STYLE OF DEFORMATION OF UPPER PLATE ROCKS
OF THE SAN MANUEL-CAMP GRANT LOW-ANGLE
NORMAL FAULT SYSTEM,
BLACK HILLS, PINAL COUNTY, ARIZONA

By

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STATEMENT BY AUTHOR

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ABSTRACT

The fanglomerates, sandstones and volcanics of the lower Miocene San Manuel Formation and the upper Oligocene Cloudburst Formation in the Black Hills, Pinal County, Arizona have been extended and rotated to eastward dips along antithetically-dipping distributed normal fault systems. The actual fault zones within these systems contain phyllonites which commonly exhibit a penetrative cleavage. These fault systems were produced by westward translation above shallowly-dipping detachment faults known as the San Manuel and Camp Grant faults, and the Cloudburst detachment. These detachments are part of a larger system of low-angle normal faults west of the Galiuro Mountains. The similarity in slip line directions of these faults and extension directions in the mid-Tertiary metamorphic core complexes twenty miles to the southwest suggests that this fault system may represent the shallower manifestations of those core complexes.
CHAPTER 1

INTRODUCTION

Purpose and Scope

The purpose of this investigation is to describe the structural geometry, kinematics and amount of strain involved in the deformation of the mid-Tertiary fanglomerates and arkosic sandstones of the Black Hills region of southeastern Arizona. These rocks, which consist of the Oligocene Cloudburst Formation and the early-middle Miocene San Manuel Formation, dip eastward and overlie shallowly inclined, west-dipping detachment surfaces known as the San Manuel and Camp Grant faults. A second objective is to integrate my observations with those of previous workers to delineate the mid-Tertiary structural history of this area, and to suggest a model to account for this deformation.

To accomplish these objectives, I mapped the geology of three areas of the Black Hills: 1) the southwest flank of the Black Hills, 2) the lower part of Camp Grant Wash, and 3) several roadcut exposures along Highway 77.

The southwest flank was mapped on air photos at a scale of 1" : 1000'. This area was previously unmapped and reconnaissance revealed several enigmatic structures in the Cloudburst Formation. The lower part of Camp Grant Wash and the roadcut exposures were mapped by Brunton and tape at scales of 1":200' and 1":20', respectively. These areas were mapped because they contained excellent exposures of the San
Manuel Formation which revealed important details about the kinematics of rotation and deformation. Mapping was done from February to July, 1981.

In addition, a gravity survey was run in Putnam Wash, directly north of Camp Grant Wash, during October 1981. The purpose of this survey was to assess the geometry of the Camp Grant fault at depth.

Location and Accessibility

The Black Hills are located about ten miles north of the Santa Catalina Mountains, and about 25 miles north of Tucson, in southeastern Arizona (Fig. 1). The three study areas are located in the northern, southwestern and southern parts of the Black Hills (Fig. 2).

Accessibility by 4-wheel drive vehicle over the entire Black Hills is fairly good and the more remote areas are easily accessible by foot from the 4-wheel drive road network. Accessibility is generally unhampered by locked gates.

The study area in the southwest flank of the Black Hills is accessible via a paved section of old U.S. Highway 77, which intersects the present highway approximately four miles east of Oracle. Roughly three miles north of this intersection, a dirt road leads northwesterly to Tucson Wash and the Black Canyon Ranch. From here, Tucson Wash, the El Paso Natural Gas pipeline roads, and roads leading from them offer ready accessibility to most parts of the site.

The Camp Grant Wash area is most easily reached from a road in Putnam Wash. This road intersects Highway 77 eight miles north of
Fig. 1. Regional Location Map
Fig. 2. Location of Study Areas and Accessibility in the Black Hills, Pinal County, Arizona.
Mammoth. A fork divides Camp Grant and Putnam Washes 2 1/2 miles west of the intersection. Four wheel drive is necessary in these washes, and caution must be exercised during July and August because of flash flooding. The Camp Grant Wash area may also be approached from the south via the pipeline road which allows access to both the southwest flank of the Black Hills and to the Camp Grant Wash road.

The roadcut exposures are located in sec. 12, T.9S, R.16E. along Highway 77 between Oracle and Mammoth (Fig. 2). Pullouts for observing these roadcuts are located along them, but caution must be used when viewing them, because of the heavy traffic along Highway 77.

**Topography and Drainage**

The Black Hills trend roughly north-northwest and cover an area of about 40 square miles. They are bounded on the east by the San Pedro River, which flows north-northwest, and on the west and north by Camp Grant Wash and its tributaries. Camp Grant Wash flows northeast and is tributary to Putnam Wash, which drains east and joins the San Pedro about eight miles north of Mammoth. The southeast flank of the Black Hills is bounded by northeast-flowing tributaries to the San Pedro River, such as Cottonwood Wash. Both the northern and southern boundaries of the hills are transitional with Tortilla and Santa Catalina Mountains respectively.

Topographically, the area consists of rounded hills of moderate relief. The highest point, Signal Peak, 4363', occurs in the southeastern part. Net elevation change between Signal Peak and the San Pedro Valley is about 2000'.
Climate and Vegetation

Both the climate and vegetation of the Black Hills are typical of the Sonoran Desert region of southeast Arizona. Annual precipitation at San Manuel and Oracle averages 13.0" and 19.6" respectively. Precipitation is generally heaviest during the thundershower months of July and August. Mean monthly temperatures range from 47.3° to 83.3° at San Manuel and from 46.0° to 80.3° at Oracle (Sellers and Hill, 1974). The Black Hills are sparsely vegetated with palo verde, mesquite, catclaw, creosote bush, cholla, prickly pear, saguaro and various other small cacti. As a result of the sparseness of vegetation, the rock exposure is generally good, depending on the soil cover.

Previous Work

As far as can be ascertained, the first detailed published account of the geology of this area was by N.P. Peterson in 1937. Peterson studied the general geology and ore deposits of the Mammoth mining camp, and actually hypothesized that rotation along curved fault surfaces may have been responsible for the tilt of the volcanics in the area. Steele and Rubly (1947) also reviewed the geology and mineralization of the San Manuel area, and they hypothesized that the San Manuel fault was originally a high-angle normal fault, which had been subsequently rotated by regional tilting.

L.A. Heindl (1965) explicitly studied the Cenozoic deposits of the Mammoth area. Previous to Heindl's work, all middle-late Tertiary unlithified gravels in the area had been called Gila conglomerate. He elevated this term to group status and first named the San Manuel and Quiburis Formations. Heindl felt the Cloudburst Formation was middle-
early Tertiary in age, and provided sedimentological arguments that the San Manuel fault was a thrust.

S.C. Creasey (1965, 1967) mapped the geology of the Mammoth Quadrangle, on the southeast flank of the Black Hills and further studied the ore deposits of the region. Creasey felt that the Cloudburst Formation was Late Cretaceous-early Tertiary in age and provided structural evidence that the San Manuel fault was a right lateral fault with more than 10,000 feet of offset. Creasey also reestablished the name "Gila Conglomerate", because he felt that Heindl's subdivision of the Gila had not produced a unit that met the requirements for a formation according to the code of stratigraphic nomenclature.

In 1968, J.D. Lowell published the results of a study demonstrating that the San Manuel ore body had been offset by low-angle normal slip along the San Manuel fault. Lowell proved this by comparison of the alteration zones around the San Manuel ore body with those of the offset portion, named the Kalamazoo ore body.

Medora H. Krieger did extensive geologic mapping in the northern part of the Black Hills and in the Putnam Wash Quadrangle. Krieger (1974a) attributed the steep dips of the Cenozoic fanglomerates in this area to low angle gravity sliding. Krieger, Cornwall and Banks (1976) reinstated the name "San Manuel Formation" and further subdivided the middle-late Tertiary conglomerates into the middle Miocene Big Dome and middle Pliocene Quiburis Formations.

A middle Tertiary date on the base of the Cloudburst Formation was established by Shafiqullah and others (1978). This substantiated
Heindl's view and was contrary to that expressed by Creasey (1965, 1967) and Krieger (1974c).

