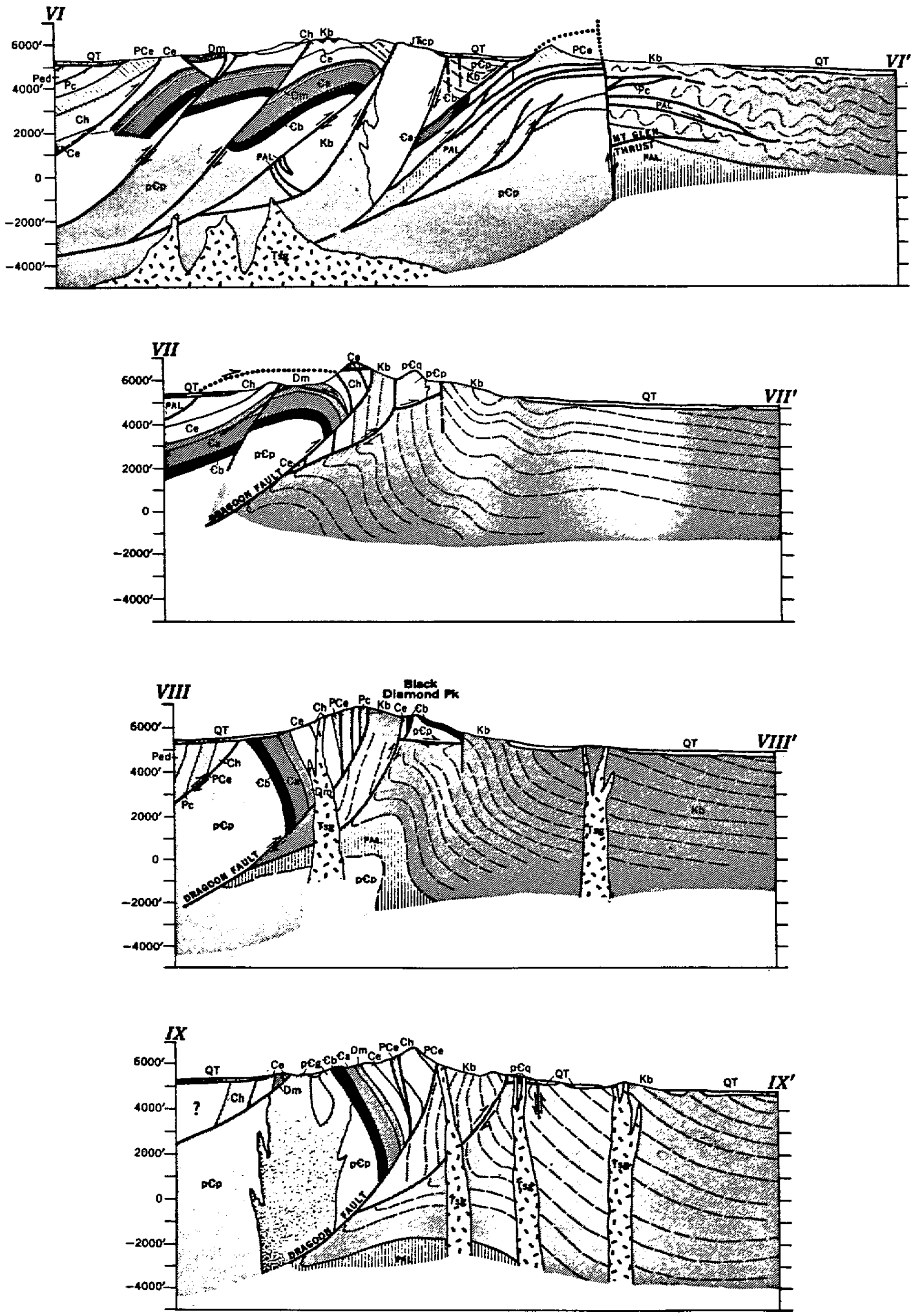

Figure 2. Geologic sections VI, VII, VIII, and IX taken from Gilluly (1956, plate 6) through the central Dragoon Mountains.

Gilluly also revised Cederstrom's igneous scheme considerably, pointing out the presence of Precambrian basement rocks beneath Black Diamond Peak and arguing that the plutonic rock in Sorens Canyon is not Stronghold Granite but is a Triassic-Jurassic analog of the Gleeson Quartz Monzonite. Gilluly (1956) named this plutonic rock in Sorens Canyon the Cochise Peak Quartz Monzonite.

The work by Gilluly has considerably influenced subsequent work. Cooper and Silver (1964) applied Gilluly thrust-fault concepts to low-angle fault phenomena in the Dragoon quadrangle to the north:

> The major structural features of the Dragoon Mountains as we have been able to determine them—dynamic thinning of formations, flowage and recrystallization phenomena, repetition of units by strike faults, structural asymmetry, and overturning to the east-northeast—suggest intense deformational movements toward the east-northeast. This conclusion is in general agreement with those of Gilluly (1956, p. 133) for the adjacent part of the range which he described as "a succession of closely folded rocks, but by folded thrusts, steep reverse faults, and flat thrust faults, the whole indicating overriding from the west." (Cooper and Silver, 1964, p. 105).

MacRae (1966) accepted the Gilluly model, but added to it a gravitational flavor in the Courtland-Gleeson area:

> The apparent underthrust relationship of the other thrust sheets in the imbricate structure may be the results of renewed but reversed movement along the thrust planes following release of the compressional forces (MacRae, 1966, p. 134).

Most recently, Drewes (this Digest) has used the Dragoon fault (renamed the Cochise thrust fault by Drewes) as evidence for a vast allochthonous system spanning southeastern Arizona and southwestern New Mexico (see also Lowell, 1974).

One significant exception to the lateral compression hypothesis is offered by Jones (1961, 1963, and 1966), who suggests that differential vertical uplift is a major factor in the structural evolution of southeast Arizona. The intriguing thing about Jones' work is that he used existing map data (principally that of Gilluly, 1956) to construct through cross sections a reasonable antithetic interpretation of differential vertical uplift. Such is the ambiguity of geologic mapping!! According to Jones (see section E-E', Jones, 1963, and compare with section IX-IX', Fig. 2) the central Dragoon Mountains are an upright anticlinal uplift of Phanerozoic sedimentary rocks draped passively over a narrow, differentially vertically uplifted core of Precambrian granite. For Jones (1963, p. 146), "the most reasonable conclusion might be that the normal faulting and thrusting occurred simultaneously in 'Laramide' time as results of a narrow, almost diapiric, uplift of Precambrian granite." Notwithstanding the alternative viewpoint of Jones, it is probably a fair statement that the current thinking of people who have done fieldwork in the Dragoon Mountains favors a compressional thrust-fault-dominated geometry for the structure of the central Dragoon Mountains.

Conflicts with Existing Mapping

That we would have several major and fundamental disagreements with the maps of Gilluly (1956) and Cederstrom (1946) quickly became apparent in our mapping. Since these disagreements bear heavily on our interpretative position, it is important to state precisely their nature. We do so by referring specifically to locations on Plate 3 (in pocket) with supplementary photographic evidence wherever possible, and we invite the reader to inspect the field relations in dispute and judge for himself. These reinterpretations are intended to promote a better understanding of the complex structural history of the region. A good working knowledge of Cederstrom's and Gilluly's geologic accounts is recommended before reading this section.

Nature of the Dragoon Fault

The mapping revealed little support for the Dragoon fault of Cederstrom (1946) and Gilluly (1956). Alternatively there is abundant evidence that the trace of the Dragoon fault is actually a depositional surface between upper Paleozoic carbonate rocks and overlying Bisbee clastic rocks. The base of the Bisbee Group here is generally marked by a limestone conglomerate which we believe correlates with the basal unit of the type Bisbee Group, the Glance Conglomerate. Both Cederstrom and Gilluly recognized a limestone conglomerate that consistently occurred between the Palèozoic carbonate section and the Bisbee Group (from Silver Cloud Peak to the southwest corner of our map). Cederstrom provisionally correlated this conglomerate with the Glance and placed the Dragoon fault between the conglomerate and the rest of the Bisbee succession. Gilluly made no effort to correlate the conglomerate with the Glance and indeed in cross section inferred the conglomerate to be intercalated within the Bisbee Group. In Gilluly's (1956, p. 143) version, the Dragoon fault is implied to lie between the conglomerate and the Paleozoic rocks:

> The Bisbee formation of the footwall of the Dragoon fault is chiefly limestone conglomerate for long distances parallel to the fault and locally dips away from it at angles as low as 25°.

We made special efforts to locate the Dragoon fault. At location 1a, Plate 3, on the southeast side of Silver Cloud Peak the contact between the limestone conglomerate and the Permian Colina Limestone (?) is well exposed for about one hundred yards along strike. As shown in Figure 3, the contact at this location is depositional. Farther southwest at locations 1b and 1c similar good exposures provide the same relationship.

Nowhere was any significant fault found in this stratigraphic interval. A small fault at location 1e appears to be related to the emplacement of a small, quartz-latite porphyry mass as it lacks any lateral extension away from the intrusive body. At location 1a small discontinuous shears (to 0.5 inch wide) are locally present at the limestone conglomerate—upper Paleozoic carbonate contact. Clasts in the conglomerate immediately adjacent to the contact are systematically deformed and imbricated with long axes trending about S 50° W. The limestone clasts are embedded in a phyllonitic matrix. However, orientation of the clasts quickly becomes random within about three feet of the contact. Local movement along the contact is conceded, but its magnitude could not have been on the scale of miles for clasts in the conglomerate bear an impressive compositional similarity to <u>in situ</u> Paleozoic carbonate rocks a few feet upslope from the overturned contact. Movement of a few feet in a N 50° E direction is entirely consistent with layer adjustments in response to a flexural slip folding which will be a major part of our alternative geometric model.

Downslope from the limestone conglomerate at location 1a, a 75- to 100-foot-thick quartzite unit rests depositionally on the limestone

Figure 3. Exposure of overturned Glance Conglomerate—upper Paleozoic carbonate contact at location Ia.

conglomerate (the section here is overturned). The quartzite is in turn overlain by a sequence of interbedded green siltstones and red shales and mudstones. At location 1d the limestone conglomerate is underlain by a friable, pink to reddish-brown sandstone which appears to have been deposited in a channel cut on Permian rocks. The presence of a basal limestone conglomerate-quartzite-siltstone-shale sequence, post-Paleozoic—pre-Bisbee topography, virtual identity of the conglomerate clasts with adjacent upper Paleozoic carbonate rocks, depositional contacts, and the conspicuous lack of any significant fault movement (much less a high-angle reverse fault) points to pre-rotation transgression of Lower Cretaceous Bisbee Group rocks over a generally low-relief topographic surface cut on Permian(?) carbonate rocks rather than synrotation, high-angle reverse faulting à la the Dragoon fault.

The Folded Overthrust Hypothesis

Little evidence exists to substantiate the folded overthrust hypothesis as proposed by either Cederstrom (1946) or Gilluly (1956). Cederstrom's overthrust contact of Bolsa Quartzite on Black Diamond Peak (locality 2a) was pointed out by Gilluly and reconfirmed by us to be a classical erosional unconformity of Bolsa Quartzite resting on a Precambrian quartz monzonite (Figure 4), a rock similar to the Dos Cabezas rapakivi quartz monzonite dated at 1375 $\pm$ 40 m.y. by Erickson (1968, 1969) in the nearby Dos Cabezas Mountains. However, the revised position of the allochthonous overthrust masses as proposed by Gilluly also appears to have little basis for support. Gilluly reports that a large allochthonous sheet of Escabrosa Limestone caps the Silver Cloud Peak area (see section VII-VII', Fig. 2, and in Gilluly, 1956, Plate 5, and p. 143-144). We reinterpret these carbonates to be recumbently folded Colina Limestone and Earp Formation on the basis of large (to one centimeter) foraminifera at localities 2b and 2c (Plate 3). Also, in the hinge area of a recumbent fold at location 2c is a low-angle fault of reverse separation that is coplanar with the axial plane. Displacement appears to be only about 50 feet because local stratigraphy reasonably correlates across the fault.

The allochthonous Precambrian crystalline—Cambrian Bolsa Quartzite slice that Gilluly interprets to cap Black Diamond Peak is very likely autochthonous. The northwest end (location 2d) of the aforementioned allochthonous mass is shown by Gilluly (1956, on plate 5 and also see text col. 2, p. 145) to be a northwest-dipping, low-angle fault contact between the Bisbee Group (here composed of Glance Conglomerate) and the Precambrian granite. Inspection of this contact disclosed that it is definitely depositional with the Glance Conglomerate resting unconformably on the Precambrian granite (Fig. 5). In addition, low-angle faults separating the supposedly allochthonous Precambrian—Cambrian thrust slice could not be found. As the one available exposure unequivocally indicates that the Glance Conglomerate rests depositionally on the Precambrian granite, we conclude the Black Diamond area consists chiefly of autochthonous Cambrian and Precambrian rocks that are overlapped by the Early Cretaceous Bisbee transgression. Similar but more ambiguous relationships were found in the northeast corner of the area (location 2e).

Age of the Cochise Peak Quartz Monzonite

The Cochise Peak Quartz Monzonite in Sorens Canyon north of Middle Pass is reinterpreted to be Precambrian rather than Jurassic—Triassic as inferred by Gilluly (1956) or an apophysis of the Stronghold Granite as held by Cederstrom (1946). This reinterpretation is based on

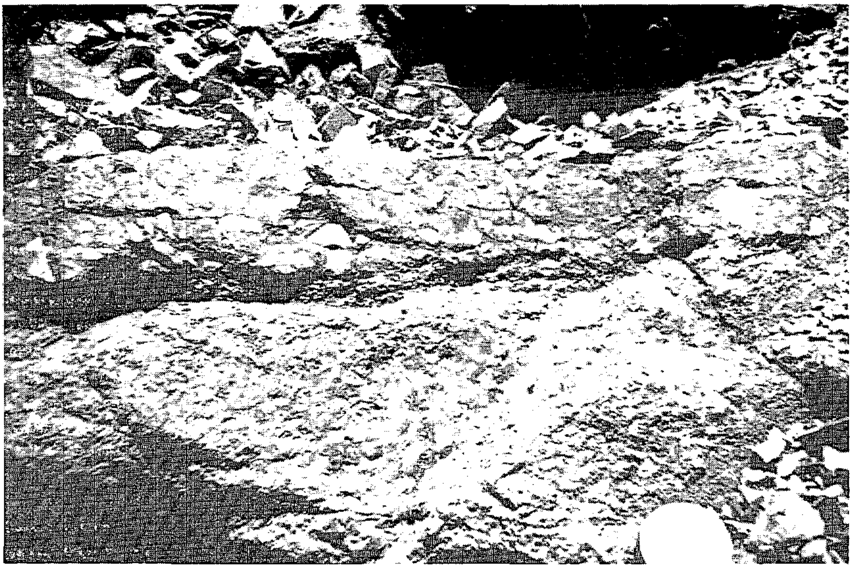

Figure 4. Exposure of basal conglomerate in the Bolsa Quartzite resting depositionally on Precambrian granite at location 2a.

Figure 5. Exposure of Glance Conglomerate-Precambrian granite depositional contact at location 2d.

contact relationships with the Bolsa Quartzite and petrographic similarity with the Precambrian granite underlying Black Diamond Peak. Gilluly (1956, col. 1, p. 64) reports Bolsa inclusions in and "frozen" contacts of Bolsa Quartzite with the granite (location 3a). We view evidence for intrusion at this site as equivocal and argue that a depositional alternative cannot be ruled out. The main premise in our Precambrian argument is from observation at location 3b (unmapped by Gilluly) where a basal quartzite–pebble conglomerate and regolithic material between the Bolsa and the underlying granite provide strong evidence for a Precambrian age assignment. Granite–Bolsa relations at the Sentinel (location 3c) are also persuasive where the basal Bolsa Quartzite consists of a coarse-grained granitic arkose compositionally similar to the underlying quartz monzonite. Gilluly's thinking on these plutonic rocks is neatly summarized on p. 65:

> The Cochise Peak quartz monzonite, despite its textural differences in the less-crushed facies, evidently closely resembles both the Precambrian (?) quartz monzonite near Dragoon Camp and the dominantly altered facies of the Gleeson quartz monzonite in both mineralogic and chemical composition. In fact, were the rock at Dragoon Camp not in relations that suggest Precambrian, little doubt exists that the Cochise Peak quartz monzonite would have been mapped as a northern representative of the Gleeson quartz monzonite (Gilluly, 1956, p. 65).

The previous three reinterpretations are the main discrepancies between our map and previous work. The principal impact of our mapping on previous interpretations for the central Dragoon Mountains is that reverse faulting of large displacement dimension probably does not exist and Jurassic intrusive activity is not present.

An Alternative Structural Model

In order to construct positively rather than comment negatively, we fully accept that the burden of proof lies with us to provide a reasonable alternative structural model. For purposes of description, the mapped area is divided into two principal structural blocks (Plate 3, inset), the Black Diamond block on the northeast and the Silver Cloud block to the southwest. The boundary between these blocks is a high-angle fault herein named the Black Diamond fault. The Silver Cloud block is divided into three subblocks which from northwest to southeast are the Santa Anna, Escapule, and Bennett subblocks. The structural geology will be discussed within each block beginning with the Black Diamond fault.

The Black Diamond Fault

The northwest-striking Black Diamond fault, one of the most conspicuous structures of the area mapped, dips steeply southwest. Underground inspection of the fault at the Black Diamond mine indicates that the fault dips steeply southwest (about 75°) and has dip-slip slickensides. North of Middle Pass near locality 3b a probably related, north-northwest fault parallel to the Black Diamond fault is exposed in a prospect pit. This fault dips 70° W and has near dip-slip slickensides which are oriented 65° S 70° W. The footwall block of the Black Diamond fault is generally composed of Bolsa Quartzite, Precambrian quartz monzonite, and Bisbee Group rocks which appear to transgressively overlap the lower Paleozoic and Precambrian rocks as detailed in the previous section. The exposed hanging wall rocks consist of interbedded green siltstones and red shales that are 1,500 to 3,000 feet above the base of the Bisbee

Group. In general then, younger rocks in the hanging wall suggest normal separation of the Black Diamond fault (not reverse as suggested by Gilluly (1956, sections VII, VIII, and IX, Fig. 2) with the Silver Cloud block depressed five to six thousand feet relative to the Black Diamond block.

Additional structural complexities exist along the Black Diamond fault. The first problem is a fault slice of Paleozoic Escabrosa Limestone along the trace of the Black Diamond fault at the Black Diamond mine. The fault slice is downthrown relative to the Cambrian and Precambrian rocks in the Black Diamond block to the northeast (about 2,000 feet of stratigraphic throw estimated from section C-C', Plate 3, and upthrown relative to the younger Bisbee rocks in the Silver Cloud block to the southwest (3,000 to 4,000 feet of stratigraphic throw). Exposures of the fault slice in the Black Diamond mine workings suggest a normal displacement of the slice with respect to the enclosing blocks (section C-C', Plate 3).

The second problem is the structural position of the Bisbee Group represented by the Glance Conglomerate, which rests depositionally on the Cambrian and Precambrian rocks within the Black Diamond block and on upper Paleozoic rocks in the Silver Cloud block. At location 2d the Glance Conglomerate rests on Precambrian granite while one-quarter mile to the southwest on the southwest side of Santa Anna Gulch the Glance overlies the uppermost Pennsylvanian Horquilla Limestone. Farther to the southwest (locations 1a, 1b, and 1c) the Glance consistently rests on the Permian Colina Limestone. In contrast to the Black Diamond block, then, virtually the entire Paleozoic section in the Silver Cloud block intervenes between the older Precambrian basement rocks and the lower Bisbee succession. The Escabrosa fault slice and the stratigraphic position of the Glance Conglomerate will be of utmost importance in unraveling the kinematic history of the Black Diamond fault to be discussed in a subsequent section.

The Black Diamond Block

Structure of the Black Diamond block essentially consists of a northeast-dipping homocline with a broad, open synclinal fold in the northwestern end. The open synclinal fold, named the Middlemarch syncline by Cederstrom (1946), trends northwesterly and plunges shallowly to the southeast, and is best developed in the Bisbee Group. The northeast limb strikes about N 30° W and dips about 40° SW, while the southwest limb strikes generally N 20° W and dips 50° NE. The fold limbs define an axial plane which is steeply inclined to the southwest.

The Silver Cloud Block

Structure of the Silver Cloud block is fold dominated of which the single, pervasive structural element is a large, overturned, southeast-trending, northeast-vergent, southeast-plunging fold pair, herein named the Silver Cloud fold. Most other minor structures are geometrically related to the Silver Cloud fold and will be discussed in conjunction with it. Due to the unique morphology of the Silver Cloud fold a monoclinal terminology is also used, as the southwest limb of the anticlinal part is structurally higher than the synclinal part. Hence, minor structures will be referred to with respect to their positions in the upper, middle, and lower limbs of the Silver Cloud fold. The southwest anticlinal hinge of the Silver Cloud fold is designated the upper hinge, while the northeast synclinal hinge is designated the lower hinge. The style and level of exposure of the Silver Cloud fold change systematically in each subblock and will, therefore, be discussed by subblocks from northwest to southeast.

As section A-A' (Plate 3) shows, the Silver Cloud fold is generally an implied subsurface structure in the Santa Anna subblock. The upper hinge is present at the surface only in the SE1/4 of sec. 24. Here the Horquilla Limestone is abruptly folded (in about ten feet) around a north-northwest-trending, near-horizontal axis and recumbent, southwest-dipping axial surface. The overturned middle limb extends one-half mile farther to the north to Gilda Spring. Here the fold is marked by overturned Bisbee rocks in the middle limb faulted against the Pennsylvanian Horquilla Limestone in the upper limb. North of Gilda Spring, the Silver Cloud fold is implied to lie in the subsurface and is truncated against the Black Diamond fault as section A-A' (Plate 3) shows. Surface fold morphologies in the northern part of the Santa Anna subblock in the implied upper limb of the Silver Cloud fold describe broad to open, northwest-trending waveforms which plunge shallowly to the southeast and northwest. Wavelengths of these folds decrease as they approach the Black Diamond fault where a sharply attenuated, open to closely folded anticline is present in the Bisbee and Horquilla formations north of the Standard Tungsten mine.

The open upright folds and the upper hinge of the Silver Cloud fold are offset at the southern border of the Santa Anna subblock by the west-northwest-striking, near-vertical Javelina fault. The Santa Anna subblock is elevated with respect to the adjoining Escapule subblock to the south. Stratigraphic separation along the Javelina fault ranges from 500 to 1,500 feet of south side down, while the upper hinge of the Silver Cloud fold is only offset about 100 feet of south block relatively down. Stratigraphic separation on the Javelina fault generally increases to the east along strike. There is also a tendency for left-lateral separation with the Escapule subblock 1,000 feet east relative to the Santa Anna subblock. Glance Conglomerate unconformably rests on the upper Horquilla formation 1,200 feet north of the Javelina fault; 500 feet south of the fault, Glance is depositional on Permian rocks (Colina Limestone?) which are about 1,000 feet higher stratigraphically than the upper Horquilla Limestone. It appears that the Javelina fault, like the Black Diamond fault, has a polyphase movement history.

Several recumbent fold structures, principally in the relatively incompetent Earp Formation, collectively make up the anomalously thickened upper hinge of the Silver Cloud fold (section B-B', Plate 3) south of Silver Cloud Peak in the Escapule subblock. The smaller scale folds have thickened, subrounded to subangular, closely folded hinge zones, recumbent, southwest-dipping axial planes, and shallowly plunging, south-southeast-trending axes; all give clues to the geometry of the large parent fold. A minor fold in the quartzite unit of the lower Bisbee is exposed in a south-facing road cut at the Escapule mine and provides an excellent small-scale version of what we believe is the hinge zone geometry of the large-scale, upper hinge geometry of the Silver Cloud fold. The western boundary of the upper hinge area of the Silver Cloud fold is marked by a northwest-trending anticlinal structure, herein named the Coyote anticline, which is defined by folded stratigraphy in the Abrigo, Martin, and Escabrosa formations.* The axial plane is moderately inclined and strikes about N 25° W. The axis displays a shallow to moderate plunge into both the northwest and southeast quadrants and the subrounded to rounded hinge zone is open to closely folded. The hinge zone shows pronounced thickening where it passes through the more incompetent stratigraphic

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*Note: our Coyote fold is the Silver Cloud anticline of Cederstrom (1946) and the unnamed fold of Gilluly (1956, p. 143).

units (especially the Abrigo Formation in N center, sec. 25). The unit that shows the least thickening in the hinge zone--and, indeed, from the map relationships might be thinner in the hinge--is the massive, relatively competent Escabrosa Limestone. A fold similar to the Coyote fold trends through Bennett Peak in the Bennett subblock.

Several reverse faults of small stratigraphic throw (up to 200 feet) are present in the southwest limb of the Coyote anticline (SE1/4 sec. 24). The faults dip moderately southwest and strike from N 5°-20° E. A mineralized, low-angle reverse fault, here designated the Escapule fault, was extensively prospected at the Escapule mine. The fault strikes N 45° W and dips 30°-50° SW. Slickensides measured in the mine workings varied in orientation from 20° S, 20° W to 45° S, 50° W. The hanging wall consists of limestones within the Horquilla formation, while the quartzite unit of the Bisbee Group forms the footwall block. Stratigraphic separation here is about 300 feet, as the Glance Conglomerate rests depositionally on the Horquilla formation 1,500 feet to the northwest. The Escapule fault is directly on trend with what Cederstrom and Gilluly mapped as the Dragoon fault. We could only trace the Escapule fault about 200 yards southeast. The fault is projected about 1,500 feet to the northwest where it is inferred to be terminated against a northwest-trending mineralized fault which dips 70° NE. One low-angle fault of reverse separation and throw was mapped in the recumbently folded Earp Formation south of Silver Cloud Peak.

The southeastern boundary of the Escapule subblock is formed in part by a largely concealed, east-northeast-striking, steeply dipping fault herein named the Catclaw fault. An exposure of the Catclaw fault in an unnamed wash that parallels the fault strongly indicates a significant strike-slip component. Here the fault dips 70° SW and bears slickensides oriented 20° N, 70° E. Inspection of the map shows that stratigraphy in the Escapule subblock is shifted about 1,200 feet northeast relative to stratigraphic analogs in the Bennett subblock.

The entire Silver Cloud fold pair is exposed to the southeast in the Bennett subblock. The upper hinge extends southeast into the Bennett subblock from the Escapule subblock and is marked by a sharp axis of overturning in the northeast-facing slope of Bennett ridge. Southeast and north of point 7151 (Plate 3), the upper hinge is truncated by a northwest-trending fault. The lower hinge is defined by folded Bisbee sediments south of Dragoon Camp and southeast of the Black Diamond fault which truncates the lower hinge in the vicinity of the Black Diamond mine. The trend of the Silver Cloud fold axes in the Bennett subblock are more southeasterly (about S 50° E); they plunge very shallowly to the southeast. The axial surface of the upper hinge is shallowly inclined, while that of the lower hinge seems to be moderately inclined. No hinge zone thickening was noticeable at the scale of outcrop but is implied in section C-C' (Plate 3). The shape of the upper fold hinge is subrounded, while that of the lower hinge is rounded. Interlimb angles may be described as open in the case of the upper hinge and close to tight for the lower hinge. The middle limb is well defined by a generally steeply overturned section of upper Paleozoic and Bisbee Group. Directly northeast of the lower hinge of the Silver Cloud fold is a steeply inclined, northeast-vergent anticline which plunges shallowly northwest.

On the northeast side of Bennett ridge about half a mile east-northeast of Bennett Summit, several masses of allochthonous Bolsa Quartzite occur. The surface between the Bolsa Quartzite and underlying Colina Limestone and Glance Conglomerate is a low-angle fault having slickensides with an average S 40° W to N 40° E trend. At the east edge of the largest allochthonous quartzite block, an anomalous conglomerate is present below the fault between the quartzite and the Glance. This conglomerate contains angular clasts of volcanics that resemble the Pierce volcanics to the northeast, designated Tertiary in age by Gilluly (1956). However, an alternative volcanic source of Jurassic age cannot be ruled out because Cooper and Silver (1964) identified Triassic-jurassic volcanics in Walnut Gap 15 miles north-northeast of the study area. Because of the proximity of this unit to unequivocal Glance, we provisionally place the conglomerate within the Glance and thereby the emplacement of the allochthonous Bolsa Quartzite is tentatively post-Glance.

Faults of the Silver Cloud Block

Several northwest-trending fault systems traverse the length of the Silver Cloud block and are of considerable interest. The first fault system, herein named the Juniper fault system, in general consists of two parallel faults which bisect the Silver Cloud block, strike about N 45° W and dip 60°-70° SW (inset, Plate 3). The fault slice in between is 300 to 1,000 feet wide and is relatively upthrown with respect to the surrounding stratigraphy. That is, displacement on the northeastern fault is relatively reverse, while that on the southwestern fault is relatively normal. The apparent discrepancy in this relationship for the Colina Limestone fault slice northwest of point 7151 is geometrically reconciled in section C-C' (Plate 3), where the lower hinge is shown to be upfaulted. This interpretative maneuver preserves the general displacement relationship. North of the Catclaw fault for about 3,000 feet, only one fault of net reverse relative displacement could be recognized. Stratigraphy is reversely juxtaposed across the fault, while axial planes of correlative recumbent folds are offset in a normal sense about 100 feet. A single reverse fault also exists north of the Standard Tungsten mine in the Santa Anna subblock. The amount of reverse stratigraphic separation for the Juniper fault system varies from 500 to 1,500 feet of southwest side up with a general increase in reverse separation southwest along strike. Normal separation on the southwesternmost faults is slightly less and also increases in magnitude southwest along the strike of the Juniper fault system. The Juniper fault system locally truncates the upper hinge of the Silver Cloud fold.

A second fault, herein named the Mesquite fault, occurs along the southwest margin of the Silver Cloud block (inset, Plate 3). In general, the Mesquite fault is a single normal fault (not reverse as indicated by Gilluly, 1956, section VIII, plate 6) which strikes about N 45° W and dips 30°-55° SW. The fault appears to split into two faults as it traverses the southwestern edge of the Escapule subblock. Stratigraphic separation varies from about 500 to 2,000 feet of the southwestern hanging-wall block down. Like the Juniper fault system stratigraphic separation on the Mesquite fault increases to the southwest along strike. The Mesquite fault apparently offsets reverse faults in the southwestern Escapule subblock and contains lead-zinc-silver mineralization presumably related to the 24 m.y. Stronghold Granite.

Relationship of the Silver Cloud Fold to the Black Diamond Fault

The Silver Cloud fold appears to be spatially related to the Black Diamond fault. As the sections show, the axial planes of the Silver Cloud fold are truncated against the Black Diamond fault. The Silver Cloud fold is present only immediately to the southwest of the Black Diamond fault. Farther southwest (see section A-A', Plate 3), only broad folds are present within the upper limb of the Silver Cloud fold. Wavelengths of these folds become progressively shorter and hinges more tightly folded as the Black Diamond fault is approached from the southwest. Shortening is maximized through the Silver Cloud fold just southwest of the Black Diamond fault and decreases to the northeast away from the Black Diamond fault.

Shortening

Fold-related shortening for the various blocks was calculated at the Bolsa-older Precambrian basement unconformity (Fig. 6) on sections A through C (Plate 3) and is tabulated on Table 2.

Table 2. Shortening within the central Dragoon Mountains study area*

Block or Subblock	Section	% Shortening	Comments
Silver Cloud + Black Diamond	A-A'	18.9	
Silver Cloud (Santa Anna)	A-A'	31.6	
Black Diamond	A-A'	8.9	
Silver Cloud + Black Diamond	B-B'	21.1	
Silver Cloud (Escapule)	B-B'	42.1	Calculated at the Black Prince—Horquilla contact
Black Diamond	B-B'	11.0	
Silver Cloud + Black Diamond	C-C'	17.0	
Silver Cloud (Bennett)	C-C'	33.0	
Black Diamond	C-C'	9.7	

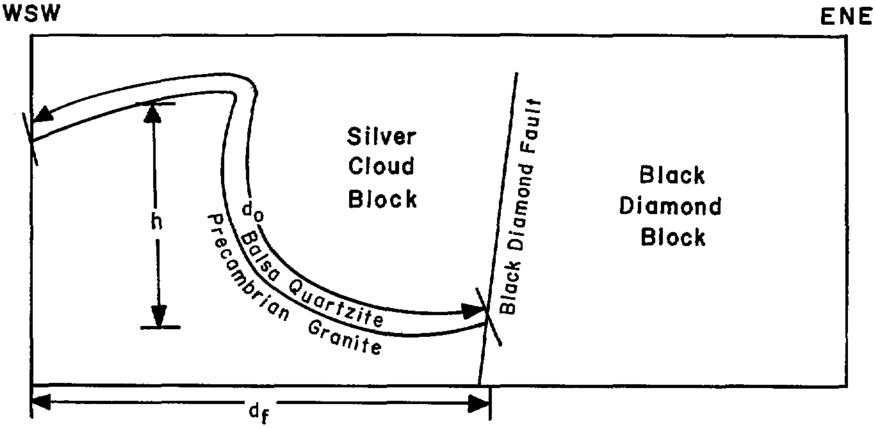
*Note: the calculated percent shortening is here a minimum figure; higher numbers may be obtained by increasing the cross section length of the middle limb for Silver Cloud fold.

Total fold-related shortening within the central Dragoon Mountains study area is about 19 percent (3,300± feet). Most of the shortening is attributable to the Silver Cloud fold. The Silver Cloud block southwest of the Black Diamond fault is shortened about 33 percent, while the Black Diamond block northeast of the Black Diamond fault is shortened only about 10 percent. Within the Escapule subblock, shortening at the stratigraphic level of the Pennsylvanian section is over 42 percent, 9 percent higher than the average amount of shortening for the Silver Cloud block. Shortening required to produce the observed fold geometrics is therefore much less than the several miles suggested by Gilluly (1956).