Weibel (1981) studied the sedimentology of the Cloudburst Formation in the area to the west and southwest of the San Manuel mine and established dates on the top of the Cloudburst and base of the San Manuel Formations. On the basis of these dates and sedimentological observations, he argued that no significant hiatus exists between these two formations, contrary to what both Heindl (1963) and Creasey (1965, 1967) had believed.
CHAPTER 2

GENERAL GEOLOGY OF THE BLACK HILLS

The Black Hills region of Pinal County, Arizona is a granitic cored horst bounded on the east and west by the grabens of the San Pedro River Valley and Camp Grant Wash, respectively. The granitic core consists of 1.4 b.y. (Giletti and Damon 1961) granodiorite, quartz monzonite, granite and alaskite, variously known as Oracle Quartz Monzonite (Creasey 1967) or Ruin Granite (Krieger 1974c). In the northeast corner of the hills, these rocks intrude Precambrian Pinal Schist and they are unconformably overlain by upper Precambrian Apache Group rocks and Troy Quartzite. All of these rocks are extensively intruded by diabase sills and dikes (1.2 b.y. Damon, Livingston and Erickson, 1962) and the granitic rocks in the central part of the hills are intruded by pegmatite and aplite dikes. The upper Precambrian rocks are disconformably overlain by Paleozoic formations, such as the Abrigo Formation, Martin Formation, and Escabrosa Limestone, which are disconformably overlain by Mesozoic(?) sediments. According to Krieger (1968b) these Mesozoic(?) rocks are in thrust fault contact with Paleozoic rocks in some places. In the southern Black Hills, a granodiorite porphyry was intruded into quartz monzonite during the Laramide. Copper mineralization associated with this intrusion is responsible for the San Manuel and Kalamazoo ore bodies.
The oldest Cenozoic formation in the Black Hills is the Oligocene Cloudburst Formation. It consists dominantly of fanglomerates, arkosic sandstones and volcanics, and is present on the southeast and southwest flanks of the Black Hills. The Cloudburst Formation is overlain conformably by the lower Miocene San Manuel Formation (Weibel 1981), a rock assemblage similar to, but less well lithified than the Cloudburst. North of the Putnam Wash, the San Manuel Formation is unconformably overlain by the fanglomerates and sandstones of the late Miocene Big Dome Formation. All three mid-Tertiary formations are unconformably overlain by the middle Pliocene Quiburis Formation, which is essentially a basin fill deposit of the San Pedro River Valley graben. Quaternary deposits (alluvium, colluvium and terrace deposits) are generally associated with the San Pedro River or Camp Grant-Putnam Wash drainage system.

The Black Hills horst is bounded on the west by the west-dipping Cowhead Well fault and on the east by the east-dipping Mammoth fault. Both faults are high-angle faults. Numerous other high-angle faults undoubtedly are buried beneath the basin fill sediments of Camp Grant Wash and the San Pedro River Valley.

Perhaps the most intriguing structural features of the Black Hills are the low-angle faults that underlie the late Oligocene-mid Miocene red beds and volcanics in the area. On the southwest flank of the Black Hills, the San Manuel fault dips 30° southwest and has been variously interpreted as a thrust (Heindl 1963), a right lateral fault (Creasey 1965, 1967), and a normal fault (Steele and Rubly 1947; Lowell
1968). To the northeast of the San Manuel fault, an east-dipping low angle detachment surface separating Oligocene Cloudburst Formation from Precambrian granitic rocks has been mapped and interpreted by Creasey (1965, 1967) as a thrust. For convenience, this fault will be referred to as the Cloudburst detachment. In the northwest part of the Black Hills, the Camp Grant fault, located on the northwest and west flank of the range, dips 15°-20° west and has been interpreted by Krieger (1947a,c) as a gravity slide fault. These low-angle faults and the deformation of the mid-Tertiary rocks above them are the subject of this report.
CHAPTER 3

GEOLOGY OF THE SOUTHWEST FLANK OF THE BLACK HILLS STUDY AREA

Stratigraphy

The rocks of the southwest flank of the Black Hills consist of Precambrian granitic rocks and middle-late Tertiary units. These units consist of the lower part of the lower Oligocene Cloudburst Formation, the lower-middle Miocene San Manuel Formation and Quaternary-Tertiary gravels.

Precambrian Granitic Rocks

The Precambrian granitic rocks consist of quartz monzonite, granodiorite and granite. The granodiorite is formed in most of the upland area of the northeast part of the map (Fig. 3). It is fine-medium grained, hypidiomorphic granular with a color index of about 20. The granodiorite is composed of quartz, plagioclase (oligoclase, andesine) biotite and hornblende. It weathers to a slight orange cast.

The quartz monzonite is found in the core of a small anticline along the pipeline road in secs. 31 and 36, T.8S., R.1E., and in the extreme northeastern part of the map area. It is a medium-coarse grained porphyritic rock with a color index of 15-20. Constituent minerals include quartz, plagioclase, hornblende and biotite and large conspicuous phenocrysts of orthoclase and microcline. Nearly all exposures are intensely grussified and unweathered hand specimens are difficult to obtain.
Granite is found in the northwestern part of the map area. It is reddish, coarse grained, hypidiomorphic granular, and has a color index of about 5. The constituent grains include quartz, potassium feldspar, plagioclase and biotite.

The granitic upland area has been extensively intruded by aplite, pegmatite and diabase dikes, which trend northwest and dip east. In general, the aplites and pegmatites crosscut the diabase dikes. Several diabase dikes also trend northeast and dip steeply. Numerous northwest trending silicified veins also transect the area and several limonitic and manganese dioxide stained zones were also noted during mapping. Finally, some andesitic(?) dikes have intruded along the margins of pre-existing dikes and into the San Manuel fault zone. These andesites(?) are olive drab green with occasional phenocrysts of quartz. Where they intrude the fault zone, they are heavily chloritized and calcified.

The quartz monzonite in this area was determined to be 1.4 b.y. by Damon (1959) by the rubidium strontium technique on biotite from the Oracle Quartz Monzonite from the Camp Bonito Mine near Oracle. Krieger (1974c) correlated the granite in the Putnam Wash area to Ruin Granite and also assigned a 1.4 b.y. age to it. The granodiorite in the area has not been radiometrically dated, but Krieger (1974c) observed xenoliths of the granodiorite in the Ruin granite in the extreme southeastern part of the Putnam Wash Quadrangle.

Oligocene Cloudburst Formation

The lower part of the Cloudburst Formation consists of fanglomerates and intercalated volcanics, including andesite, latite(?), minor
basalt and an ignimbrite. A lenticular sedimentary breccia, similar to those observed by Creasey (1967) and Krieger (1977) was also mapped. A lithologic section was measured through the lower Cloudburst and is shown in Figure 4.

The base of the Cloudburst is exposed in the core of a small anticline in sec. 31, T.8S., R.16E., and sec. 36, T.8S., R.15E., along the pipeline road (Fig. 3). Creasey (1965, 1967) and Creasey, Jackson and Gulbrandsen (1961) considered the Cloudburst/Oracle contact here to be a thrust. Shafiqullah and others (1978) followed suggestions of W. Rehrig and S.B. Keith (Weibel 1981) and expressed the opinion that this was a depositional contact. My field observations support the latter view, for the following reasons:

1. No distinct dislocation surface was observed in this area, nor was any severe brecciation or chloritization noted near the contact. Admittedly, the contact is somewhat poorly exposed in this area, but where it can be observed, such as on the southwest flank of the small anticline, it appears to be gradational from granite into grus into a thin pebbly fanglomerate.

2. Detailed mapping indicates that a thin bluish volcanic unit (probably a lahar) can be traced nearly continuously around the exposure. If the quartz monzonite exposure is a window below a thrust where there is a large angular discordance between the thrust plane and the overlying sediments, as Creasey (1967) suggests, it is unlikely that this unit could be traced continuously around the exposure, or that the
Granodiorite

Top of section is the San Manuel fault; an andesite sill has intruded along the fault, and has become subsequently chloritized.

Fanglomerate, maroon, dominantly volcanic clasts with some sandstone and granite clasts.

Welded tuff, phenocrysts of biotite feldspar, sanidine, occasional quartz, light purple groundmass; lower half nonwelded, upper 5-10' welded eutaxitic, upper 5' nonwelded;

Flow breccia; poorly sorted, dominantly andesite fragments.

Volcanic fanglomerate, large cobble sized angular clasts.

Covered, alluvium.

Fanglomerate, grey-maroon, poorly bedded, matrix supported, clasts to cobble size consisting dominantly of volcanics (latite(?), vesicular andesite, andesite) and some granite.

Fanglomerate, very sandy, light reddish grey-brown, evenly bedded with large cobble sized clasts of granite (50%) and dark grey scoriaceous andesite (50%).

Monolithologic megabrecia: angular fragments of quartz monzonite ranging from pebble sized to very large boulder sized in a crushed granitic matrix; top grades into fanglomerate with volcanic fragments, base is covered.

Fanglomerate, grey-maroon, poorly bedded, matrix supported, clasts to cobble size consisting dominantly of volcanics (latite(?), vesicular andesite, andesite) and some granite.

Latite(?) or andesite, purplish-brown, maroon, olive-green, conspicuous glomeroporphyritic calcic laths which probably represent plagioclase laths altered to calcite. No flow banding, occasional amygdales at base.