Post-Bisbee Intrusions

The entire mapped area is pervasively cut by a northwest-striking rhyolite dike swarm which constitutes the bulk of the igneous bodies mapped. The rhyolite dikes strike N 15°-70° W, average about N 45° W, and consistently dip about 75° SW. Dike-related extension increases from northwest to southeast and was calculated at 3.4, 4.2, 5.3 and 7.1 percent for sections A through D (Plate 3), respectively.

$$\text{Percent Shortening} = \left(\frac{d_o - d_f}{d_o}\right)100$$

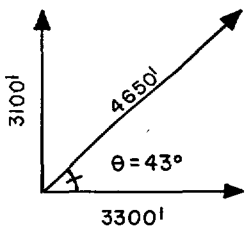


$$\bar{s} = \frac{(d_o - d_f)A + (d_o - d_f)B + (d_o - d_f)C}{3} = \frac{3100 + 3700 + 3000}{3} \approx 3300$$

$$\bar{h} = \frac{h_A + h_B + h_C}{3} = \frac{2900 + 2900 + 3500}{3} = 3100$$

SYMBOLOGY

$\bar{s}$ = Average Shortening
d_o = Unshortened Distance
d_f = Shortened Distance
$(d_o - d_f)A$ = Shortening for Section A-A'
$(d_o - d_f)B$ = Shortening for Section B-B'
$(d_o - d_f)C$ = Shortening for Section C-C'
$\bar{h}$ = Average Vertical Distance
h_A = Average Vertical Distance for Section A-A'
h_B = Average Vertical Distance for Section B-B'
h_C = Average Vertical Distance for Section C-C'
θ = Angle of Inclination for the Greatest Principle Stress (σ_1) Within an ENE Near Vertical Plane



$\theta = \arctan(\bar{h}/\bar{s})$
$= \arctan(3100/3300)$
$= \arctan(.94)$
$\approx 43°$

Figure 6. Geometrical basis for and calculation of percent shortening and inclined movement vector within an ENE-striking vertical plane.

A small sheared quartz latite porphyry mass was mapped northwest of the allochthonous Bolsa Quartzite in the Bennett subblock, and numerous small masses of andesitic material were mapped throughout the area. Where the andesite was in dike form a tendency to strike northeast was noted. Also, an apparent correlation between andesite and base-metal mineralization was observed. Two small masses of granodiorite porphyry were mapped in the vicinity of the Black Diamond mine and may be related to the skarn mineralization in the Escabrosa fault slice at the mine.

Post-Paleozoic Geologic History

Discussion is restricted to post-Paleozoic phenomena; Paleozoic and Precambrian are summarized by Gilluly (1956). Structural evolution of the study area is depicted as six stages (Fig. 7). Figure 7a is essentially undeformed sediments. The highest Permian stratigraphic unit in the mapped area is the Colina Limestone, but the entire section is inferred to have been present in the Black Diamond block at the close of the Paleozoic for there are no clastic wedges, facies shifts, or rapid thickness changes that would be expected if the Black Diamond fault were influencing Paleozoic depositional patterns. However, the Black Diamond fault could have been a preexisting fault in the older Precambrian basement and as such was simply inactive throughout Paleozoic time, but evidence to support this was not found.

The Black Diamond fault was active between the close of the Paleozoic and the Early Cretaceous (Fig. 7b). Glance Conglomerate was subsequently deposited on the upper Paleozoic section one-quarter mile southwest of the fault and on Precambrian granitic rocks northeast of the fault (see p. 182 for details). About 2,500 feet of stratigraphic separation occurred sometime between Permian and Early Cretaceous time with the Paleozoic section preserved on the relatively downthrown southwestern block. The Paleozoic fault slice at the Black Diamond mine is interpreted as a remnant of this early movement. Movement of the Black Diamond fault probably occurred a considerable time prior to deposition of the Bisbee Group, since any clastic detritus that would have been shed from erosional stripping of the Black Diamond block is missing.* Deposition of the Glance Conglomerate was upon a fairly low relief, mature topography; and isopachs of the Glance Conglomerate do not change drastically across the Black Diamond fault--indeed, the Glance is thicker northeast of the fault, suggesting that the area to the northeast was a basin of deposition for carbonate detritus shed from relatively higher Paleozoic terrain to the southwest. Similar low-relief, pre-Cretaceous topography is present in the Mule Mountains 17 miles to the south. There, Jurassic Juniper Flat Granite, dated by the Rb-Sr method on biotite at 176 and 178 m.y. (Creasey and Kistler, 1962) and the K-Ar method on biotite at 163 m.y. (Marvin and others, 1973), has been intruded into the Pinal Schist, beveled flat, and overlapped by the Bisbee succession. If the pre-Cretaceous topographies of the Mule and Dragoon Mountains are correlative, then the Juniper Flat Granite places a maximum age of about 170 m.y. for much of the pre-Bisbee erosion. A minimum age of Early Cretaceous (about 140 m.y.) is, of course, given by the Bisbee group itself for the topography it overlapped. The relationship of pre-Bisbee movement on the Black Diamond fault to Jurassic-age intrusive activity in the Mule Mountains is conjectural, although an interesting parallel between the Black Diamond and the Dividend fault at Bisbee will be discussed later. Because of the mature pre-Bisbee

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*A possible exception to this point could be the volcanic—clast-bearing conglomerate below the allochthonous Bolsa in the Bennett subblock (refer to p. 185 for details).

topographic situation, the post-Paleozoic—pre-Cretaceous movement on the Black Diamond fault is inferred to be Early Jurassic or Triassic in age.

Rotation of the Paleozoic strata due to pre-Bisbee movement on the Black Diamond fault appears to have been slight due to a general concordance between the Paleozoics and overlying Lower Cretaceous Bisbee strata. Vertical pre-Cretaceous movements on the N 70° W-striking Javelina fault are implied by the distribution of Glance Conglomerate on either side of the fault (see p. 183) and may also be coincident with pre-Cretaceous Black Diamond fault movement.

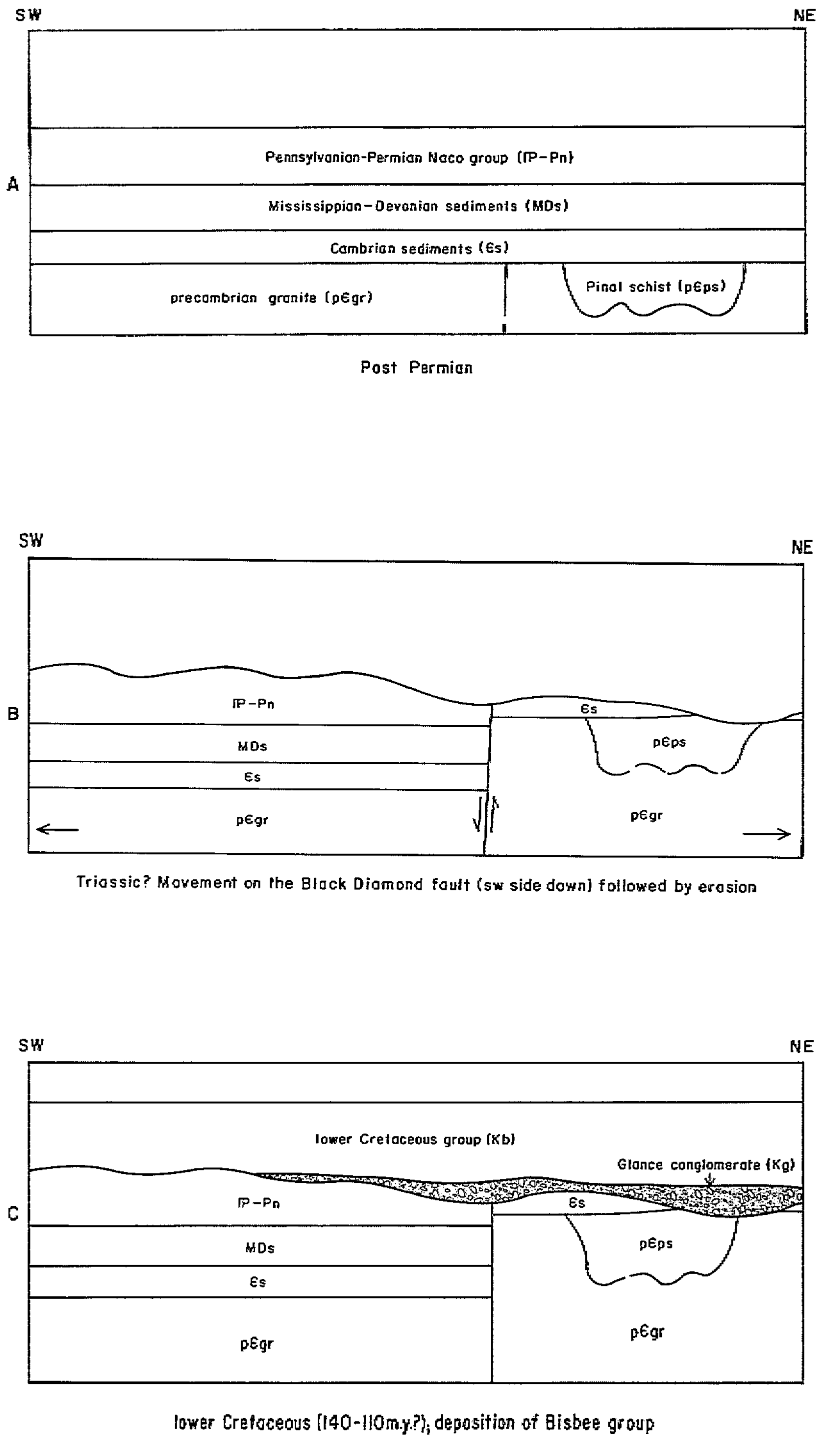
Transgression by Early Cretaceous Bisbee seas over the study area resulted in deposition of a thick succession of conglomerate, siltstone, shale, graywacke, and mudstone (Fig. 7c). Termination of Bisbee deposition at the end of the Early Cretaceous (about 110 m.y.?) provides a maximum age for the major rotational event (via folding) in the central Dragoon Mountains (Fig. 7d). A minimum age for the folding of about 24 m.y. is set by the emplacement of the radiometrically well dated Stronghold Granite which clearly intrudes the folded rocks (Cederstrom, 1946; Gilluly, 1956). Damon and Bikerman (1964) obtained a K-Ar age of 22 ± 3 m.y. on biotite, while Marvin and others (1973) report a K-Ar age of 26 ± 2 m.y. on a different biotite from the same pluton. Unfortunately, then, the folding is only bracketed in the study area between about 24 m.y. and ± 110 m.y.

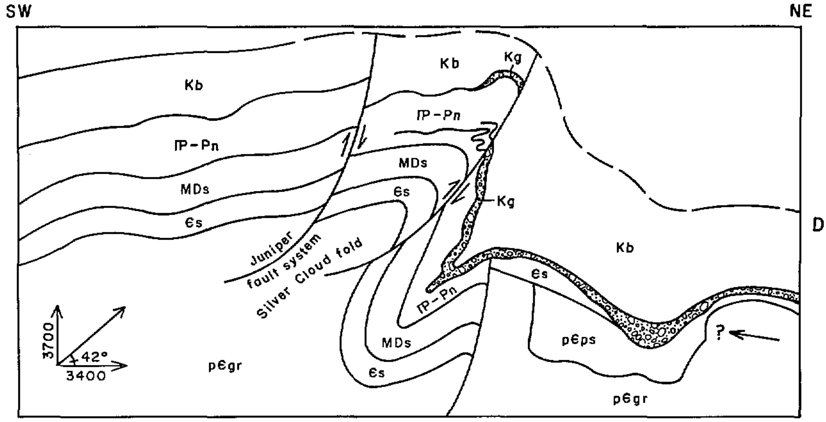
However, better precision can be obtained by considering geologic relationships in adjoining areas. In the Courtland-Gleeson area, the Sugarloaf quartz latite dated at 72 m.y. (Marvin and others, 1973) predates similar rotational deformation. At Johnson Camp 15 miles north of the study area, the Texas Canyon Quartz Monzonite was dated between 47.4 and 54.2 m.y. on several minerals by the K-Ar method (Livingston and others, 1967). Marvin and others (1973) report concordant K-Ar ages of 50 ± 3 m.y. on a biotite and 52 ± 3 m.y. on a hornblende for the same pluton. The Texas Canyon Quartz Monzonite intrudes low-angle faults which truncate eastward-rotated Paleozoic rocks (Cooper and Silver, 1964), a structural situation similar to that in the central Dragoon Mountains. Thus, relationships in adjacent areas suggest folding in the central Dragoon Mountains (and Dragoon Mountains, in general) occurred between 72 and 52 m.y., or in "Laramide" time. Formation of the Silver Cloud fold, all other northwest-trending folds, reverse fault structures, and strike-slip motion on the Catclaw, and, less certainly, on the Javelina fault occurred in the "Laramide" time interval (stage 4).

Further displacement on the Black Diamond fault (Fig. 7e) occurred post-folding but pre-intrusion of the 24-m.y. Stronghold Granite because axial planes of the Silver Cloud fold and folded Cretaceous sediments are offset by the Black Diamond fault, which in turn has probably been intruded north of the study area by the Stronghold Granite. Renewed movement in the Black Diamond fault zone is inferred to have locally broken west of the older Triassic-Jurassic break creating the Paleozoic fault slice at the Black Diamond mine. Similar normal motion on the Juniper fault system at this time is interpreted to have resulted in the fault slice aspect of that system as well. Formation of the Mesquite fault in this interval is also entirely consistent with the observed data. The allochthonous Bolsa Quartzite in the Bennett subblock may have been emplaced at this time.

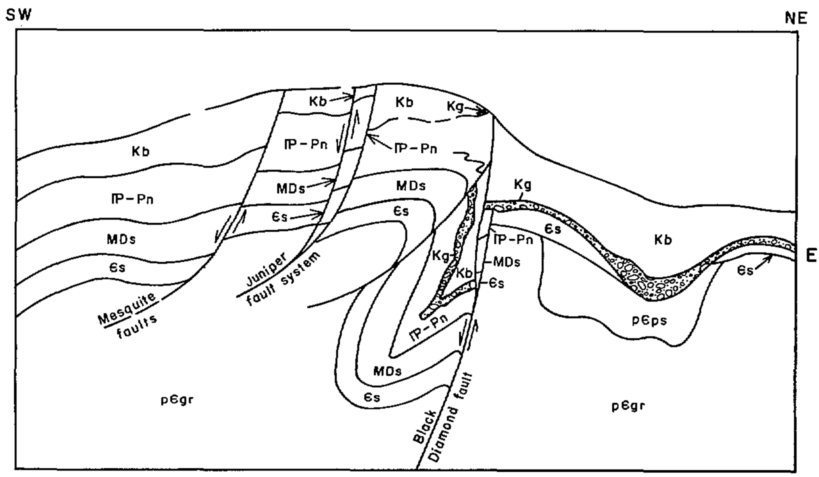
The period of normal fault motions (Fig. 7e) was followed by the emplacement of the Stronghold Granite and related phenomena (Fig. 7); not the least of these were hydrothermal phenomena which are present in many of the preexisting faults, including the relatively young Mesquite

Figure 7. Post-Paleozoic geologic history of the central Dragoon Mountains study area.

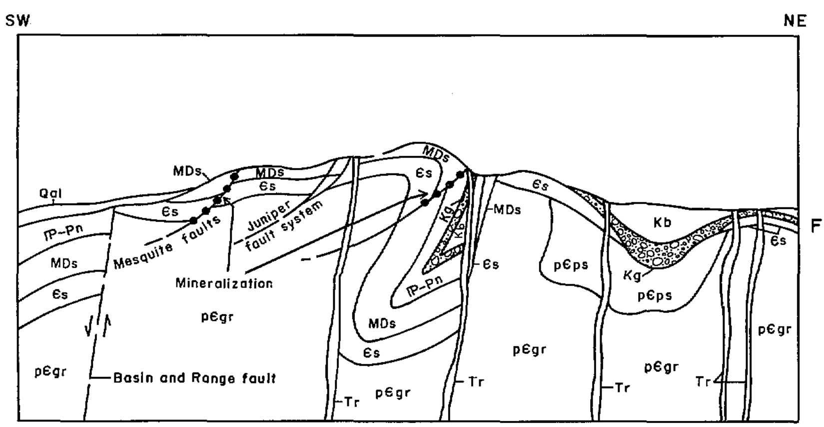




post-Sugarloaf quartz latite (72m.y.)-pre-Texas Canyon quartz monzonite (52m.y.) "Laramide" uplift and compression.



pre-Stronghold granite (±24m.y.)-post-compression gravitational adjustment



syn-Stronghold granite (±24 m.y.) dike intrusion, extension, and mineralization; post-Stronghold granite Basin-Range faulting and development of present topography fault. These hydrothermal phenomena are probably related to the Stronghold Granite as the base-metal mineralization and contact metasomatism increase in metamorphic grade, intensity, and volume toward the Stronghold pluton just northwest of the mapped area. Subsequent to the main stage of base-metal and skarn mineralization, numerous, relatively unmineralized, northwest-trending dikes were emplaced. Both Cederstrom (1946) and Gilluly (1956) feel that the rhyolite dike emplacement is comagmatic with the Stronghold Granite.* Radiometric dating is needed to verify this hypothesis. If the dikes were emplaced vertically, then about 15 degrees of northeastward rotation postdates the dikes that now consistently dip about 75° SW. The general southeastern plunge of the Silver Cloud fold system may reflect rotation of the preexisting fold systems away from the Stronghold Granite intrusion.