Interbedded andesite and andesite flow breccia, dark grey to black and medium-dark brown, very vesicular and coarsely (>1''), amygdaloidal; amygdales consist of zeolites (analcline?), chalcedony, calcite. Unit is a resistant hogback-former consisting of numerous lenticular flows. The flow breccias may represent the tops of flows; thickness of this unit was estimated from the geologic map and cross-sections.

Interbedded andesite porphyry and andesite flow breccia; porphyry: medium gray, gray-brown, red-brown, light purple, green-brown, often trachycent texture, amygdaloidal in parts, phenocrysts of pyroxene(?) Flow breccias: similar color to porphyries, very fine sand to large cobble sized clasts, weather reddish-purple.

Olivine basalt, black, weathered pink, dense; phenocrysts of olivine, biotite; poorly-exposed.

Andesite flow breccia, red-brown, weathers light purple-gray; olivine, pyroxene phenocrysts.

Interbedded arkosic sandstone, very coarse grained, poorly sorted, coarse pebble conglomerate and sandy planar mudstone layers, red-brown, thick- thinly bedded.

Andesite flow breccia, mottled brick red and dark brown-grey, all volcanic clasts to boulder size; phenocrysts as below.

Andesite, grey, weathers to yellow green and grey grey, phenocrysts of pyroxene(?) weathering to hematite and rare plagioclase phenocrysts.

Fanglomerate, dark red-brown, indurated, vague parallel laminar and slightly lenticular bedding, very sandy, matrix supported;

Fanglomerate, maroon and purple-brown, massive or indistinct bedded with occasional vague parallel sandy laminae, generally at the tops of thinning upward lenticular sequences 3-10' thick; matrix supported; clasts to boulder size, consisting of granite, maroon and olive green volcanics, quartzite and quartzite breccia.

Lahar - 100% bluish volcanic clasts in a volcanic matrix.

Quartz monzonite, groundmass, grades to fanglomerate, above.

FIGURE 4. MEASURED SECTION. LOWER CLOUDBURST FORMATION
(See Figure 3 for location of section.)
Cloudburst would dip steeply west on the west side of the exposure, as it does.

Outside the study area, the Cloudburst Formation was reported to be depositional on Precambrian quartz monzonite in at least two other locations. Peterson (1937) reported that volcanic flows overlie a granite arkose deposited on quartz monzonite at the 300 foot level of the abandoned Mohawk mine, one mile northeast of the San Manuel mine. In addition, Heindl (1963), Creasey (1965, 1967), and Weibel (1981) show a depositional contact two miles southwest of the San Manuel mine.

The fanglomerates of the lower part of the Cloudburst Formation are granitic-volcanic matrix supported pebble conglomerates, generally dusky red, weathering to greyish red and maroon. The bedding is massive in general, but lenticular bedding, cut-and-fill structures and fining upward sequences are sometimes visible. Reddish brown, thin to thick-beded arkosic sandstones and mudstones within the grade into the fanglomerates. Generally, the clasts of the fanglomerates are made up of 50 percent granitic fragments, 45 percent volcanic fragments, and 5 percent reworked sedimentary rock fragments, but the composition varies from unit to unit. Figure 5 summarizes the results of three clast counts within the fanglomerate. The clasts range from very fine sand to large boulder size, and average about 1.5" in diameter. They are angular to rounded and the fanglomerates are all poorly sorted. The matrix of the fanglomerates consists of clay, silt and sand, and the rock is cemented by clay, which is sometimes slightly calcareous. Exposure of the fanglomerates varies from excellent in the stream
SEDIMENTS

PLUTONICS AND

METAMORPHIC ROCK FRAGMENTS

VOLCANICS

© San Manuel, Camp Grant Wash
+ San Manuel, SW Flank of the Black Hills
* Cloudburst, SW Flank of the Black Hills
• Cloudburst, (Weibel, 1981)
★ Quaternary-Tertiary Gravels, SW Flank of the Black Hills

Fig. 5. Clast Counts of Tertiary Conglomerates, Black Hills.
bottoms to poor on some hillsides. The fanglomerates generally form slopes. Total thickness for all fanglomerates along the measured section is 1100 feet.

The andesites of the lower Cloudburst Formation consist of flows and flow breccias. The color of the andesites is extremely variable: purplish grey, light reddish grey, greyish green, pink, black, tan and dark brown. For mapping purposes, the andesites were divided into two units: a lower, lighter phase, and an upper darker, vesicular phase. Morphologically, the darker phase forms the large broad hogback of the central part of the map area. The contact between the two units is best distinguished on air photos. In the field, the contact was observed to be gradational and in thin section, there is little difference, except for the vesicularity of the darker phase.

In general, the andesites are fairly altered, to the point that the original mineralogy often cannot be ascertained. A thin section from a sample of the dark phase near the pipeline road/Tucson Wash intersection showed phenocrysts of fine to medium-grained highly altered ferromagnesium minerals (pyroxenes?) and disseminated magnetite in a fine grained felty ground mass of plagioclase laths of andesine-labradorite (An$_{50}$Ab$_{50}$) composition. The ferromagnesian minerals have altered to hematite, biotite, sericite, clay and probably, to clinozoisite. The plagioclase laths commonly show an alteration to calcite in the centers of large crystals.

Vesicularity is most pronounced in the upper darker andesite. The vesicles are up to an inch in size and are amygdaloidal in part. The
Amygdules consist of chalcedony, quartz, chlorite, calcite and some zeolites.

The map pattern of the lower lighter phase clearly reveals the lenticular nature of these flows and flow breccias. Maximum thickness of the lighter phase is estimated at 670 feet, and was measured at 260 feet. The thickness of the darker phase (900 feet) was estimated from the geologic map pattern using a dip of 45°. Total thickness of the andesites in the lower Cloudburst therefore is about 1200 feet.

Within the light phase andesite, an olivine basalt, 18 feet in thickness was observed. The basalt is black and very hard and dense, but weathers easily to a layer of pink boulders and cobbles. The upper and lower contacts were not observed, but it was traced along the same horizon for over a mile and is probably a basalt flow.

In thin section, basalt shows phenocrysts of biotite, forsterite, and magnetite in a fine grained felty ground mass of plagioclase of andesine composition. The biotite was observed to be both euhedral and as a replacement of olivine. In turn, it is altering to hematite. The forsterite is altering to clinozoisite.

Flows and flow breccias of porphyritic greenish grey or purplish grey volcanic rock speckled with white phenocrysts overlay the dark phase andesite with a fairly sharp depositional contact. These volcanics were distinguished from the underlying vesicular andesites primarily on the basis of overall color and by phenocryst type and texture. Some amygdules and vesicles were noted at the base of this unit, also.
Creasey (1967) called these rocks latites or trachy andesites, primarily on the basis of their norm chemistry, although the rocks have probably sustained some calcic alteration since their deposition. The term latite(?) is used here, although Creasey (1967, p. 15) states that in their original unaltered state, the rocks may have been andesites.

In thin section, these rocks consist of medium-grained glomeroporphyritic feldspar(?) laths in a felty ground mass of plagioclase. Both the phenocrysts and groundmass have been highly altered to calcite. Other minerals observed in thin section included magnetite (altered to hematite) biotite and rutile.

The latite(?) is a lenticular, fairly non-resistant unit. The upper contact of these rocks with the fanglomerate above it is a fairly sharp. A fair amount of relief must have existed at the time of fanglomerate deposition, as shown by the anomalous depositional contact in the SW 1/4, SW 1/4, sec. 19, T.8S., R.16E., (Fig. 3). The thickness of the unit, along the line of the measured section, was 306 feet.

The rocks above the latite(?) consist predominantly of fanglomerates. These are similar to the fanglomerates described above, but in general, they contain a higher proportion of volcanic clasts. Within these fanglomerates, a monolithologic breccia and a welded tuff are interbedded.

The monolithologic breccia consists of angular fragments of quartz monzonite in a comminuted matrix of the same kind of material
The clasts within the breccia range from sand to very large boulder size, and in some outcrops, the brecciated nature of the rock is indiscernible. This may indicate that some very large blocks are present also. The angular fragments show no sedimentary structures, but the breccia appears to grade upward into a well-bedded, sandy clast-supported fanglomerate at the top. The fanglomerates consist of about half volcanic clasts and half granitic clasts. The lower contact of the breccia is poorly exposed. The deposit is clearly lenticular as shown on the geologic map. The thickness of 145' was measured along the line of section for this sedimentary breccia.

The welded tuff is approximately 30 feet in thickness and is located in the SW 1/4, sec. 19, T.8S., R.16E. It is a lapilli tuff with accessory lithic volcanic clasts that range upward to small pebble size. The groundmass is light purplish grey and the lapilli are cream colored. The lower 15 feet of the tuff is non-eutaxitic and heavily fractured. For about 10 feet above this, the tuff is welded and exhibits a pronounced eutaxitic texture. The upper five feet is pink, fissile and non-eutaxitic. In general the tuff is a slope former.

Numerous minerals can be observed in thin section in the tuff. These include plagioclase (albite), chert, magnetite, sanidine, quartz, biotite, orthoclase, microcline and muscovite. Because plagioclase appears to be much more abundant than potassium feldspar, and because quartz and chert are fairly abundant, the tuff would be classified as a dacite. Volcanic rock fragments, exemplified by plagioclase laths in an opaque matrix, are common also.
Fig. 6. Granitic Monolithologic Breccia in the Cloudburst Formation.
In the central part of sec. 31, T.8S., R.16E., Creasey (1965) mapped a rhyodacite intrusive body, which has been displaced by a fault. This fault was extended into my map area, where it has offset a group of dacite flows and pyroclastic beds. Probably, the dacite I have mapped and the rhyodacite intrusive mapped by Creasey are the same. The dacite has a light purplish grey phenocrysts of plagioclase, quartz, magnetite, biotite and some orthoclase. It is approximately 100 feet thick, and the upper 20 feet consists of bedded conglomerate, coarse grained sandstone, and tuffaceous material. The upper contact appears to have been baked and the lower contact is not well exposed. The amount of plagioclase observed in thin section was substantially more than potassium feldspar, and hence the rock was called dacite. The tuffaceous sedimentary beds in the top part of the unit suggests that this unit is a flow or series of flows, rather than a sill.

The age of the lower Cloudburst has been bracketed by Shafiqullah and others (1978) and by Weibel (1981). Shafiqullah and others (1978) reported a date on the olivine basalt within the light phase andesites of 28.30±.63 m.y. (whole rock analysis). Previous to this, the Cloudburst had been considered late Cretaceous-early Tertiary by Creasey (1965, 1967) and as mid-Tertiary (Pantano equivalent) by Heindl (1963). Weibel (1981) established a date on a rhyolite tuff pebble from near the top of the Cloudburst Formation in sec. 29, T.8S., R.16E., in the Mammoth quadrangle to the east as 22.5 ± 0.5 m.y. (K-Ar, sanidine). By simple interpolation between the dated localities, the age range of the lower Cloudburst in the map area is approximately 29 - 27 m.y.
The radiometric age data for the Cloudburst Formation suggest that it was deposited roughly contemporaneous with the Galiuro Volcanics, east of the San Pedro River, which have been dated at 29 - 23 m.y. (Creasey and Krieger 1978). As far as can be ascertained, no measured section of the Galiuro Volcanics has been published. Any lithologic correlation between the Galiuro Volcanics and the Cloudburst will be contingent upon this.

Miocene San Manuel Formation

The San Manuel Formation is exposed in two parts of the map area: in a gulch in the extreme northern part of the area and in the rolling uplands of the southwestern part of the area. From lithologic descriptions given by Heindl (1963), the southwestern exposures are probably equivalent to the Kanally Wash member of the San Manuel Formation. Creasey (1965, 1967) called this formation the "lower member of the Gila Conglomerate", but Krieger and others (1973) reestablished the name "San Manuel Formation" for these rocks.

Exposure of the San Manuel is poor in the map area, primarily because it is poorly lithified and because younger overlying unconsolidated gravels obscure it. As a result, a measured section through the San Manuel Formation could not be obtained.

The San Manuel Formation is a poorly-sorted cobble conglomerate that weathers light grey brown and reddish brown. Bedding varies from massive to parallel, in thin to thick beds. It is dominantly clast-supported, and clast size ranges from silt to very large boulder sized (to 10 feet in diameter). The largest clasts consist of quartz
monzonite, but clasts of granite, diabase, volcanics, quartzite, limestone were also observed. The clast constituency is summarized in Figure 5.

A number of paleocurrent measurements, based on the orientation of imbricate clasts within the San Manuel Formation, were taken in sec. 1, T.7S., R.15E., and sec. 36, T.7S., R.16E. The rose diagram that displays these measurements (Fig. 7) shows wide scatter, but an easterly trend (vector mean, N69E) is indicated. This seems reasonable. The abundant large quartz monzonite boulders in the Kanally Wash member imply that it was deposited proximal to a quartz monzonitic source area, such as the upland area near Oracle to the southwest. The San Manuel Formation in this area probably represents a proximal alluvial fan facies, which dipped off a highland located to the west.

Weibel (1981) dated a basalt flow at the base of the San Manuel Formation in the Putnam Wash area to the north at 22.1 ± 0.5 m.y. This probably approximates the age of the San Manuel in the map area, and establishes it as lower Miocene.

Quaternary-Tertiary Gravels

Gravel deposits blanket the western part of the map area. In general, these gravels are poorly exposed except in some of the deeper washes. They plainly unconformably overlie the San Manuel Formation in the northwestern part of the map area.

The gravels are poorly sorted, dominantly clast supported pebble and cobble conglomerates. For the most part, they are unconsolidated and their clast constituency often reflects that of older rocks adjacent
Fig. 7. Rose Diagram of Paleocurrents in the San Manuel Formation, Southwest Flank of the Black Hills; 28 measurements, vector mean - N69E.
to them. Because they dip gently basinward, are often found adjacent to the Cowhead Well fault (a range-bounding normal fault), and show imbrications indicating westward-flowing paleocurrents, the gravels are considered basin fill deposits analogous to the Pliocene Quiburis Formation of the San Pedro River Valley. In the Putnam Wash quadrangle to the north, however, Krieger (1974c) considered these deposits to be Quaternary. As a distinct age could not be resolved during fieldwork, a Quaternary-Tertiary age was assigned to them.

**Structural Geology**

Generally, the southwest flank of the Black Hills is a granitic upland area overlain by a west-dipping low-angle normal fault (the San Manuel fault). Above this fault, late Oligocene sediments and volcanic of the Cloudburst Formation dip homoclinally eastward. To the west of this, both Cloudburst strata and granitic rocks are separated from the San Manuel Formation and Quaternary-Tertiary gravels by the Cowhead Well fault, a north-trending high-angle normal fault. Both the Cloudburst and San Manuel Formations and the San Manuel fault have been folded by drag along this fault. Numerous right-separation faults can be recognized in the Cloudburst Formation, and three small allochthonous blocks have also been mapped.

San Manuel Fault Zone

**Geometry and Map Relations.** As mapped by Creasey (1967), the San Manuel fault zone (SMFZ) strikes roughly northwest and dips 35-40° west. In the area to the west of Creasey's map however, the strike
of the fault changes to southwest and it dips shallowly to the southeast (Fig. 3). Hence the surface of the fault is a broad synform. To the northwest of the hinge zone of this synform, a small remnant of Cloudburst Formation is present. This remnant is underlain by the SMFZ, which dips shallowly west here. Thus, the fault surface between this dip and the southeast dip mentioned above must be broadly antiformal.

Physiological Description of the Fault Zone. Where the San Manuel fault is best exposed, it is a zone up to 50 feet thick. Within this zone, the rock is often heavily chloritized, brecciated and foliated (Fig. 8). Rocks within the fault zone are also commonly bleached and travertine has been deposited along the fault from place to place. A tectonite fabric is locally developed in the SMFZ, generally within diabase. Chloritization and foliation progressively become more conspicuous in the granodiorite footwall as the fault zone is approached.

Figure 9 is a contour diagram of poles to foliations in this tectonite. It presents measurements collected along the southwest trending segment of the San Manuel fault. Two maxima are apparent, representing surfaces whose orientations are \( N37E \ 30^\circ SE \) and \( N4E \ 42^\circ E \). The orientation of the fault along this segment is probably about \( N37E \ 30^\circ SE \). Very few striations or other lineations were observed elsewhere along the fault.

Some intrafolial folds were recognized within the tectonite (Fig. 10). A plot of poles to axial planes shows some scattering orientations, but in general the axial planes have an easterly component of dip, similar to and sometimes steeper than the foliations of the tectonite (Fig. 11). The
Fig. 8. Foliated and Chloritized Rock of the San Manuel Fault zone.
Fig. 9. Lower Hemisphere Equal-Area Contour Diagram of Poles to Foliations in the Southwest Trending Segment of the San Manuel Fault.
Fig. 10. Intrafolial Folds in the Tectonite of San Manuel Fault Zone. The fault zone dips about 30° to the right.
Fig. 11. Lower Hemisphere Equal-Area Projection of Poles to Axial Planes in the Tectonite of the San Manuel Fault Zone. The planes were measured along the southwest trending segment of the fault zone.
axes of intrafolial folds show wide scatter. Unfortunately, the number of folds present is too small to attempt to analyze their kinematics by the Hansen separation arc method.