After emplacement of the rhyolite dikes and possible northeastward rotation about 24 m.y. ago, the central Dragoon Mountains were block faulted into their present-day physiographic outline by northwest-striking Basin-Range faulting. The traces of these presumed faults are now buried by alluvium derived from erosion of the modern mountain system. When Black Diamond Peak emerged as a topographic entity, the Bolsa cliff on top of the Precambrian quartz monzonite was progressively undercut; portions of Bolsa broke away and now rest as allochthonous megabreccia masses on the northwest side of the peak. Mass wastage in the form of large landslides containing house-sized boulders of Bolsa Quartzite has occurred on the steep southwestern slopes of Black Diamond Peak. Streams currently are entrenching themselves as evidenced by numerous gullies in the pediment areas.

Dynamic and Kinematic Analysis of the Triassic–Jurassic and "Laramide" Deformational History

Our analysis deals primarily with formation of the Black Diamond fault and the Silver Cloud fold and the spatial-temporal relationships between these two structures.

Triassic-Jurassic Motion on the Black Diamond Fault

A definitive statement simply cannot be made at this time concerning the dynamic nature of Triassic-Jurassic movements on the Black Diamond fault (Fig. 7b) owing to the lack of data. The Triassic-Jurassic motion is conjectured to be largely dip slip at the Black Diamond mine and near location 3b (see p. 181). The Black Diamond fault is intruded by dikes probably related to the Stronghold Granite so that the dip-slip slickenside formation may be fairly imputed to early Tertiary displacement on the Black Diamond fault. No drastic facies changes in the Bisbee Group sediments are present across the fault, so that large, post-Bisbee, strike-slip faulting can probably be ruled out. A similar weaker argument may be made for the Triassic-Jurassic motion because Precambrian granite and Pinal Schist lithologies, along with Cambrian Bolsa and Abrigo lithologies are not noticeably different on either side of the fault. Given the existing data, the simplest interpretation is to produce the required geometry by simple, pre-Cretaceous, dip-slip motion. Triassic-Jurassic motion on the Black Diamond fault is then very provisionally the product of west-southwest—east-southeast extension over the domain of the mapped area.

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*Cederstrom (1946) reported that the rhyolite dikes cut the Stronghold granite. However, Gilluly (1956, p. 108) claims that none of the rhyolite dikes he mapped could be traced into the Stronghold Granite.

The "Laramide" Deformational Interval

The creation of the proto-Black Diamond block northeast of the Black Diamond fault is interpreted to be a profound antecedent structural control in the localization and development of the Silver Cloud fold and related structures during the 72-52 m.y. "Laramide" deformational pulse. The geometry of the Silver Cloud fold in part owes its origin to east-northeast-directed compression. However, an associated vertical uplift component may also be important.

Initial compression of the near-horizontal layering in the down-dropped Paleozoic section southwest of the Black Diamond fault resulted in the production of broad, open waveforms which took up the strain by buckling. However, the previously uplifted basement of the Black Diamond block did not fold easily and acted as a buttress. With continued compression the sedimentary pile to the southwest was literally "jammed up" against the unyielding buttress to the northeast. This "jamming" effect is most graphically illustrated in the Escapule subblock which has been "shoved" differentially about 1,000 feet more to the east than adjacent Santa Anna or Bennett subblocks. Northeastward translation of the Escapule subblock is interpreted to have been facilitated by tear fault motion on the Javelina and Catclaw faults. As the Escapule subblock crumpled against the granitic buttress to the northeast, migration of incompetent strata (particularly, the Earp Formation) toward the upper hinge of the Silver Cloud produced numerous, minor recumbent fold structures and the Coyote anticline.

As compression continued, strain that would normally have been transmitted farther to the northeast was taken up by the layered rocks immediately southwest of the Black Diamond fault. The result was the disproportionately large, disharmonic Silver Cloud fold pair. Overturning of the middle limb was accompanied by uplift as the basement block below the Silver Cloud fold rose up and to the northeast.

Fold mechanics were predominantly by layer-controlled flexural slip with the exception of the recumbent folding south of Silver Cloud Peak which was probably dominated by flexural flow in its late stages. Several small-scale phenomena indicate a flexural slip mechanism. In the Bisbee Group local bedding plane, southwest-northeast-trending slickensides are present and are probably a reflection of bedding plane slippage during flexural slip folding. The slickensides are thus interpreted as an 'a' tectonic lineation in the Sander coordinate system and are consistent with east-northeast-directed compression. Bedding plane slippage has produced tension fractures in the quartzite unit of the Bisbee Group which strike N 35° W and dip 34° SW at the Escapule mine. These fractures are interpreted as "gash" or tension fractures created by local differential right-lateral shear along bedding plane surfaces. The kinematics of this movement are completely consistent with predicted right-lateral bedding plane slippage during flexural slip folding in the middle limb of the Silver Cloud fold (Fig. 8). The S 50° W elongated pebbles associated with local discontinuous shear surfaces at the Glance Conglomerate—upper Paleozoic contact at location 1a (p. 177) are interpreted as products of flexural slip. The Glance Conglomerate—upper Paleozoic contact separates materials of high ductility contrasts, and, thus, it is reasonable to expect small amounts of differential movement at this contact during flexural slip folding. Indeed, it would be surprising if such motion did not occur. The S 50° W trend of the pebbles is then interpreted to be an 'a' lineation consistent with east-northeast, compression-induced, bedding plane slippage during flexural folding in the middle limb of the Silver Cloud fold.

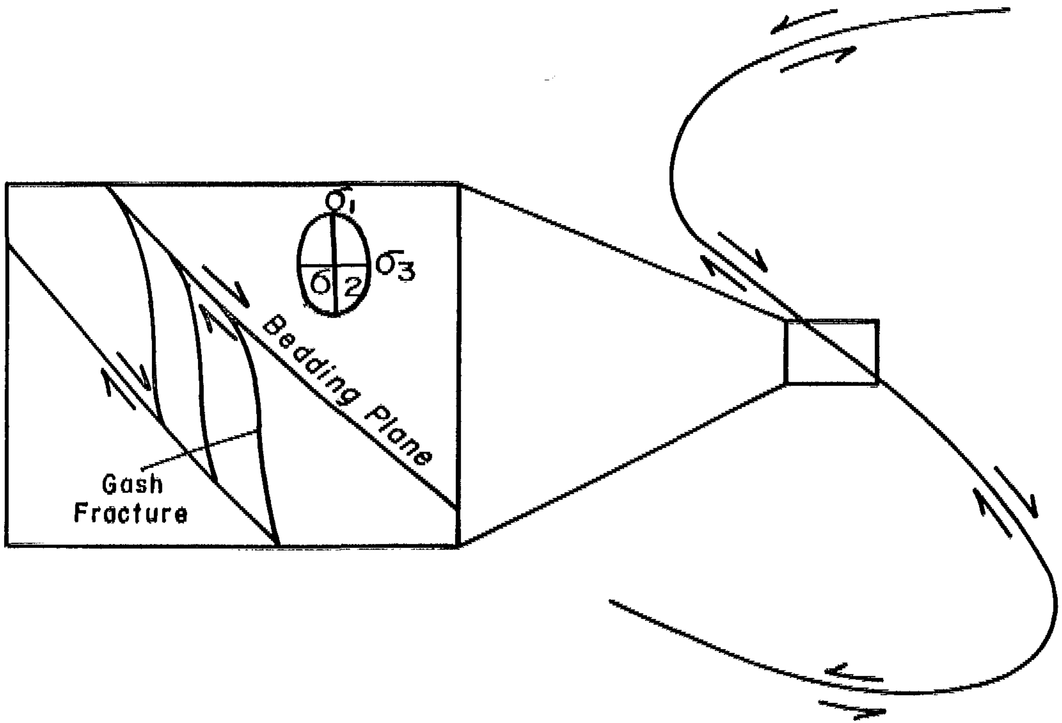

Figure 8. Kinematic relationship of small-scale gash fractures to the Silver Cloud fold parent structure.

Rock type exerted considerable local control on fold morphology. In the incompetent Earp Formation, extensive migration of material toward the fold hinges took place in the recumbently folded section south of Silver Cloud Peak and implicates a flexural flow mechanism for at least the later stages of fold development. In contrast, folding developed through the massive crinoidal limestones of the Escabrosa is not noticeably thickened in the hinge area. Rather than flowing, the Escabrosa simply fractured and the results in some instances were startlingly dramatic. As one approaches the hinge area of the Coyote fold on either east-west-trending ridge west of Silver Cloud Peak, the Escabrosa Limestone becomes penetratively fractured into cross and longitudinal joint sets consistent with the geometry of the Coyote fold. At the hinge zone, the Escabrosa is so pervasively and mechanically recrystallized that it takes on the sheen of a phyllitic schist (Fig. 9), not unlike some units in the Pinal Schist! The recrystallization of the Escabrosa is quite reasonably attributable entirely to mechanical deformation during folding. Any thermal element is conspicuously lacking for the underlying Martin Formation is unmetamorphosed.

When the layered rocks could no longer deform by flexing, high-angle reverse faults broke through and incipient, low-angle transport via thrusting took place locally (especially within the more foreshortened Escapule subblock). However, compression ceased before any large-scale tectonic transport could take place. Rather than folding being the effect of thrusting as suggested by Gilluly (see quotation on p. 172), in our model the opposite sequence occurred. The reverse faulting which is present is by our model an effect of progressive compressional deformation which is subsequent to folding and does not precede it. Intermediate- to high-angle reverse faults of the Juniper system, the Escapule fault, and the high-angle reverse faults west of Silver Cloud Peak are results of this late-stage compressive deformation.

Release of compression triggered gravitational adjustments within the elevated compressional structures. The early Tertiary normal dip-slip motion on the Black Diamond fault, formation of the Mesquite fault, and normal dip-slip motion in the Juniper fault system are interpreted to be products of gravitational adjustment subsequent to the release of compression. In the case of the Black Diamond fault zone and the Juniper fault system new breaks of normal dip-slip motion formed southwest of the older breaks and are inferred to be rooted to the older breaks at depth in cross section. The result was the fault slice aspect of these systems which has been previously discussed.

Depth of cover during deformation is conjectural, but available evidence suggests that the Silver Cloud fold is a very high level crustal phenomenon. Rocks involved in the fold lack dynamic regional metamorphism that would indicate deeper formational environments. Predominance of flexural slip fold mechanics, calcite-filled open-space tension cracks, numerous brittle fracture phenomena, and normal, low- to intermediate-angle, gravity-induced faults all argue for near-surface deformational conditions. Most convincing of all, however, is that 72 m.y. surface rocks (the Sugarloaf Quartz Latite at Gleeson) have been involved in the rotational deformation. The currently exposed structure in the central Dragoon Mountains probably did not form in excess of a kilometer deep and the Silver Cloud fold almost certainly had a surface expression.

Compression and subsequent release of that compression have been employed by us to explain the structural geometry of the central Dragoon Mountains. The presence of the Black Diamond buttress explains the lack of a more harmonic fold geometry, but net uplift of the Silver Cloud block relative to the Black Diamond block during folding has not been explained and cannot at first glance be accommodated by

Figure 9. Highly jointed phyllitic Escabrosa Limestone near axis of Coyote anticline.

strict lateral compression. It appears that the Silver Cloud fold has a monoclinal aspect to its geometry with the middle limb of the Silver Cloud fold being a "drape" off the northeast edge of the uplifted Silver Cloud block (see section A-A' and B-B'). It is thus essential that some appraisal of the vertical and lateral components of motion be made.

The magnitude of the vertical and horizontal geometric components of the Silver Cloud fold may be approximated by the geometric argument summarized in Figure 6. Calculations indicate that the vertical and horizontal components are nearly equal in magnitude. Combination of these components yields an inclined vector within the east-northeast-striking, nearly vertical plane. Since derivation of this inclined vector depends heavily on geometric assumptions, it cannot be directly interpreted as the vector of greatest principal stress. More reasonably, the vector is inherently kinematic in aspect, stating something about the overall movement of the Silver Cloud block relative to the Black Diamond basement buttress on the northeast.

That the greatest principal stress vector was also inclined, using the former geometric analogy is not, however, an unreasonable speculation. The dynamic speculation is pictorialized as Figure 10. In the cartoon, the inclination of the greatest principal stress (σ_1) systematically increases from the horizontal as the Black Diamond block is approached from the southwest; that is, the preexisting anisotropism of the Black Diamond block produced a systematic perturbation of the σ_1 stress trajectory from the horizontal immediately southwest of the Black Diamond fault. If Figure 10 is taken to its logical extreme, then faults that formed as a result of compression would, from left to right, initiate as low-angle reverse faults, become progressively steeper as they approach the basement irregularity, and then reflatten as they passed northeast of the Black Diamond fault. Thus, the Black Diamond fault acts as a structural hinge much in the manner that the north-northeast-trending Paleozoic hinge between areas of miogeosynclinal and platform sedimentation in Nevada and Utah is inferred by Burchfiel and Davis (1972) to have controlled Sevier-age, eastward-directed, low-angle tectonic transport. Theoretically then, all of the observed structures in the study area could be produced by east-northeast-directed regional compression which adjusts to the crustal irregularity imposed by the uplifted Black Diamond block.

Three notes of caution are immediately emphasized here. First is that the above analysis lacks experimental support. Second, no low-angle reverse faulting has been recognized in the Black Diamond block. It is interesting, however, that the high-angle reverse faults in the Silver Cloud block are predicted by the model. Third, the same structures can be produced by having an active vertical force in the basement in the presence of compression. In this context, a strict differential vertical uplift component (Jones, 1961, 1963, 1966) is worth considering for a moment. Vertical differential uplift could account for the net difference in structural relief and for some of the upward flattening as the basement "shoves" upward from below. Uplift would also preclude low-angle, compression-induced tectonic transport and explain the high-angle reverse faults as marginal to the uplift. But there are two fundamental features that the vertical uplift position fails completely to account for. The first feature is that all the observed fold structures have northeast-vergent axial planes that require some horizontal component of northeast-directed compressional shear for their formation. The second point is that upward flattening by physical laws requires some sort of equal and opposite "shove" which the atmosphere simply does not have in terms of mass. Structures near the actual uplifting block might be flattened due to the overlying lithostatic load, but the overall required flattening of the Silver Cloud fold is very dubious since the structure prob-

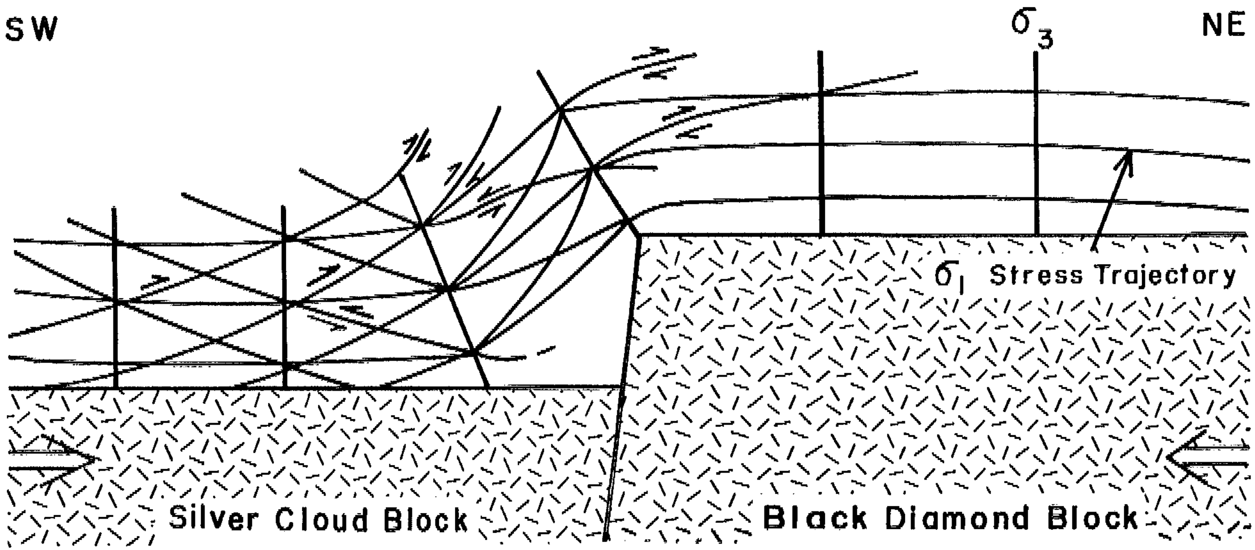

Figure 10. Schematized cross section showing hypothetical deflection of greatest principal stress (σ_1) trajectory across the study area and curvature of reverse faults in the Silver Cloud block.

ably did have a surface expression. One constraint is then clear: the presence of compression. Some form of compression is required to obtain the Silver Cloud fold geometry. Vertical uplift could have, but need not have, played a part.

Implications for Adjoining Areas

The Silver Cloud fold—Black Diamond fault extends northwest and southeast out of the area mapped. Several hypothetical implications of this structure for surrounding areas are discussed below.

1. The middle limb of the Silver Cloud fold pair continues three miles southeast out of the mapped area to South Pass where it is truncated by an east-west-striking transverse structure. Inspection of Gilluly's (1956) map in the vicinity of Courtland-Gleeson shows that the highly faulted Paleozoic section there dips variably east (mostly steeply east). The possibility exists that the Courtland-Gleeson eastward-rotated system may owe its origin to a monoclinal rotation similar to that for the central Dragoon Mountains. Emphasis on thrusting is minimized, although the Courtland overthrust is real and must still be accounted for. Possibly, the Courtland overthrust can be viewed as a thrust at the northeast corner of the Courtland-Gleeson block and, as such, may be a product of eastward translation of the Courtland-Gleeson block with respect to the central Dragoon Mountains block. Large-scale thrusting, as in Drewes (this Digest), in the Courtland-Gleeson block is, in our view, therefore unnecessary to explain the existing rock distributions.

2. Similar eastward rotation of Paleozoic and Lower Cretaceous strata is found to the north in the adjoining Dragoon quadrangle. It may be conjectured that tectonics responsible for the Silver Cloud fold can be extended at least 15 miles to the north to include the east-dipping Apache Group and Paleozoic sections in the Johnny Lyon Hills, the Little Dragoon Mountains, and the Gunnison Hills where the rotation predates the emplacement of the Texas Canyon Quartz Monzonite. Some post-Texas Canyon Quartz Monzonite tilting is also possible, particularly if the Stronghold Granite-related, northwest-striking dike swarm has in fact been rotated about 15 degrees to the northeast. Bryant and Metz (1966) also report 15 degrees of mid-Tertiary rotation of the Mule Mountains. Possibly the monoclinal tectonics recurred in the mid-Tertiary. Well-documented northeastward rotation of Miocene age has occurred in the Tortilla Mountains (Krieger, 1974), which are 55 miles northwest of and on trend with the Dragoon Mountains. Krieger has interpreted this northeast rotation as monoclinal.

3. An interesting analogy can be drawn between the Black Diamond fault and the Dividend fault at Bisbee 25 miles to the south. The faults have similar geometries and movement histories. At Bisbee, the Dividend fault is a principal control for the Jurassic-age porphyry copper mineralization (see Ransome, 1904, and Bryant and Metz, 1966, for detailed descriptions of this fault). Briefly, the Dividend fault strikes west-northwest, becoming more northwesterly at its western end, dips steeply southwest, and is a normal fault with upper Paleozoic strata in the footwall block and Precambrian Pinal Schist in the hanging wall. Glance Conglomerate rests depositionally on the upper Paleozoic strata southwest of the Dividend fault and on the Pinal Schist immediately northeast of the fault. Post-Bisbee motion has also occurred in the same sense. Bryant and Metz (1966) infer that the pre-Bisbee movement consisted of down dropping the southwestern block several thousands of feet with reference to the northwestern block. It has been speculated that the southwesterly contact of the Juniper Flat Granite coincided with the northwesterly extension of the Dividend fault due to its linear nature and

favorable orientation. At this point it is outrageous speculation to suggest that the Dividend and Black Diamond faults are one and the same, although the remote possibility does exist. It is more reasonable to suggest that they reflect the same pre-Cretaceous—post-Paleozoic tectonic event, that of northeast-southwest extension. As such, the Black Diamond and Dividend faults could be elements of the more extensive N 50° W pre-Cretaceous fault system proposed by Titley (1973, and this Digest).

4. The extensive thrusting shown by Gilluly (1956, sections II-VI, plate 6) around the Stronghold Granite is seen now from a different perspective. Rather than a more imbricated area along strike of the Dragoon fault system (which now has no basis for support southeast of Cochise Stronghold), the low-angle faults of which the principal element is the Mount Glen fault are alternatively viewed as low-angle faults induced by gravity tectonics associated with the emplacement of the 24 m.y. Stronghold Granite. Proximity of the low-angle faulting to the Stronghold Granite, general dip of the Mount Glen and other similar faults away from the Stronghold Granite to the north and south, and generally younger upper-plate rocks, which suggest low-angle <u>normal</u> faulting, are consistent with gravity-induced gliding of roof rocks away from the top of the Stronghold Granite intrusion. If folds are present in these rocks, a fold analysis would verify either alternative. Fold geometries for the Gilluly thrust model would have consistent northwest trends and northeast vergence, while in the gravity model they should show a general vergence away from the Stronghold pluton. It is, of course, possible that a combination of thrust and gravity models could be the case.

Conclusions

Although our model is vastly different in detail from that of Cederstrom (1946) and Gilluly (1956), the overall dynamic interpretation for "Laramide" tectonism is not. Both Cederstrom and Gilluly propose horizontal east-northeast-directed compression at this time to account for the geometry of their observed structures. We agree, but add a possible vertical component to the model. Our interpretation is also similar to the stress field proposed by Rehrig and Heidrick (1972) to explain fracture systems in 75-55 m.y. plutons. For Rehrig and Heidrick, the plane containing the axes of principal and intermediate stress is oriented east-northeast. In our model for the Silver Cloud block, the axis of principal stress is speculated to be inclined at some angle from the horizontal within an east-northeast plane.

The model we have developed does, however, place constraints on the magnitude of low-angle tectonic transport produced by compressive deformation, and this is where we disagree with Cederstrom (1946), Gilluly (1956), and Drewes (this Digest). The lack of any significant low-angle tectonic transport renders inoperable the geometry proposed by Gilluly (1956) and eliminates the possibility of a suture (the Cochise thrust fault of Drewes, this Digest) between two major thrust lobes in the central Dragoon Mountains. Proponents of the mega-thrust hypothesis will have to look elsewhere for support. What they will find in the central Dragoon Mountains is instead a large, overturned fold pair, intimately associated with a high-angle, northwest-trending normal fault.

Acknowledgments

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George Davis and his advanced structural geology class at The University of Arizona spent a day in the field reviewing the critical contacts lending additional insight to the interpretative aspects of the paper.

Postscript

Since the time this paper was written, Harald Drewes (this Digest) has suggested that our data are ambiguous enough that the alternative of thrusting is still feasible for the central Dragoon Mountains. The comments by Drewes constitute useful input, elicit a response that further clarifies our interpretative position, and hopefully are a step toward solution of the complex structural geology in the central Dragoon Mountains. Our response is in approximate sequence to the points raised by Drewes.

Nature of the Black Diamond Fault

Drewes comments that we portray the Black Diamond fault as a normal or <u>reverse</u> fault. We restate that the available evidence from surface and underground exposures strongly indicates only normal juxtaposition of stratigraphic units (see text, pp. 181-182).

Regional Continuity of Thrust Faults

Drewes indicates that both he and Gilluly find structural interpretations involving major thrust faults northwest and southeast of our mapped area to be attractive working hypotheses and therefore find it reasonable to <u>project</u> them through the central Dragoon Mountains. We have no evidence to contradict such interpretations. A major intent of our paper, however, was to show that in the central Dragoon Mountains —where presumably some of the best exposures of thrust faults and therefore the least interpretation might be expected—there is no evidence to support the physical or interpretative reality of such major thrust faults. Indeed, in our view, a perusal of existing maps suggests that our model may have reasonable application to adjoining areas (pp. 199-200 in text). The differential vertical uplift exercises with existing map data by Jones (1961, 1963, 1966) are also indicative of the ambiguity of existing map data. We, like Drewes, also encourage further detailed mapping efforts in adjoining areas that will hopefully place more physical constraints on interpretative efforts.

The Disharmonic Nature of the Silver Cloud Fold

Drewes states that the Silver Cloud fold nowhere involves the Precambrian crystalline rocks, is therefore disharmonic, and is therefore separated from the crystalline rocks by a fault (the "structural ungluing" concept of Gilluly, 1956). He then states that the principal difference between our models concerns the amount of movement on this fault. We agree that laterally and perhaps vertically with respect to neighboring fold structures that the wavelength and amplitude of the Silver Cloud fold is disproportionately large and therefore disharmonic in the <u>geometric</u> sense of the term. We do not intend any mechanical overtones, such as separation of the layered rocks from the crystalline basement by a (thrust?) fault. No such fault is mentioned in our text. In point of fact, there is no surface evidence for such a fault at the key contact—namely, the contact of the Bolsa Quartzite with the Precambrian granite (see Figure 3 of text). Exposures of the contact in the southwestern portion of the mapped area are also clearly depositional and show no evidence of movement.

There is no mechanical necessity in our model for such a fault. Any bedding plane movements in such a zone could, however, be readily interpreted as bedding plane slippage during flexural slip folding (see analogous arguments for the Glance-Paleozoic contact at p. 193).

The question of whether the isotropic Precambrian granitic rocks are involved in the folding is necessarily problematic as there are no layer markers in the granite to indicate the presence or absence of folding. It is interesting that where there are such markers the presence of folding has been confirmed. For example, Krieger (1974) mentions folded diabase sills below the monoclinally folded Apache Group rocks which rest depositionally on the "Ruin" granite west of Kearny, Pinal County, Arizona.

The Systematic Nature of the Silver Cloud Fold

Drewes asks why, if the Silver Cloud fold buckled against the buttress of an uplifted block, was the fold overturned rather than upright or erratically crumpled. In our view, the Silver Cloud fold is part of a regional compressive tectonic framework and retains the systematics of that framework. That is, the northeast vergence and the northwest-trending fold axes suggest that a regional east-northeast-directed compression was at work between 72 m.y. and 52 m.y. ago. The location, disproportionate size, and disharmonic nature of the fold are the result of a local, pre-compressional basement uplift with a northwest-striking, southwest-dipping edge. Had that edge been oriented east-northeast, for example, a completely different set of fold morphologies would perhaps have ensued. As the case was, the basement discontinuity acted as a steep ramp against which the Silver Cloud fold initially buckled and in its later stages attempted to override (see Figure 6 in text).

Suggestion That a More Fluid Situation Favors Thrust Fault Movement

Drewes suggests that a large overturned fold is indicative of a more fluid situation that facilitates thrust fault movement. Fluid media by their nature do not transmit stress but flow in response to an imposed stress. Thrust faults, then, are impossible in true fluid situations. Drewes probably intends an intermediate situation between a fluid and solid-state system; that is, a plastic state. However, evidence from our study area does not indicate a "fluid situation" nor is there any necessary mechanical connection between an overturned fold and a "fluid situation." Rather, as stated in our text (p. 195), field evidence overwhelmingly favors a high crustal level, solid-state system in which deformation proceeded predominantly by brittle fold and fracture mechanics, not flow mechanics. Indeed, Drewes himself points out that a subdued topographic ramp at the site of the eroded uplift block may have promoted deflection of thrust faults. Clearly, if the surface topography is exerting controls on thrust faults, then we should expect the mechanics of that thrust faulting to be brittle and not plastic in nature.

The Jurassic Stratigraphic Problem

The lack of any stratigraphic record of the uplift of the Black Diamond structural block is somewhat perplexing. But then, so also is the lack of any similar record for other well-documented faults with pre-Cretaceous, post-Paleozoic movement histories (for example, the Dividend fault at Bisbee). We have no good explanation for this mystery (see discussion on pp. 188-189), but do suggest that answers to this problem are not unique to our area but apply to southeastern Arizona as a whole. Jurassic tectonism in this region is, from the available geology, something we know very little about. The paper by Titley (this Digest) is a good summary of that part of the geologic record and also indicates how little we know about the Jurassic with respect to other events, such as the "Laramide." Much new work is needed in that part of the record.

In response to Drewes' final question of whether, in fact, a basement buttress localized folding or whether a thrust occurred over a subdued topographic ramp, we can only refer back to our first-hand field observations. As we have attempted to show, there is simply no field evidence to support the concept of a thrust fault geometry along which large-magnitude tectonic transport has taken place. The available evidence, on the other hand, strongly supports a pre-Cretaceous uplift along the Black Diamond fault and the existence of a large, northeast-vergent fold pair. The strong evidence for this geometry implictly excludes other geometries (for example, thrust faults) from consideration unless, of course, one wants to draw in hypothetical alternatives above or beneath the plane of our field observations which we, for the present, view as unnecessary.

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TECTONICS OF THE CENTRAL DRAGOON MOUNTAINS: A NEW LOOK

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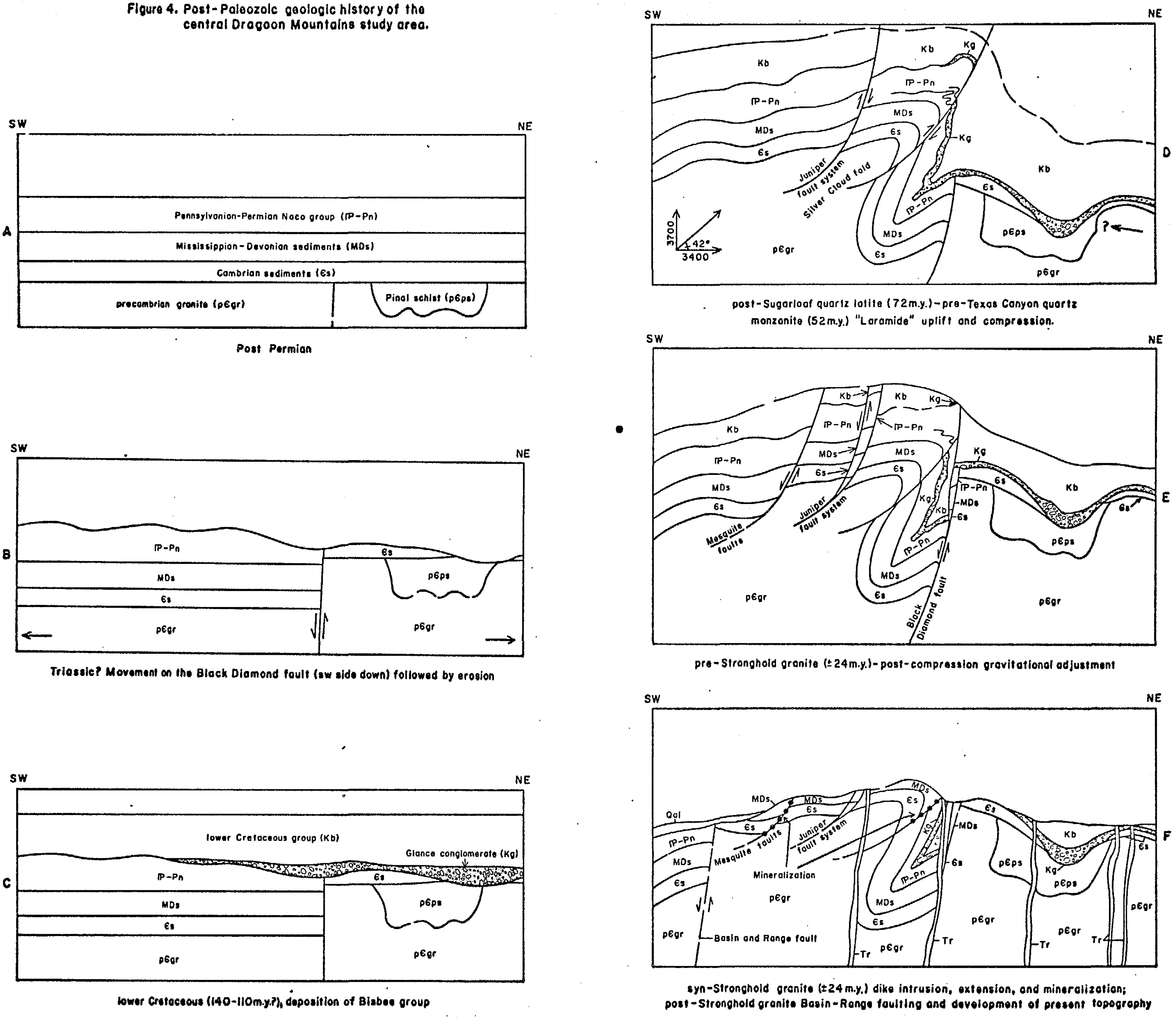
Traditional interpretations of the structural geology of the central Dragoon Mountains hold that the predominant tectonic fabric resulted from compression-induced, low-angle tectonic transport via thrusting, the principal element of which is the Dragoon fault. Evidence based on new detailed mapping is presented that 1) establishes that intrusions previously mapped as Triassic-Jurassic have Precambrian ages and 2) invalidates the thrust fault hypothesis. Rather, the complex structural geometry consists of a large, northeast-vergent, northwest-trending southeast-plunging fold pair named the Silver Cloud fold, which is parallel to a northwest-striking, high-angle normal fault named the Black Diamond fault. The Black Diamond fault had considerable pre-Cretaceous movement of southwest side down, which predates formation of the Silver Cloud fold. The Silver Cloud fold formed in response to northeast-directed compression between 72 and 52 m.y. ago. The Black Diamond fault considerably influenced the locality and geometry of the Silver Cloud fold. Relatively downthrown Paleozoic rocks southwest of the Black Diamond fault were compressed against an unyielding, upthrown buttress of Precambrian crystalline rocks on the northeast resulting in the disproportionately large, disharmonic Silver Cloud fold. Implications of this structure for adjoining areas are also discussed.

Figure 4. Post-Paleozoic geologic history of the central Dragoon Mountains study area.