In thin section, the tectonite was observed to be an olive-green cataclasite with angular–very angular porphyroclasts up to 1.5 inches in diameter. They consist both of monocrystalline and polycrystalline fragments of plagioclase, orthoclase, sanidine and quartz. The long axes of the clasts are often oriented subparallel to each other and the clasts often show distorted albite and pericline twinning. This may be indicative of ductile deformation during development of the tectonite. The matrix consists of subparallel chlorite plates that forms a schistosity pervading the tectonite where it is developed to the utmost. Leucoxene trains follow throughout the chlorite and calcite is present as an alteration product. The matrix shows radically bent chlorite plates, micro-boudins and ductile normal faults (Fig. 12).

Physical Description of the Footwall and Hanging Wall Adjacent to the Fault. The granodiorite of the footwall has been brecciated. This breccia is most pronounced in silicic veins and aptite dikes in the granodiorite adjacent to the northwest trending segment of the fault. The breccia zones are very angular, cobble-sized clasts of silicic material in a comminuted matrix of the same composition. The zones are parallel to the trend of the fault and appear to have been re-silicified.

In the northernmost exposure of the fault, the basal part of the Cloudburst Formation is a granite breccia. This breccia
Fig. 12. Photomicrograph of the Fabric of the Tectonite
Note the ductile normal fault in center of photo.
consists of angular to very angular unsupported clasts of granite whose size ranges upward to a few inches. The matrix consists dominantly of clay and fine-grained clasts probably derived from the comminution of the granite below and volcanics above the breccia. A foliation is not developed in the breccia nor are the clasts oriented.

Strata of the Cloudburst Formation in the hanging wall of the fault have been extensively sheared by repeated movements along the fault. Several of these shear zones are pictured in Figure 13. Although the shear zones display an apparent dip of 20–25°S, the true dip is 35–45°S, similar to the foliations in the tectonite. The curved traces of the faults may be an expression of fault grooves or mullions. As is evident from Figure 13, the shear zones successively and complexly cut each other.

**Kinematics and Slip of the San Manuel Fault.** The San Manuel Fault has been variously interpreted as a thrust (Wilson 1957), Heindl 1963), a right lateral fault (Creasey 1965, 1967), and a normal fault (Steele and Rubly 1947, Schwartz 1957, Lowell 1968). Lowell's conclusion was based upon the interpretation that large mullions in the fault surface about four miles east of the study area were indicative of normal movement. His interpretation resulted in the discovery of the Kalamazoo orebody, which is the upper plate equivalent of the truncated San Manuel copper porphyry. In addition, Lowell demonstrated the similarities in alteration zones around each orebody and thus conclusively proved the low-angle normal fault nature of the fault. According to Lowell, the net slip on the San Manuel fault is about 8000', 27°, S55W.
Fig. 13. Shear Zones in the Cloudburst Formation Adjacent to the San Manuel Fault.
The average strike of the shear zones is nearly parallel to the wash, giving the illusion of very low dip.
The sense of movement implied from the vergence of intrafolial folds observed in the tectonite of the SMFZ at first appears to contradict Lowell's conclusion (Fig. 10). As stated previously, the SMFZ has been folded into a broad antiform, and the intrafolial folds are exposed on the southeast flank of this antiform. If this antiform was developed subsequent to the tectonite (possibly as a result of later faulting), the intrafolial folds may have been rotated to their present orientation by flexural development of the antiform. Thus, although a sense of thrust movement is implied by the folds shown in Figure 10, the actual sense of movement may be normal.

The age of the San Manuel fault is somewhat enigmatic. Weibel (1981) established a date of 22.7 m.y. on a rhyolite tuff at the top of the Cloudburst Formation in sec. 29, T.8S., R.16E., which is probably cut off by the fault. Hence the age of faulting is early Miocene or younger.

The San Manuel fault zone has been extensively intruded by andesites. Unfortunately, these andesites are too heavily chloritized to provide a reliable radiometric date. An andesite intrusion into the fault zone is shown in Figure 14.

Cowhead Well Fault

The other major fault in the southwest flank of the Black Hills is the Cowhead Well fault. Krieger (1947c) mapped and named this fault in the Putnam Wash quadrangle to the north. It trends northwest/southeast through the study area. Lowell (1968) mapped part of it as the Red Rock fault.
Fig. 14. Andesite Intrusion Into the San Manuel Fault Zone. Hammer lies on the intrusion.
The Cowhead Well fault is a north to northwest-striking, high-angle (40°-80°) west-dipping normal fault. The slip is dominantly dip slip with a small component of left slip (Fig. 15), although some striations that were observed disclose some right-handed normal-slip movement. The fault surface is excellently exposed in the north central portion of sec. 24, T.8S., R.15E. (Fig. 16).

The net slip on the fault is unknown, but in the NW¼, sec. 36, T.8S., R.15E., the San Manuel Formation appears to have been offset by a minimum of 5000' (see cross section B-B', Fig. 17). This offset is considered minimum because it was measured from a projection of the top of the uppermost Cloudburst beds shown on the cross-section above the San Manuel fault to the top of the San Manuel Formation exposed on the other side of the Cowhead Well fault. Farther to the southeast, in the Mammoth quadrangle, where Creasey (1965) has mapped the base of the San Manuel Formation in two places on either side of the fault, the offset may be as much as 6300', assuming a dip of 20° for this unconformable contact (Fig. 17, cross-section C-C').

Because the Cowhead Well fault offsets basin fill deposits considered correlative with the middle(?) Pliocene Quiburis Formation, its age is considered Late Tertiary. Furthermore, because the Cowhead Well fault cuts off the San Manuel fault, the age of San Manuel faulting can be more explicitly bracketed to post early Miocene to pre-Late Pliocene.
Fig. 15. Lower Hemisphere Equal-Area Projection of Striations and Poles to the Fault Plane Measured on the Cowhead Well Fault.
Fig. 16. Striations on the Cowhead Well Fault that Disclose Left Handed Normal Slip Displacement. Fault dips toward observer. This exposure of the fault is located in SW\&\textdegree, NW\&\textdegree, NE\&\textdegree, sec. 24, T.8S., R.15E., and is accessible via the road to Hidden Well from the El Paso Natural Gas Pipeline road.
Faults in Lower Plate Rocks

A breccia zone was traced from the northwest trending segment of SMFZ further to the northwest to the Cowhead Well fault. It was mapped on the basis of brecciation observed in the granodiorite and on the basis of several bent and displaced diabase dikes (Fig. 3). The sense of separation is right lateral, as deduced from the drag of one dike near the Cowhead Well fault and from the offset of another located north of the change in strike of the San Manuel fault.

Another fault was mapped in the northeast corner of the map area (in sec. 12, T.8S., R.15E. and secs. 7 and 18, T.8S., R.16E.). This fault displays left lateral separation, but it is dominantly a dip slip fault. The net slip of this fault, as deduced orthographically from the offset of a nearly vertical diabase dike and striations observed on the fault plane is 1100', along a 44°, S72W plunge, with left-handed reverse slip movement. No minor structures indicative of compression were observed around the dike however, and the fault plane seems more typical of the type associated with normal faulting in this area. It may be that the striations resulted from late Tertiary re-activation of this fault.

Faults in Upper Plate Rocks

Numerous right and left handed normal-slip faults dissect the Cloudburst Formation (Fig. 3). Generally, these faults display a right lateral separation. The poles to these faults and their associated striations were contoured and are shown in Figures 18 and 19. As shown by these diagrams, most of the faults dip southwesterly. Striations
Fig. 18. Lower-Hemisphere Equal-Area Contour Diagram of Poles to All Faults Measured in the Cloudburst Formation in the Southwest Flank of the Black Hills
Fig. 19. Lower Hemisphere Equal-Area Contour Diagram of all Striation Measurements in the Southwest Flank of the Black Hills Study Area.
plunge dominantly to the west. Curiously, many of the faults have arcuate traces, such as 1) the fault in east central part of sec. 24, T.8S., R.15E., 2) the fault in NE corner, sec. 25 and SE corner, sec. 24, T.8S., R.15E, and 3) the small fault 1300' north of NW corner, sec. 15, T.8S., R.15E. In addition, some of these faults were observed to be arcuate in cross-sectional view. The similarity between the maxima of the orientations of these faults and striations (Figs. 18 and 19) with the orientations and striations of the Cowhead Well fault tenuously suggests that many of these faults were formed in the same deformational episode as the Cowhead Well fault.