A: Post Permian

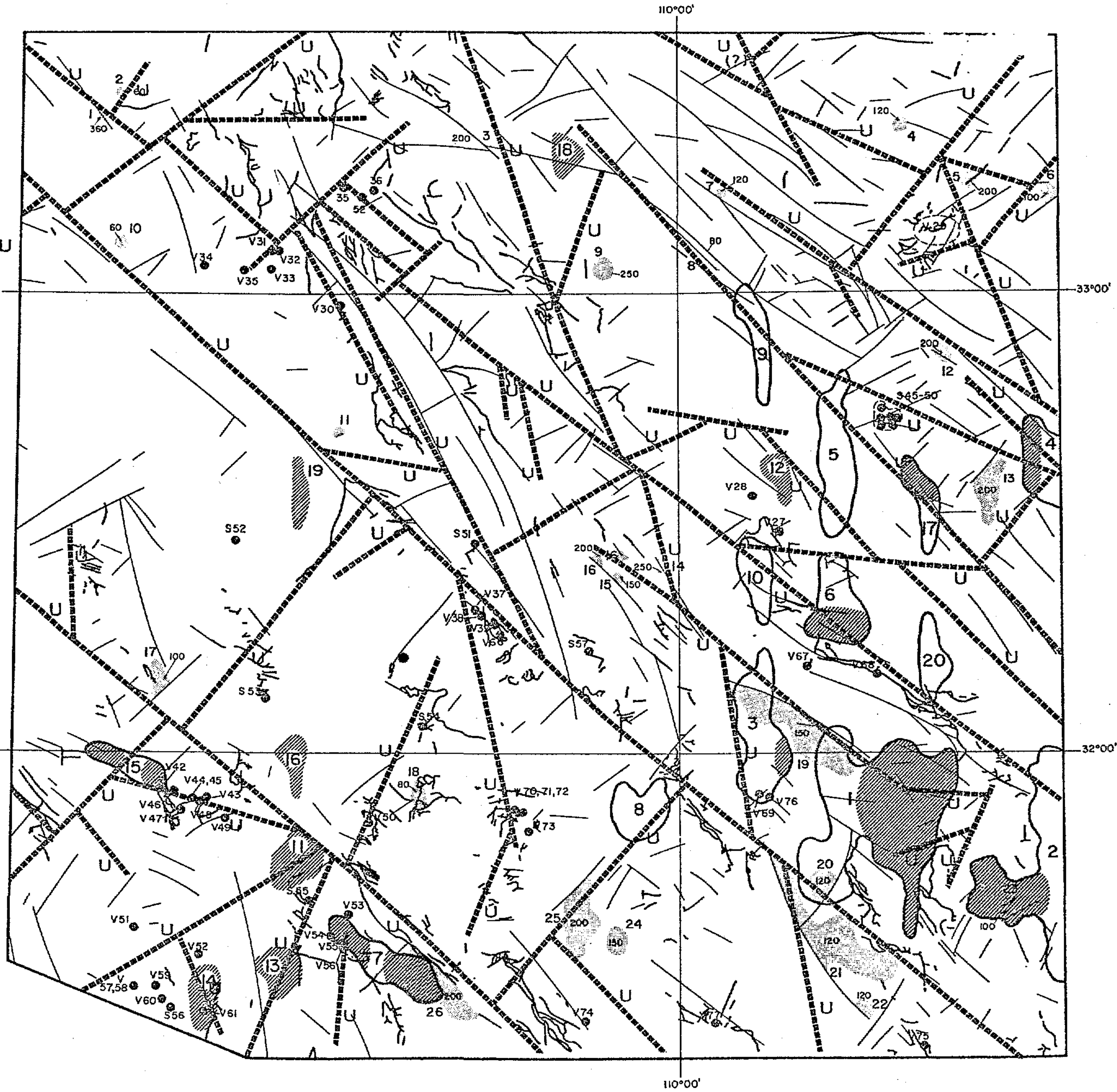
B: Triassic? Movement on the Black Diamond fault (sw side down) followed by erosion

C: lower Cretaceous (140-110m.y.?), deposition of Bisbee group

D: post-Sugarloaf quartz latite (72m.y.)-pre-Texas Canyon quartz monzonite (52m.y.) "Laramide" uplift and compression.

E: pre-Stronghold granite (±24m.y.)-post-compression gravitational adjustment

F: syn-Stronghold granite (±24m.y.) dike intrusion, extension, and mineralization; post-Stronghold granite Basin-Range faulting and development of present topography



FAULTS INFERRED FROM AEROMAGNETIC CONTOUR MAP

FAULT INFERRED FROM PROFILE DATA

KNOWN FAULTS

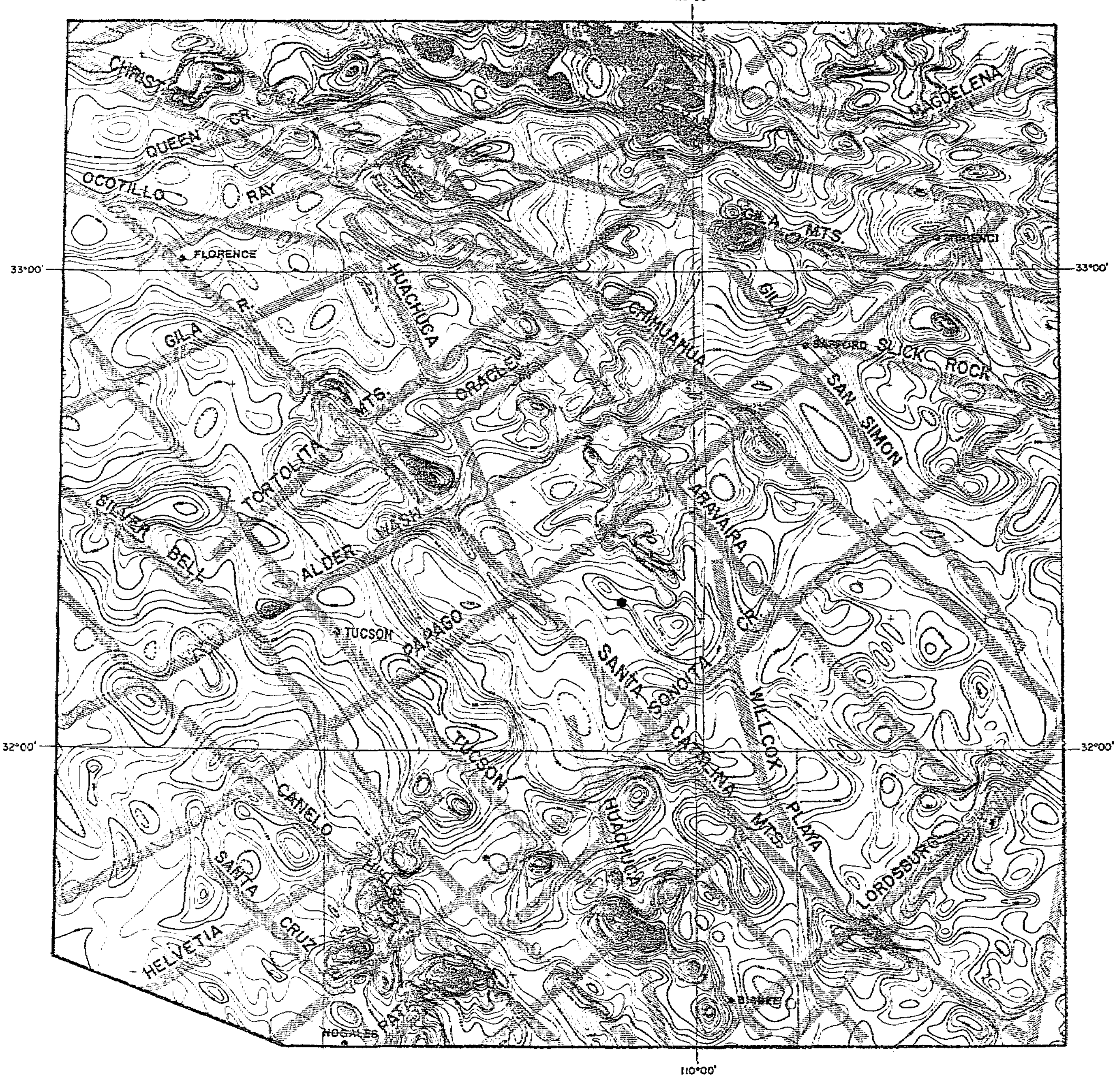
KNOWN URANIUM OCCURENCES

16 200 SELECTED MAGNETIC ANOMALIES AND INTENSITY IN GAMMAS WITH IDENTIFICATION NUMBER

ANOMALIES LEAST SUSPECT OF INVERSION EFFECT

ANOMALIES MORE SUSPECT OF INVERSION EFFECT

Figure VI-3. Relationship of Major Magnetic Lineaments or Inferred Faults to Uranium Occurrences and Anomalies



REGIONAL LINEAMENTS DERIVED FROM ERTS IMAGERY

Figure VI-4. ERTS (Landsat)-Derived Lineaments and Aeromagnetic Data

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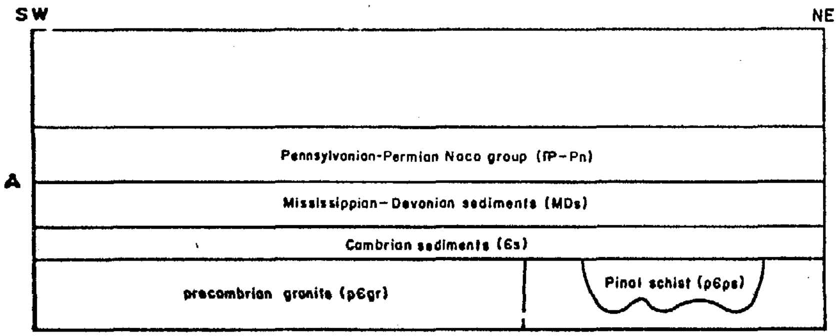
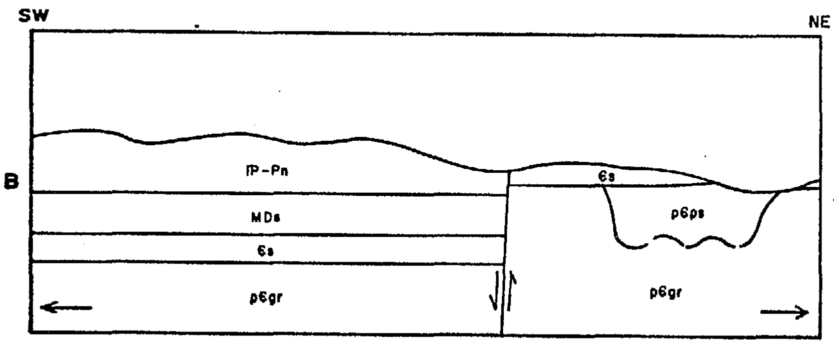
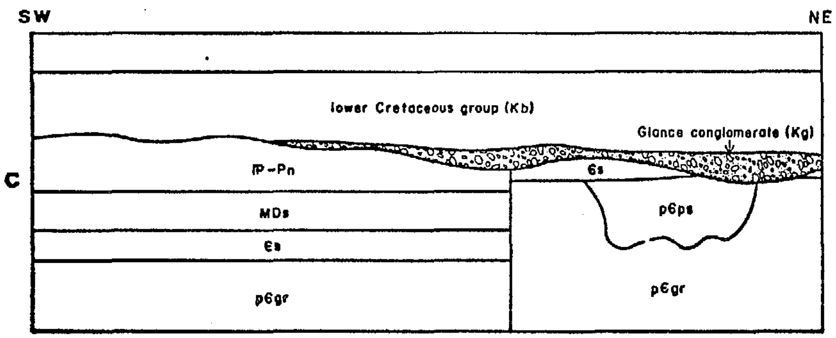


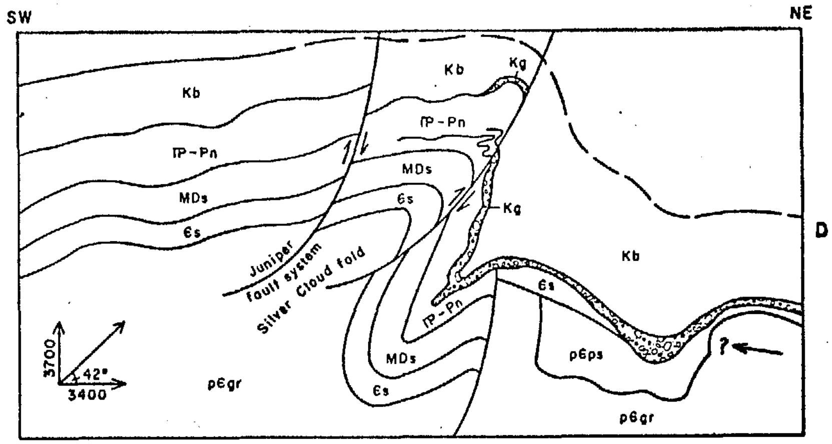
Post Permian



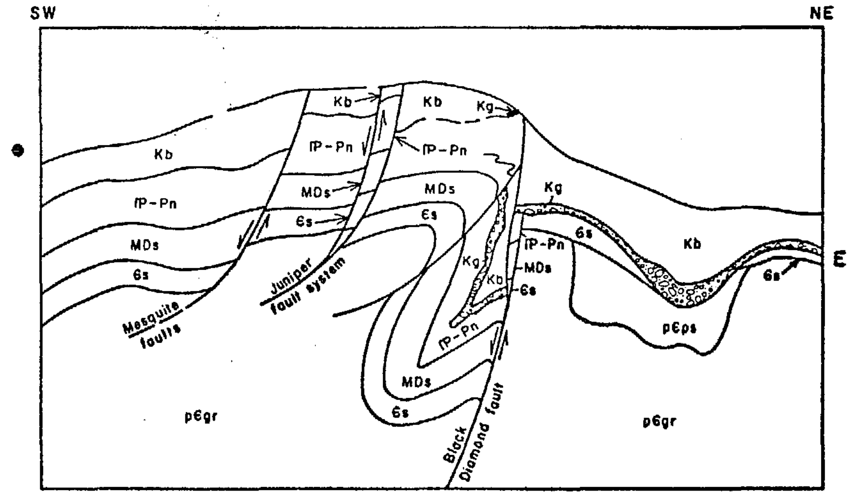
Triassic? Movement on the Black Diamond fault (sw side down) followed by erosion



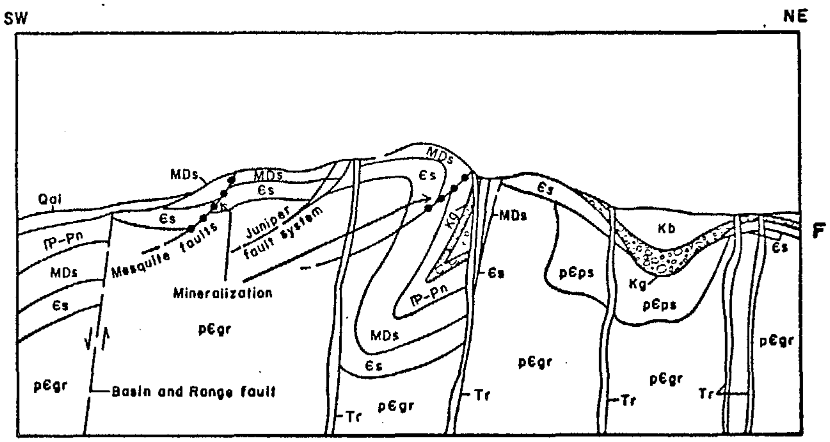
lower Cretaceous (140-110m.y.?), deposition of Bisbee group



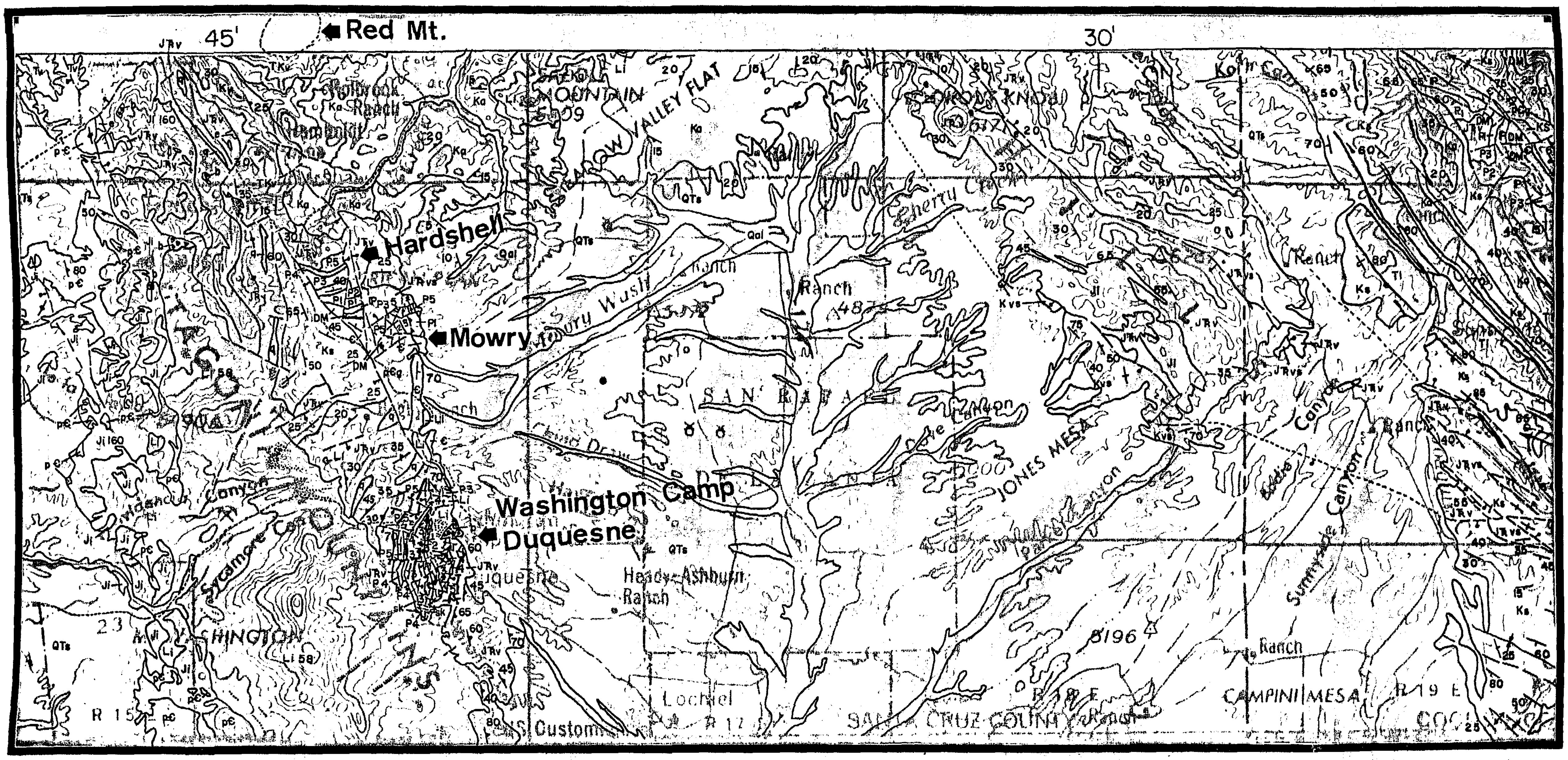
post-Sugarloaf quartz latite (72 m.y.) - pre-Texas Canyon quartz monzonite (52 m.y.) "Laramide" uplift and compression.



pre-Stronghold granite (±24 m.y.) - post-compression gravitational adjustment



syn-Stronghold granite (±24 m.y.) dike intrusion, extension, and mineralization; post-Stronghold granite Basin-Range faulting and development of present topography



Geology of the southern portion of the Patagonia Mtns., Canelo Hills and Huachuca Mtns; Santa Cruz County, Arizona.

Scale: 1" = 2 miles

SEDIMENTARY ROCKS

Qal	Alluvium, Gravel, Sand and Silt
QTs	Gravel, Sand and Conglomerate
Ts	Conglomerate, Sandstone and Volcanics
Kvs	Cretaceous Volcanics and Sediments K-Ar Age = 72 M.Y.
Ks	Cretaceous Sediments of the Bisbee Group, Salero and Ft. Crittenden Formations
J₸vs	Jurassic-Triassic Rhyolite and Sediments
e	Exotic Blocks of Paleozoic Sediments in J₸v and J₸vs Units
P5, 5	Permian Concha Limestone
P4, 4	Permian Scherrer Formation
P3, 3	Permian Epitaph Formation
P2, 2	Permian Colina Limestone
P1, 1	Perm.-Penn. Earp Formation
IP	Pennsylvanian Horquilla Limestone
DM	Devonian and Mississippian Martin and Escabrosa Limestone
€	Cambrian Bolsa Quartzite and Abrigo Limestone

NACO GROUP (P5,5 – P1,1); P

METAMORPHIC ROCKS

Pi	Precambrian Pinal Schist
p€	Precambrian Granitic and Metamorphic Rocks

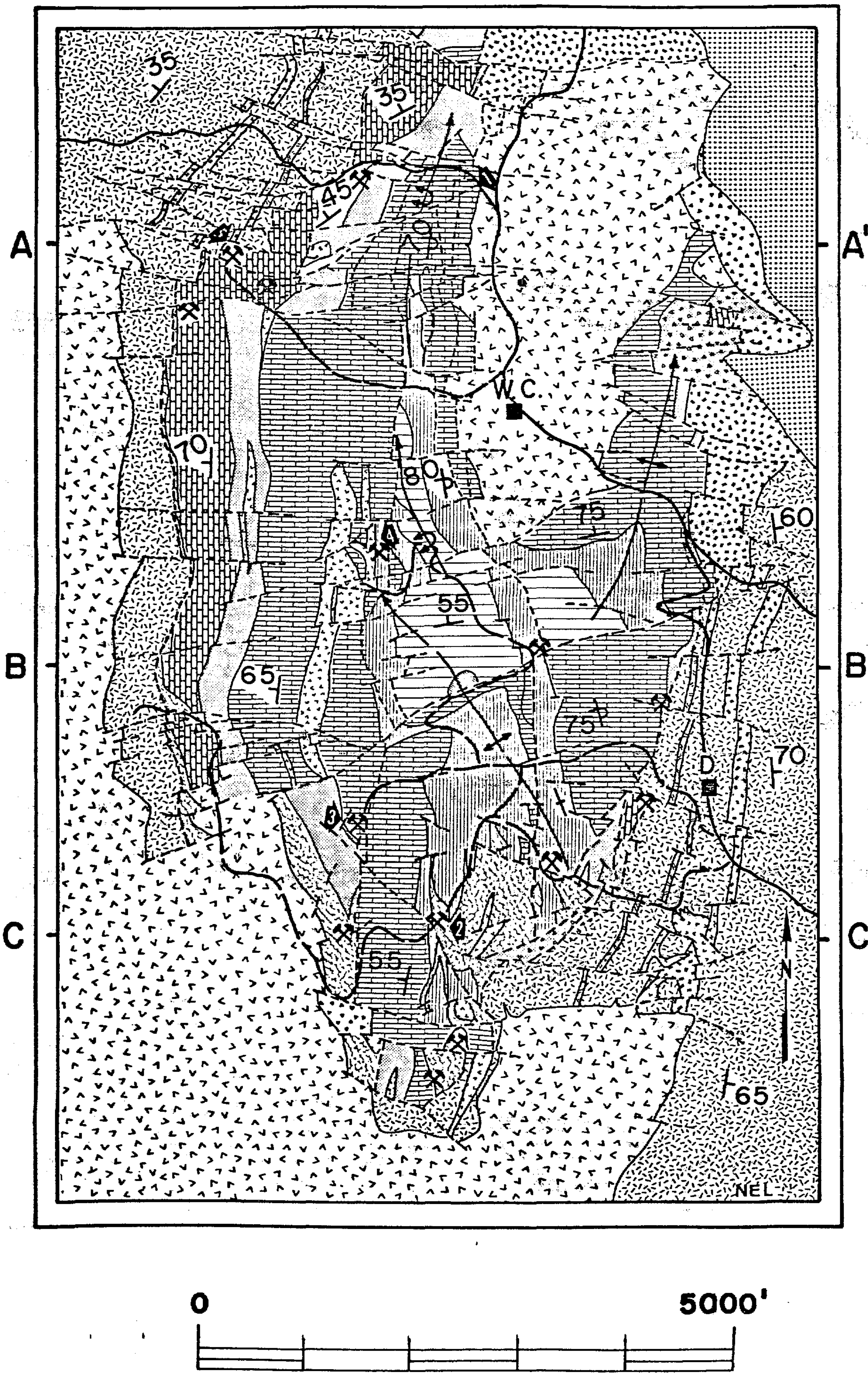
IGNEOUS ROCKS

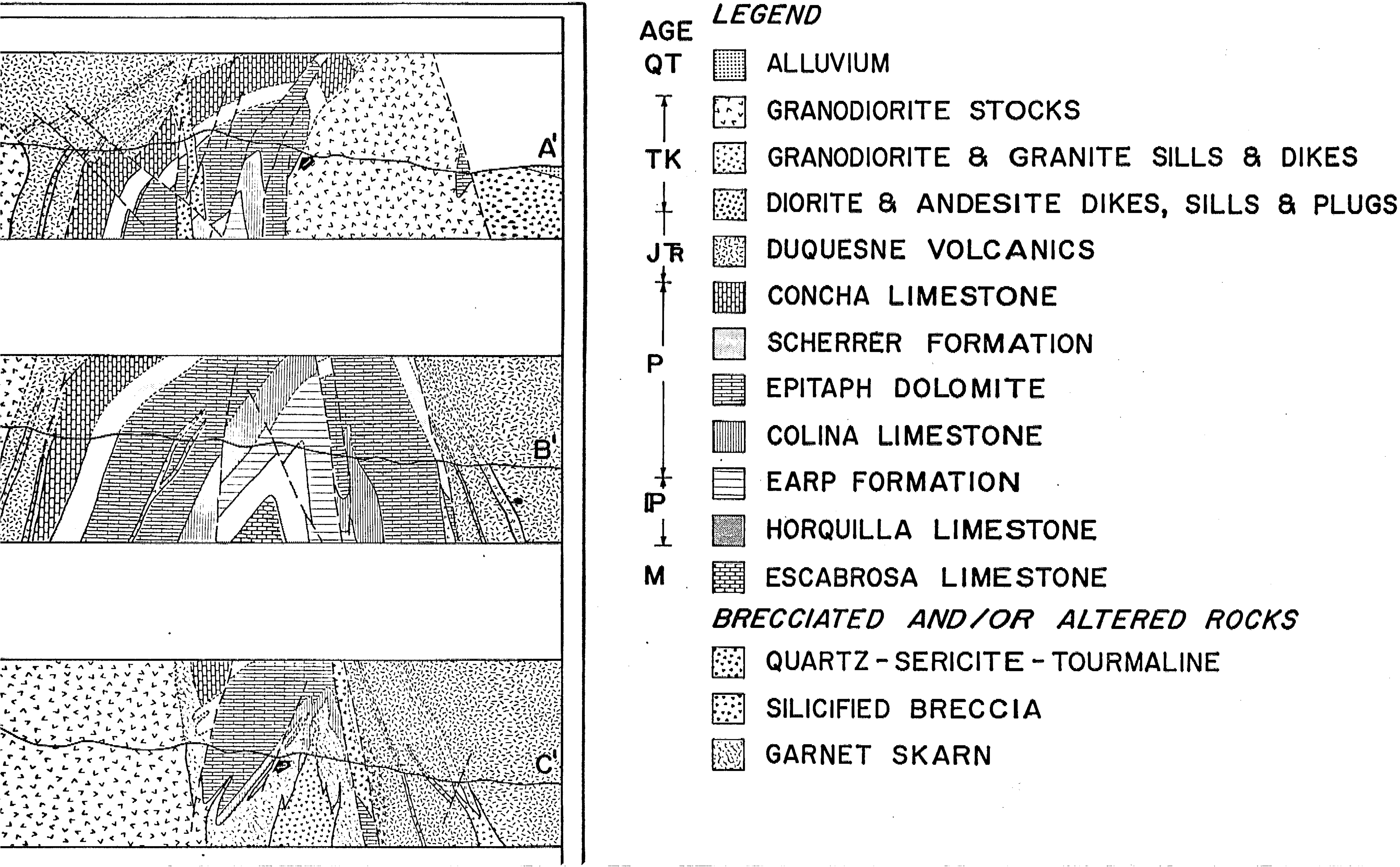
Tv	Oligocene to Paleocene Rhyolite-Rhyodacite Flows and Tuffs
Ti	Tertiary Quartz Monzonite and Granodiorite Intrusives
Li 58	Laramide Granodiorite, Monzonite and Diorite K-Ar = 58 M.Y.
(dike symbol)	Laramide Dikes
TKv	Rhyolite Flows and Tuff
Ka	Cretaceous Trachyandesite Flows (K-Ar = 72 M.Y.); Andesite Flows in the Glance Cg. (Huachuca Mtns.)
Ji 160	Jurassic Granitic Intrusive Rocks K-Ar = 160 M.Y.
J₸v	Jurassic and Triassic Rhyolite-Latite Flows and Tuff of the Canelo Hills, Mt. Wrightson and Duquesne Volcanics
pCg	Precambrian Granitic Rocks

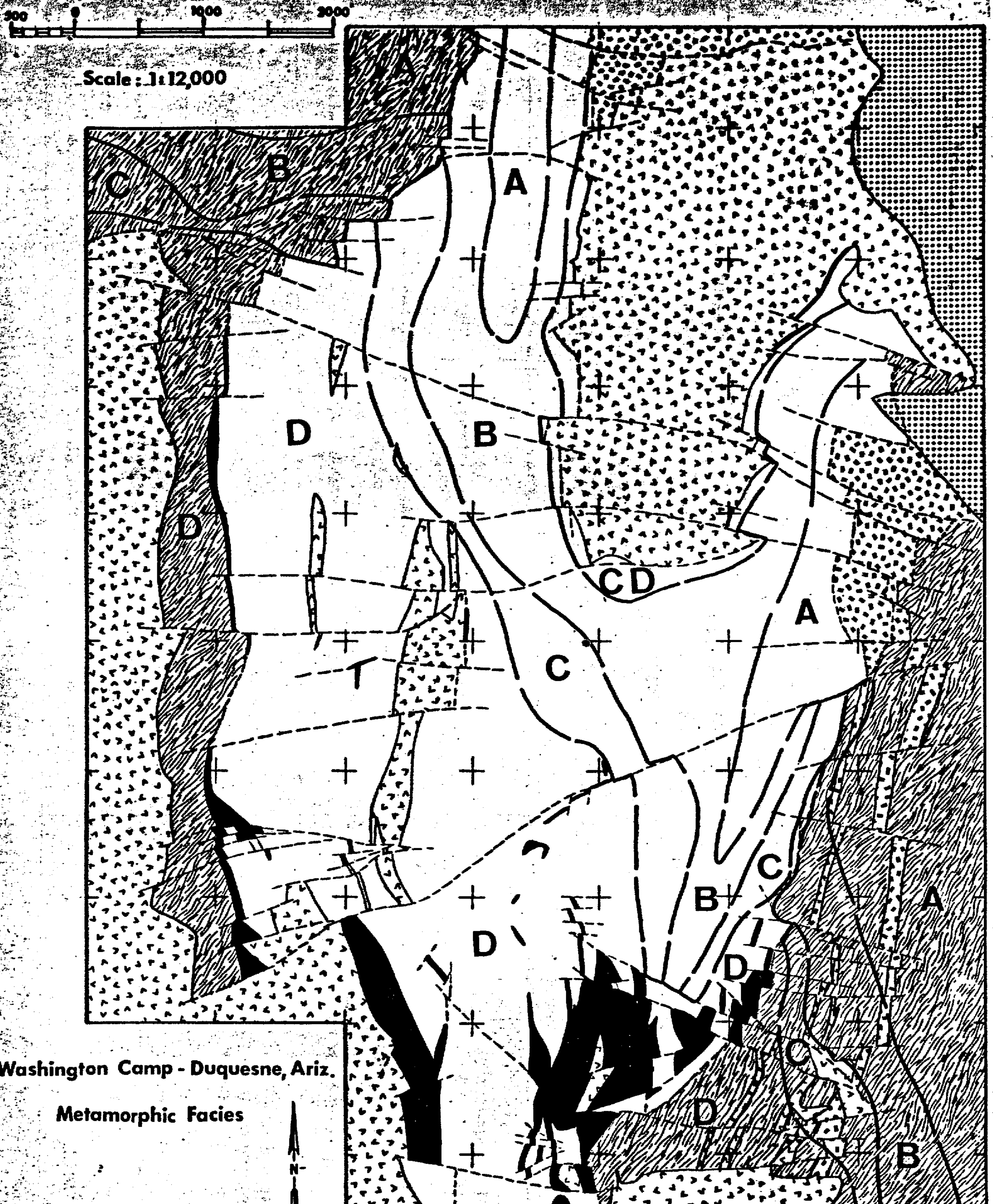
SYMBOLS

	Contact
40	Bedding
80	Overturned Bedding
	Vertical Bedding
70	Foliation
	Vertical Foliation
	Fault, Symbol on Downthrown Side
	Thrust Fault
	Fold Axis
	Overturned Fold Axis
b	Breccia
q	Quartz
	Altered Rock
sk	Skarn

WASHINGTON CAMP - DUQUESNE DISTRICT




A'
B'
C'
LEGEND
AGE
QT
ALLUVIUM
GRANODIORITE STOCKS
TK
GRANODIORITE & GRANITE SILLS & DIKES
DIORITE & ANDESITE DIKES, SILLS & PLUGS
JTR
DUQUESNE VOLCANICS
CONCHA LIMESTONE
SCHERRER FORMATION
P
EPITAPH DOLOMITE
COLINA LIMESTONE
EARP FORMATION
IP
HORQUILLA LIMESTONE
M
ESCABROSA LIMESTONE
BRECCIATED AND/OR ALTERED ROCKS
QUARTZ-SERICITE-TOURMALINE
SILICIFIED BRECCIA
GARNET SKARN



Washington Camp - Duquesne, Ariz.

Metamorphic Facies

	FACIES	LIMESTONE	DOLOMITE	CLASTIC	VOLCANIC
A	ALBITE-EPIDOTE HORNFELS (I)	Rx Cal-Chl-C	RxDol-Chl-C	RxQtz-C	Qtz-Ser-Musc Qtz-Chl
B	ALBITE-EPIDOTE HORNFELS (II)	Cal-Trem-Tlc	Dol-Trem-Tlc-Phlog	Trem-Ep-Bio-Musc	Qtz-Bio Bio-Trem-Zois-Musc Phlog-Trem-Zois
C	HORNBLENDE HORNFELS	Cal-Dol-Diop Cal-Diop-Trem Cal-Trem-Horn	Dol-En Dol-En-Per	Horn-Ab-Ksp	Horn-Ksp-Bio Bio-Horn-Clzo-Ab-Ksp Horn-Plag-Bio
D	PYROXENE HORNFELS	Cal-Woll-Diop-Gr Cal-Woll-Diop	Dol-For-En-Woll Dol-Br-Woll-Per	Diop-Ab-Ksp	En-Musc Diop-Hed-Plag Anorth-Microcl

Alluvium

Garnet Skarn

Silicic Plutonic Rocks

Mafic Plutonic Rocks

Duquesne Volcanics

Paleozoic Sediments

THE HARDSHELL SILVER DEPOSIT, HARSHAW MINING DISTRICT, SANTA CRUZ COUNTY, ARIZONA

Davis, Steven R.
ASARCO
P.O. Box 5747
Tucson, Arizona 85703

The Hardshell deposit is located in the northern Patagonia Mountains about 15 miles northeast of Nogales, Arizona and 4 miles south of the Red Mountain porphyry copper deposit. The greater Hardshell zone is situated on the eastern margin of a large altered zone and includes several small mines which had an aggregate silver production of approximately 1,000,000 ounces.