The Cloudburst Formation has also been deformed by low-angle normal faulting, above the San Manuel fault. Three small allochthons with normal offset were discovered during mapping in sec. 25, T.8S., R.15E. In the central part of this section, the light phase andesites are underlain by a low-angle dislocation surface that is folded. This folding probably resulted from movement on the Cowhead Well fault. The fault is a sharp, planar, manganese dioxide stained discontinuity between brecciated brown and olive-green andesite above and maroon Cloudburst sediments below. The discontinuity generally dips less than 40°. A stereographic projection of poles to the fault plane and striations on the fault plane is shown in Figure 20. Assuming that this surface has been folded cylindrically, this diagram indicates that the "best fit" fold axis to this warped surface is 7°, N.20W, which is very similar to the axis of the dome in sec. 36. Although the striation data are meager, they suggest that the striations lie on a small circle which has a similar axis. If this is the case, the low-angle discontinuity has been
Fig. 20. Pi Diagram of Striations and Poles to the Surface of the Low Angle Normal Fault in Sec. 25, T.8S., R.15E.
deformed by flexural folding subsequent to its emplacement.

In the eastern part of this section, a small piece of the dark phase andesite has been faulted against the lighter phase. This discontinuity strikes about N30W and dips 30° west. It is marked along its entire outcrop length by a 6" calcite vein. Also, some of the dark phase andesite was observed near the Cowhead Well fault in the center of sec. 25. It is underlain by a low-angle, east-dipping fault, but for the most part, the contact is poorly exposed.

These allochthons may have resulted from either a block-glide landsliding event or from a true low-angle normal faulting event associated with mid-Tertiary extension. The andesite strata of the allochthons are poorly exposed, and hence, it is difficult to assess the amount of shattering in the upper block. A small, poorly exposed outcrop of east dipping olivine basalt within the largest allochthon (see Fig. 3) may indicate that some stratigraphic continuity has been maintained. In addition, this makes it possible to estimate net slip on the fault: 900', 25° S48W. The geologic map, Figure 3, shows that the allochthonous block is cut off by the Cowhead Well fault. This fact, coupled with the similarity of net slip directions of the San Manuel fault and the largest of these faults, and with the suggestion that some stratigraphic continuity has been retained in the upper block, suggests that this block is an example of true low-angle normal deformation rather than landsliding. The type of fault may be similar to one of those depicted in cross-sections by Anderson (1971) Fig. 3 or Proffet (1977) (Fig. 21).
Fig. 21. Low Angle Normal Faults Within the Upper Plate Rocks as Shown by Anderson (1977) and Proffett (1977)
Folds

In general, the Cloudburst Formation in the southwest flank of the Black Hills is homoclinally tilted northeastward. A lower hemisphere equal-area contour diagram of poles to all bedding measurements taken in the study area illustrates this (Fig. 22). The maximum is N15W, 45E and the variance from this maximum on the diagram reflects that the sediments have been gently folded, probably as a result of movements on the Cowhead Well fault.

The most conspicuous fold in the map area is a doubly plunging anticline along the pipeline road in the SE\(\frac{1}{4}\) sec. 25 and NE\(\frac{1}{4}\) sec. 36, T.8S., R.15E., and NW\(\frac{1}{4}\), sec. 31, T.8S., R.15E. The axis of the southeastern half of the fold plunges 23°, S5E. while the axis of the northeastern half trends 3°, N31W, based on limited data (Figs. 23 and 24). Both axes nearly parallel the trace of the Cowhead Well fault. The axial plane of the southeastern half dips N45W, 76°E, while the axial plane of the northwestern half dips about N20W, V\(\pm\). As illustrated by a down-structure view of the southeastern half (Fig. 3), the fold has a gentle interlimb angle (130°) and it is a Class 1A to 1B fold (Ramsey, 1967). The dip isogons of the eastern limb of this fold are moderately to strongly divergent. Some of this divergence may be due to the original lenticularity of the sediments and volcanics involved in folding. The western limb of the fold has been strongly faulted in the southeastern half, and several smaller parasitic folds are evident from mapping in the northwestern half. In the center of sec. 31, a fault which offsets a dacite flow appears to have been folded along the same axis. Because of the proximity and similarity
Fig. 22. Lower-Hemisphere Equal Area Contour Diagram of Poles to All Bedding Measurements in the Cloudburst Formation, Southwest Flank of the Black Hills
Fig. 23. Pi Diagram of Bedding Poles for the Southeast Nose of the Anticline in Sec. 31, T.8S., R.15E.
Fig. 24. Pi Diagram of Bedding Poles for the Northwest Nose of the Anticline in Sec. 31, T.8S., R.15E.
of trends between this fold and the Cowhead Well fault, the fold is interpreted to have resulted from drag along the fault, and the age of this structure is probably late Tertiary.

To the north of this fold, the fault plane of the largest allochton has been folded. The axes probably trend 7°, N20W, with nearly vertical hinge surfaces (Fig. 20). Since the striations appear to lie on a small circle, the fault plane has probably been deformed by flexural folding about these axes. This orientation (7°, N20W) is similar to the orientation of the Cowhead Well fault in this vicinity, which suggests a genetic relationship.

The San Manuel fault has also been folded in this area. As mentioned previously, the fault trends northwest as it enters the map area from the east, then trends southwest through the project area. Creasey (1965) determined an attitude for the San Manuel fault immediately east of the map area: N57W, 45°W. This attitude and the maximum of foliations in the tectonite in the southwest trending segment (N37E, 30 SE), indicates that it is folded across a synform axis trending 28° S26E. This synform has an interlimb angle of 132° and an axial surface which dips N22W 80°E. To the northwest of the southwest trending segment, the fault crops out again, but is too poorly exposed to obtain a fault plane altitude. The geological map however indicates that it probably dips west, and at a fairly shallow angle (15° estimated). This dip and the southeast dipping foliations in the tectonite in the southwest trending segment indicates that the fault has been warped into an antiform. Given the above dips, the axis of this fold would trend about
7° S25W and the axial surface would dip N22E 82W. The fold would have a gentle interlimb angle of 137°. The similarities in trends of the synform axis with the Cowhead Well fault also suggests that they have genetic affinities. The trend of the antiform, however, is forty degrees southwest of this trend and it does not parallel the Cowhead Well fault. The location of this broad fold, however, coincides with a slight change in strike of the Cowhead Well fault from N3W in the southern part of sec. 24 to N26W in the northern part of sec. 24.

The San Manuel Formation in the map area dips westward, contrary to the dip of the same formation in quadrangles to the north and to the east. The average dip is N40E, 14°NW (Fig. 25). A broad anticline has been developed in sec. 1, T.9S., R.15E. (Fig. 3). A plot of points around the fold (see Fig. 3 for domain) tenuously indicates that the axis of the anticline plunges 8°, S68W (Fig. 26). The fold has an interlimb angle of 160° and a vertical hinge surface.

A syncline is present in the San Manuel Formation in the southern part of the map area. This fold extends eastward into the area mapped by Creasey (1968). A pi diagram of bedding measurements taken by myself and utilizing data shown by Creasey (1967) indicates this fold has an axis which plunges 12°, S78E (Fig. 27). The axial plane dips N77W, roughly vertical and the fold has a gentle interlimb angle (about 140°). The fold trends obliquely into the Cowhead Well fault.

A syncline was also observed and mapped west of the Cowhead Well
Fig. 25. Lower Hemisphere Equal-Area Contour Diagram of Poles to Bedding in the San Manuel Formation in the Southwest Flank of the Black Hills
Fig. 26. Pi Diagram of Poles to Bedding Around a Broad Anticline in Sec. 1, T.9S., R.15E.
Fig. 27. Pi Diagram of Poles to Bedding Around the Syncline South of the Cowhead Well Fault, Southern Black Hills
fault, in the northern part of the area. Although bedding attitudes are difficult to obtain here, the fold appears to be similar to the other folds observed in the San Manuel Formation: it has a nearly vertical axial plane and a gentle interlimb angle (Fig. 28). The axis trends N15E and plunges 15° northeast.

An anticline, in the Quaternary-Tertiary sediments adjacent to the Cowhead Well fault was observed and mapped in two places in sec. 25, T.8S., R.15E. (Fig. 3). A pi diagram of bedding measurements around this fold is not very revealing (Fig. 29). The axis trends north-south and the axial plane is probably nearly vertical. The proximity of the anticline to the fault suggests that it is a reverse drag feature which resulted from movement along the Cowhead Well fault.
Fig. 28. Pi Diagram of Bedding Attitudes Measured Around the Northernmost Syncline in the Southwest Flank of the Black Hills Map Area.
Fig. 29. Lower Hemisphere Equal-Area Projection of Poles to Bedding in Quaternary-Tertiary Sediments Adjacent to the Cowhead Well Fault, in Sec. 25, T.8S., R.15E.
CHAPTER 4

GEOLOGY OF THE CAMP GRANT WASH STUDY AREA

Stratigraphy

Geologic mapping by M.H. Krieger (1974c) in the Putnam Wash Quadrangle has shown that a very thick (greater than 10,000') sequence of east-dipping fanglomerates and sandstones of the San Manuel Formation overlies a west-dipping detachment surface, known as the Camp Grant fault. The fault separates San Manuel Formation from Ruin Granite and Pinal Schist.