The areal geology consists of a complexly faulted mountain range with Precambrian to Tertiary units exposed. The Hardshell zone occurs in a fault block composed of volcanic rocks which unconformably overlie upper Paleozoic sedimentary rocks. Mineralization is localized along minor feeders and replacement zones in Paleozoic sedimentary rocks and most importantly as a manto-like zone of disseminated silver mineralization in the overlying Mesozoic volcanic and fine-grained sedimentary rocks. Intrusions present in and adjacent to the mineralized area include rhyolite, latite porphyry and diabase.

The silver mineralization occurs in a complex silica and manganese oxide deposit with associated lead and zinc. The silver is closely associated with manganese and lead oxides and to a lesser extent with massive hydrothermal silica. Silver content correlates more closely with lead than manganese. Argentian cryptomelane has been identified in significant quantities. Although the deposit is oxidized, supergene enrichment has not significantly modified the geometry or tenor of mineralization.

A possible magmatic source for the mineralizing solutions appears to be a Laramide granodiorite pluton exposed approximately two miles west of the deposit.

Field Notes — March 20, 1976

The attached map shows the generalized geology of the Hardshell Canyon area and the route to be taken by the current field trip. The zone of anomalous silver mineralization is restricted to the southeast 1/4 of the map area.

Proceeding up the Hardshell Canyon we will be descending in the geologic section. The diabase and andesite are of probable late Cretaceous or early Tertiary age; all the other rock units on the map are of probable Mesozoic age. A brief summary of the rock units to be encountered follows:

1. Andesite and diabase constitute the youngest rock units in the map area. These units have been referred to in previous publications as trachyandesite, doreite, pyroxene monzonite, and quartz diorite. Both rock units are very probably co-magmatic, and both extrusive and intrusive phases are present.

   The andesite is commonly aphanitic and vesicular to finely crystalline and massive. Minor calcite and celadonite are common as vesicle coatings and fillings, and as yet unidentified zeolites are also locally present. The andesite is not significantly altered in the Hardshell Canyon area.

   The diabase exhibits a medium crystalline, moderately diabasic texture in an aphanitic groundmass. It is locally propylitized and where affected commonly displays weak chlorite flooding and epidote fracture coatings and veinlets. Near its contact with the older rock units, the diabase is occasionally clay sericite altered for a few feet from the contacts.

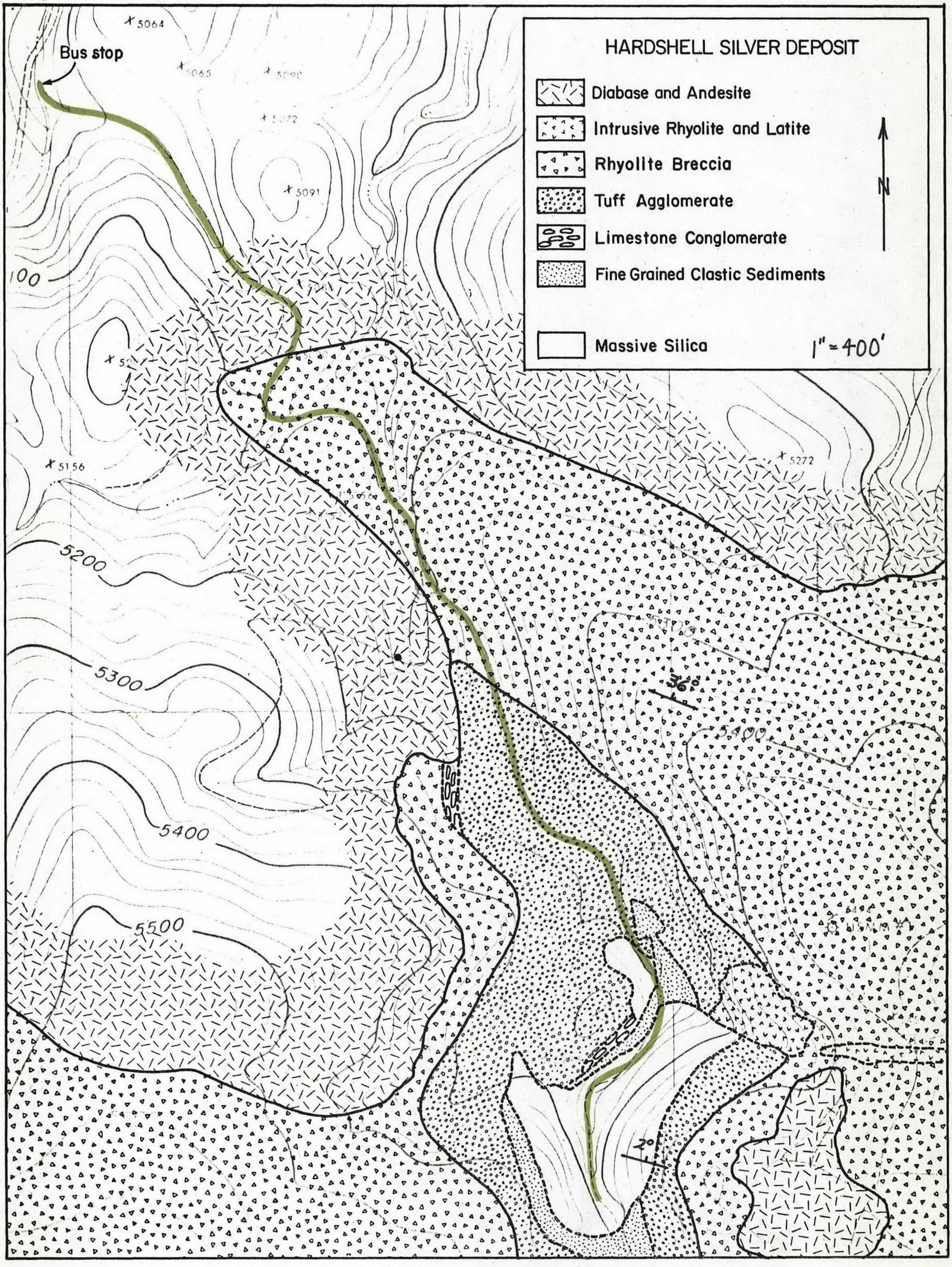
2. The intrusive rhyolite and latite shown occur as small, variably porphyritic dikes and sills. These dikes and sills do not extend into the mineralized zone and do not appear to have affected the distribution of mineralization. Although the smaller rhyolite and latite masses are pervasively clay altered and exhibit moderate to strong iron oxides after pyrite, the larger latite porphyry masses are fresh or very weakly altered.

3. The rhyolite breccia is a silicic, volcanic breccia containing a large variety of rhyolitic to latitic fragments, minor tuff, and rare rhyolite flows. The fragments vary from less than 1 inch to over 6 feet in diameter, are dominantly angular to subangular and flow banded. The rhyolite breccia is commonly clay altered and silicified and contains locally abundant limonite and hematite after disseminated pyrite.

4. The tuff-agglomerate complex can best be described as an air fall tuff with occasional agglomeratic horizons and rare bedding. Fragments, where present, are usually tuffaceous to cherty, less than 2 inches in diameter, and commonly subrounded to rounded. Limestone conglomerates and probable landslide breccias also occur locally within the tuff-agglomerate unit. The contact between the tuff-agglomerate and overlying rhyolite breccia is a transitional, interlayered zone. The tuff-agglomerate is clay-silica altered, similar to the rhyolite breccia, and contains a lesser amount of limonite and hematite after pyrite. Serpentine(?) and chlorite are locally present in significant quantities. Disseminated Ag, Mn, Pb, & Zn mineralization is locally strong and is apparently a function of source channels and favorable porosity-permeability.

5. The fine-grained clastic unit is comprised of impure siltstones and fine to medium-grained sandstones; minor mudstones are also noted. Locally, more coarsely clastic horizons contain recognizeable fragments of older sandstones and limestones of probable Paleozoic origin, as well as rare volcanic fragments. These fine-grained clastic rocks are usually clay altered and/or bleached with moderate limonite and hematite after pyrite. Silicification and associated Ag, Mn, Pb, & Zn mineralization are locally intense and in the main zone of mineralization effectively mask all previous rock and alteration textures.

6. Massive cryptocrystalline silica pervades the main mineralized zone and commonly is widespread peripheral to the zone; i.e., especially in the more porous and permeable rock types. The silica occurs as a replacement of pre-existing rocks, but remnant rock textures are seldom preserved.

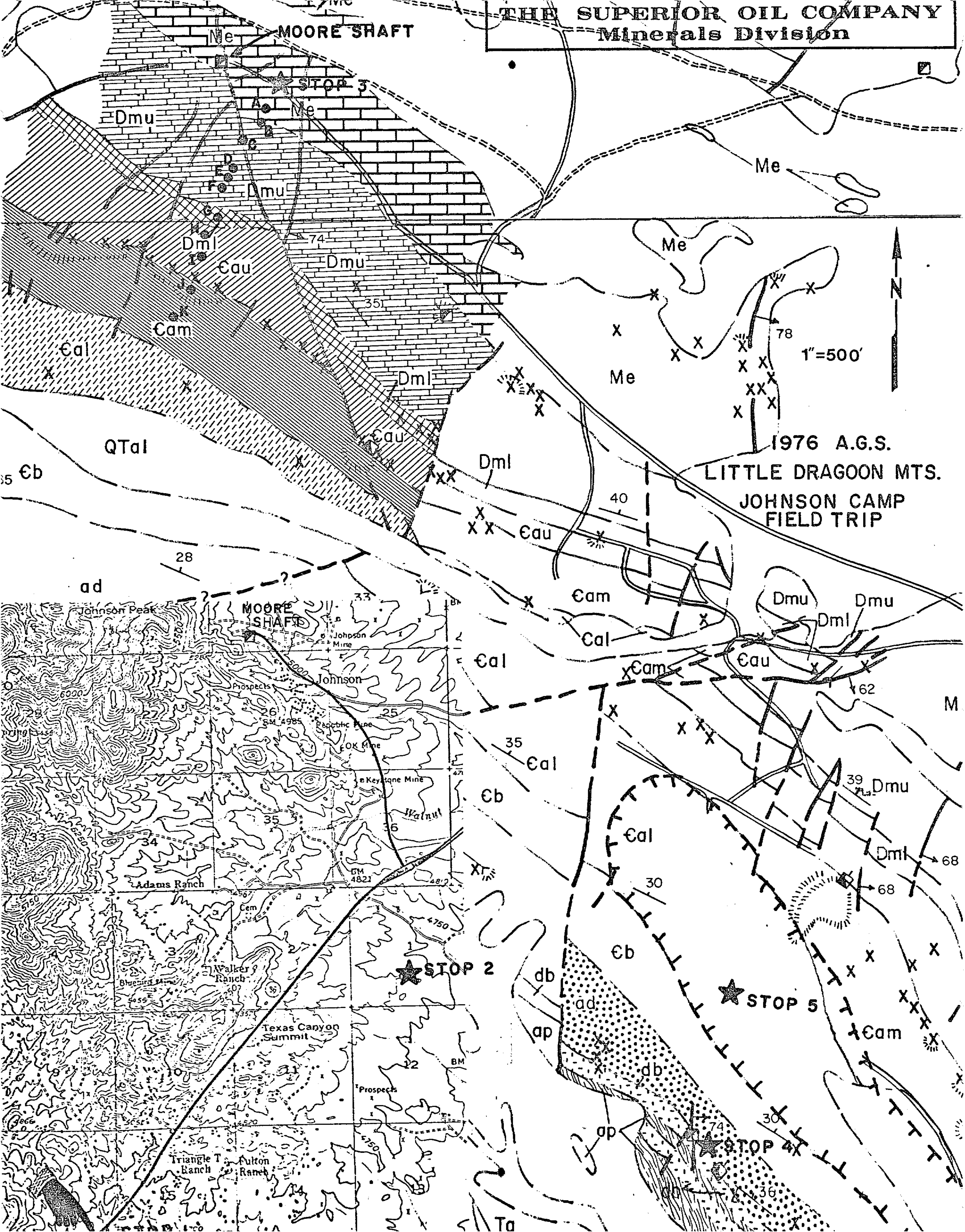


HARDSHELL SILVER DEPOSIT
Diabase and Andesite
Intrusive Rhyolite and Latite
Rhyolite Breccia
Tuff Agglomerate
Limestone Conglomerate
Fine Grained Clastic Sediments
Massive Silica
1" = 400'
N
Bus stop
5064
5065
5090
5072
5091
5156
5272
5200
5300
5400
5500
36°
2°

PREMINERAL STRATIGRAPHIC SECTION
SILVER CITY AREA

AGE	FORMATION	LITHOLOGY	THICK.(FT.)	CHARACTER AS HOST
K-T	"ANDESITE"	FLOWS,BRECCIA,TUFF	300-1000	VERY POOR
K	COLORADO	SANDSTONE&SHALE	300-2200	POOR
	BEARTOOTH	ORTHOQUARTZITE	60-140	POOR; LIMEY BEDS OK
P	ABO	RED BEDS, CALC. SANDSTONE&SHALE	0-265	FAIR TO EXCELLENT METAMORPHIC
IP	SYRENA	LIMESTONE, SILTY SOME SHALE	0-390	GOOD TO EXCELLENT METAMORPHIC
	OSWALDO	LIMESTONE, BASAL SHALE	450-490	EXCELLENT METASOMATIC
M	LAKE VALLEY	LIMESTONE, CLEAN, CHERTY	300-480	EXCELLENT METASOMATIC
D	PERCHA	SHALE, SOME IMST. NODULES	350-430	POOR TO GOOD (?) UNPROVEN METAMORPHIC
S	FUSSELMAN	DOLOMITE	200-300	POOR, SMALL METASOMATIC
O	MONTOYA	DOLOMITE, WITH CHERT & IMST.	200-350	POOR SMALL METASOMATIC
	EL PASO	DOLOMITE, LIMEY & SILTY	520	FAIR METASOMATIC, GOOD (?) UNPROVEN METAMORPHIC
€-O	BLISS	ORTHOQUARTZITE	190	POOR
P€		GRANITE		POOR

138-75 MWD


THE SUPERIOR OIL COMPANY
Minerals Division
MOORE SHAFT
STOP 3
Dmu
Dml
Cau
Cam
Cal
Me
QTal
Cb
ad
1"=500'
N
1976 A.G.S.
LITTLE DRAGOON MTS.
JOHNSON CAMP
FIELD TRIP
Johnson Peak
MOORE SHAFT
Johnson Mine
Johnson
Prospects
Republic Mine
OK Mine
Keystone Mine
Walnut
Adams Ranch
Walker Ranch
Bluebird Mine
Texas Canyon Summit
Triangle T Ranch
Fulton Ranch
STOP 2
STOP 5
STOP 4
db
ap
Ta

LITTLE DRAGOON MTNS
JOHNSON CAMP FIELD TRIP

Stop 1 — Highway I-10 Dragoon turnoff - Texas Canyon Quartz Monzonite-porphyritic stage with K-spar phenocrysts in quartz, plagioclase, K-spar, biotite groundmass.

Stop 2 — Highway I-10 .8 mile south on Johnson Road - Altered phase of Texas Canyon Quartz Monzonite. Quartz veining, muscovite, weak argillic alteration. Copper-tungsten.

Stop 3 — Johnson Camp - Moore Shaft stratigraphic section.

3A - Mississippian Escabrosa fm. cherty limestone and basal dolomite
3B - Devonian Martin fm - hornstone marker (Unit 7)
3C - Copper Chief fault
3D - Devonian Martin fm. - granular dolomite (Unit 6)
3E - Devonian Martin fm. - upper serpentine marker (Unit 5)
3F - Devonian Martin fm. - white tactite-diopside rich (Unit 4)
3G - Devonian Martin fm. - dolomitic marble (Unit 1)
3H - Cambrian Abrigo fm. - upper unit - lower serpentine marker
3I - Cambrian Abrigo fm. - upper unit - white tactite
3J - Cambrian Abrigo fm. - middle unit - garnetite - ore horizon
3K - Cambrian Abrigo fm. - middle unit - crenulated limestone

Stop 4A — Precambrian Apache Group - Dripping Spring quartzite, Barnes conglomerate, Diabase, Pioneer shale

4B — Leach Pads

Stop 5 — Johnson Pit - Middle Abrigo garnetite, Lower Abrigo hornfels, Bolsa quartzite - mineralization and alteration.

Geologic Legend

Me	Escabrosa fm.
Dmu	Martin fm. - upper unit
Dml	Martin fm. - lower unit
Cau	Abrigo fm. - upper unit
Cam	Abrigo fm. - middle unit
Cal	Abrigo fm. - lower unit
Cb	Bolsa
ad	Dripping Spring with Barnes conglomerate at base
db	Diabase
ap	Pioneer fm.