Krieger (1974c) has subdivided the San Manuel Formation into five map units, from oldest to youngest, as follows.

1) Olivine basalt--This rock is dark brownish grey to maroon with phenocrysts of olivine and clinopyroxene. It is similar to the vesicular andesites of the Cloudburst Formation to the south. The contact relations between this basalt and the overlying San Manuel Formation are poorly exposed. Weibel (1981) dated this basalt at 22.1 ± 0.5 m.y.

2) Older granitic alluvial deposits--These are pale red and light grey brown, coarse to fine-grained sandstones and conglomerates, which are poorly exposed and poorly consolidated. They are composed of clasts of granitic rock with some Pinal Schist and Cretaceous granodiorite porphyry. The unit becomes coarser grained to the west.
3) Granite playa(?) deposits—These are yellow grey and light brown sandstone and conglomerate composed largely of clasts of light colored granitic rocks. They are thinly bedded moderately well exposed.

4) Non-granitic alluvial deposits—This unit consists of alternating beds of sandstone, siltstone and pebble-cobble conglomerate. The clasts consist of Pinal Schist, diabase, Precambrian and Paleozoic sedimentary rocks, andesite and granite. The rocks are moderately well exposed, generally brown and yellow-olive gray and thinly bedded, with many channels.

5) Non-granitic red alluvial deposits—These conglomerates, sandstones and mudstones are maroon, thinly-thickly bedded and somewhat poorly exposed. The conglomerates contain clasts up to 10 feet in diameter, consisting of Pinal Schist, diabase, Precambrian and Paleozoic sediments and early Miocene rhyolite. This unit contains megabreccias—monomict lenticular beds with very angular clasts in a matrix of small fragments and pulverized rock of the same composition. Krieger (1974c) has mapped megabreccias of Escabrosa Limestone, Martin Formation, Abrigo Formation, Bolsa Quartzite, diabase, andesite, Troy Quartzite, Dripping Springs Quartzite, Ruin Granite and Pinal Schist (Fig.30). She has interpreted deposits like these in the Kearney Quadrangle to the north as landslide deposits (Krieger 1977).
Fig. 30. Monolithologic Breccia in the Camp Grant Wash Area
Clasts are from the Upper Devonian Martin Formation.
All of the mapping in the detailed study area was done in the non-granitic alluvial deposits. Two types of sedimentary rocks were mapped: fanglomerates and arkosic sandstone (Fig. 31).

The fanglomerates are reddish-brown cobble conglomerates. Five clast counts were performed in the Camp Grant Wash study area and the results are shown in Figure 5. Of the total clasts counted, 29.8 percent were granite, 28.2 percent were diabase, 31.0 percent were sandstone, 7.8 percent were black igneous rock, 1.2 percent were limestone, and 1 percent was conglomerate and shale. Clast size ranges from very fine sand to boulder size, with an average of about one inch. The clasts are angular to subrounded in a sand and clay matrix. The fanglomerates are both matrix and clast supported, and the bedding is generally thick or massive. In the map area, the fanglomerates are generally found adjacent to the Camp Grant fault, and they probably represent proximal to middle alluvial fans.

Paleocurrent indicators, derived from pebble imbrications, were difficult to find in the study area, due to the matrix-supported nature of many of the fanglomerates. Despite this, 40 good examples of pebble imbrications were taken, and they show a strong vector mean of S35W and a mode at S15-30W (Fig. 32). The clast composition of the fanglomerates is certainly compatible with a source to the northeast, as nearly all rock types observed as clasts can be found within three miles to the northeast.

The sandstones are interbedded with the fanglomerates. They are light grey brown to medium grey, thinly bedded to laminar with some
Fig. 32. Paleocurrents in the Camp Grant Wash Study Area.
massive units and planar crossbeds. Where sandstones are adjacent to the Camp Grant fault, they are noticeably conglomeritic. Depositionally, the sandstones may represent a sandy alluvial fan facies.

**Structural Geology**

The mid-Tertiary sandstones and fanglomerates of the San Manuel Formation of the Putnam Wash-Camp Grant Wash area are floored by the Camp Grant fault, which dips 20°W. The lower plate consists of 1.4 b.y. Ruin Granite. Detailed mapping within the San Manuel Formation has revealed that it has been rotated to dips of 30-45° along an imbricate west-dipping listric(?) normal fault system. These normal faults terminate against the basal discontinuity. The Cowhead Well fault also extends northward into the area and dies in the vicinity of Putnam Wash. Several broad folds in the San Manuel Formation are associated with this fault.

**Camp Grant Fault**

The Camp Grant fault is excellently exposed in Camp Grant Wash about ¼ mile southwest of the juncture of this wash and Putnam Wash (Fig. 33). The fault extends southward from this point for about three miles to where it is cut off by the Cowhead Well fault and northward for ¼ mile to Putnam Wash (Krieger, 1974c). There the fault is offset by a tear fault exposed along the wash and it crops out again one mile to the west. From this point, the fault extends 1½ miles to the north, and it has been offset by several parallel high-angle normal faults. Further north, the trace of the Camp Grant fault
Fig. 33. The Exposure of the Camp Grant Fault Above the Juncture of Camp Grant and Putnam Washes. Note the sense of upward concavity of the fault on the left. Note line drawing on back of preceding page.
is buried except for a small exposure in which Krieger has inferred the fault to be present. Two miles west of this exposure another low-angle fault is present which extends northwest for about five miles (see Fig. 34). Kreiger (1974c) has tentatively correlated this fault and the inferred fault in the small exposure with the Camp Grant fault.

As exposed in Camp Grant Wash, the fault is lined by a 5-6 inch thick zone of phyllonite, which exhibits a fracture cleavage that dips eastward (Figs. 35 and 36). The phyllonite is a brown to light brown, fairly hard, noncalcareous rock having a highly polished "mother-of-pearl" sheen. Striations abound on all fragments taken from this rock. The phyllonite has apparently formed at the expense of the fanglomerate. Small pebbles from the fanglomerate have been incorporated into the phyllonite zone, but granitic fragments have not.

In thin section, the phyllonite consists dominantly of silky microcrystalline sericite or muscovite and a brownish clayey groundmass. Interspersed within this matrix are porphyroclasts of quartz, orthoclase, plagioclase and volcanic and plutonic grains (Fig. 37). Porphyroclasts make up less than 7 percent of the rock.

The cleavage within the phyllonite is penetrative at the hand specimen scale, and the distance between the cleavage planes is less than ½ mm. In general, it dips shallowly eastward indicating a sense of normal-slip movement on the Camp Grant fault (Fig. 36). The cleavage planes are often sigmoidal in profile, and they are separated into packages bounded by longer anastomosing fractures. These fractures are commonly calcite filled, with attitudes roughly parallel to the dip of
Fig. 35. The Camp Grant Fault Fanglomerate is above, Ruin granite is below.
Fig. 36. Closeup of the Phyllonite and the Cleavage in it.
Fig. 37. Photomicrograph of Phyllonite From Camp Grant Wash Fault
Photo looks perpendicular to cleavage.
Plain light above, crossed-nichols below.
the Camp Grant fault. The sigmoidal shape of the cleavages is interpreted to have resulted from drag due to successive normal movements along the long fractures within the phyllonite, after the cleavage had been formed (Fig. 38). It is apparent therefore that numerous normal movements have occurred along the Camp Grant fault.

At the outcrop where this cleavage is visible, the tilted fanglomerates are separated from the phyllonite zone by a mass of fanglomerate which contains an ash bed. This ash bed is distinctive because it is extremely rich in coarse euhedral biotite and because no other volcanic beds exist in the San Manuel Formation in this vicinity. The attitude of this ash bed approximates the dip of the Camp Grant fault. The upper boundary of the fanglomerate-ash bed mass is a minor fault, whose orientation also approximates the phyllonite. The ash bed is exposed for about 30 feet before it is pinched off at either end by the fault and phyllonite. Intriguingly, this same ash bed is interbedded within the fanglomerate sequence about 40 feet upstream from where it is pinched off. Unfortunately, this exposure is difficult to photographically document because of the vegetation cover in Camp Grant Wash. The sketch accompanying Figure 33 illustrates these observations and Figure 39 is a picture of the ash-fanglomerate mass.

This zone is basically a horse in which the dip of the bedding approximates that of the fault plane. It is interpreted to have occurred as a result of fault drag and subsequent detachment of a sequence of fanglomerates, which included this ash bed, during normal faulting along the Camp Grant fault. It may have occurred by emplacement and
Fig. 38. Development of Sigmoidal Cleavage by Subsequent Fractures.
Fig. 39. The Ash Bed in the Horse Between Tilted Fanglomerate Above and the Camp Grant Fault Below
rotation, drag and detachment, as illustrated in Figure 40.

Low-Angle Normal Faults

Low-angle normal faults are ubiquitous in the San Manuel Formation of the Putnam Wash Quadrangle. Unfortunately, continuous exposures of the San Manuel Formation are rare, because the formation weathers so easily. The best exposure occurs along Camp Grant Wash, along a 3700' stretch approximately 2000 feet upstream from the Camp Grant Wash Putnam Juncture (SE\(\text{\%}\), NW\(\text{\%}\) sec. 18, T.7S., R.16E.). This area was mapped at a scale of 1":200', in order to describe the geometry of the faults in detail (Fig. 31).

This mapping and subsequent structural analysis has revealed that the San Manuel Formation has been deformed by a distributed system of west-dipping low-angle listric(?) normal faults (Figs. 41, 42 and 43). Figure 44 is lower hemisphere equal-area contour diagram of poles to all faults measured in this study area. The plot shows that most faults dip southwest with the maximum at N14W 32°SW. Striations were only rarely observed.

These faults were generally observed as truncations of small lenses of fanglomerate or sandstone. Generally a thin line of clay gouge represents the fault plane, but in places, a phyllonite greater than one inch thick may be developed. These phyllonites are very similar to, but never as thick as, the phyllonite of the Camp Grant fault. In places where the phyllonite was observed it was impossible to estimate the apparent offset of the faults, which suggests that the magnitude of slip may be large.
Fig. 40. Development of Oriented Cobbles and Bedding Parallel to the Camp Grant Fault.
Fig. 41. Low Angle Normal Faults Along Camp Grant Wash.
Fig. 42. Low Angle Normal Faults Along Camp Grant Wash, slightly further west than Fig. 41.
covered

Camp Grant Fault

alluvium

fgl - fanglomerate
ss - sandstone
gr - granite
Fig. 43. Normal Faults and Camp Grant Fault Along Camp Grant Wash. Note line drawing on back of preceding page.
Fig. 44. Lower Hemisphere Equal-Area Contour Diagram of Poles to All Faults Measured in Camp Grant Wash
The relationship between the low-angle normal faults and the Camp Grant fault was only observed in a few instances, primarily because exposure of the basal discontinuity is somewhat limited. In outcrops where the basal fault plane was observed, some normal faults intersect the basal discontinuity abruptly, but do not break it, and are definitely not listric (Fig. 33). Other faults nearly parallel the discontinuity as they approach it, and although the intersection is not seen, they appear to be slightly listric (Fig. 33).

A fabric of oriented pebbles and cobbles is very commonly developed adjacent to the low angle faults with large displacements. The pebbles and cobbles are oriented parallel to the fault plane. Generally, the zone of aligned pebbles and cobbles is about one to two feet thick, typically bounded by the major fault and a smaller, less conspicuous fault. These zones of oriented clasts are interpreted as zones of fairly plastic material in which the larger clasts have been rotated parallel to the fault as a result of shear and fault drag adjacent to the fault.

High-Angle Normal Faults

The most prominent high angle normal fault in the area is the Cowhead Well fault, which strikes N10W and dips steeply to the west (Fig. 34). The amount of displacement must gradually decrease from the southwest flank of the Black Hills study area northward, because Krieger (1974c) indicates that the fault dies shortly after intersecting Putnam Wash.

Another high-angle normal fault extends to the north-northwest,
along the same trend as the Cowhead Well fault, roughly 2 miles north of Putnam Wash (Fig. 34). This fault dips steeply east and extends into the Winkleman quadrangle to the north where Krieger (1974d) indicates that it separates Upper Precambrian sediments and San Manuel Formation. Strata in the area between these two faults have been broadly folded.

Several other high-angle faults exist in the Putnam-Camp Grant Wash area. Krieger (1974c) mapped two high-angle normal faults approximately 5½ miles southwest of the junction of Camp Grant and Putnam Washes. The faults bring Ruin Granite and San Manuel Formation into contact. In addition, she has mapped a fault that places Quaternary gravel against Ruin Granite about 6½ miles west of the Camp Grant-Putnam Wash juncture. Finally, the Camp Grant fault has been repeated by high-angle normal faults in the area north of the tear fault. Kreiger shows all of these faults as west-dipping, with the western block downthrown. The displacement on all these faults is smaller than the maximum value that the Cowhead Well fault attains.

Folds

In general the beds of the San Manuel Formation dip eastward. The amount of dip varies between 10-40°. In the area of detailed study along Camp Grant Wash, the modal dip bedding orientation plane was determined to be N33W, 30°, with an error cone of about 22° (Fig. 45).

Krieger has mapped six folds in the San Manuel Formation within this area, and I have inferred the existence of two others based on the bedding attitudes shown by her. For the most part, these folds are
Fig. 45. Lower Hemisphere Equal-Area Contour Diagram of Poles to Bedding in the Camp Grant Study Area
adjacent to the Cowhead Well fault, in the area north of where it dies in Putnam Wash.

Bedding attitudes measured by Krieger were utilized to construct pi diagrams of these folds. In all cases the axes of the folds were found to plunge shallowly north in varying amounts (Figs. 46-50). The axial traces of some folds, notably those north of Putnam Wash, are curvilinear (Fig. 34). The dip of the axial surfaces, as deduced from the pi diagrams, was found to be subvertical-vertical.

The age of folding is at least post middle Miocene, as the Big Dome Formation has been folded in this area. Because the folds are adjacent to and of similar trend as the Cowhead Well fault, the folds are assigned a late Tertiary age.

Geophysical Investigations of the Camp Grant Fault

The geometry of the Camp Grant fault along Putnam Wash was examined by two dimensional gravity modeling. The original intent of this gravity survey was to examine the shape of this basal discontinuity at depth, to ascertain if it was listric or not, and to establish the depth to granite. Because the discontinuity is the boundary between granite and fanglomerate, it was hypothesized that a sufficient density contrast between the two rocks would be present and that the interface would be plainly shown by gravity modeling.

Methodology

The locations of points chosen for the gravity survey are shown in Figure 51. The gravity points were located as closely as possible to distinctive topographic features to facilitate location of them on
Fig. 46. Pi Diagram of Bedding Measurements for Anticline in Secs. 9 and 16, T.7S., R.16E., in the San Manuel Formation. Data from Krieger (1976c)
Fig. 47. Pi Diagram of Bedding Measurements for Syncline in Sec. 10, T.7S., R.16E. in the San Manuel Formation
Data from Krieger (1974c)
Fig. 48. Pi Diagram of Bedding Measurements for Anticline in San Manuel Formation in W\textsubscript{4}, Sec. 11, T.7S., R.15E.

The axis and axial plane of this fold are not distinctly apparent from this plot, but it appears that the axial plane is nearly vertical, and the axial trend is similar to the synclinal axis shown by Krieger in Sec. 10 to the west: about N12W., curving to N20E near Putnam Wash. Data from Krieger (1974c).
Fig. 49. Pi Diagram of Bedding Measurements Around a Syncline in the San Manuel Formation, E$x^2$, Sec. 22, T.7S., R.15E.
Fig. 50. Pi Diagram of Bedding Measurements for Anticline in the San Manuel Formation, NE\(\frac{1}{2}\), Sec. 23, T.7S., R.15E.
Data from Krieger (1974c).
Fig. 51. Location of gravity survey points.
U.S.G.S. 7.5' quadrangle maps. These maps were then used to determine the latitude and longitude of the gravity point.

For the purposes of the gravity survey, it was necessary to establish the elevation of these points to within five feet. The contour interval of the 7.5' quadrangles was 40 feet and estimations of the elevations of the point were probably only good to within ten feet at best. Six benchmarks have been established by third order leveling (1957) in Putnam Wash, and the elevations of the gravity points could be established from the benchmarks by using relative changes in altitude derived from altimeters. Of the six benchmarks shown on the topographic maps, three were located in the field (points 4,7 and 13).

The altimeter survey was performed in the very early morning hours of Sept. 9, 1981. This was done to insure that changes in temperature, and hence, marked changes in altitude, could be held to a minimum. Sunrise was approximately 6:35 a.m. on this day and the weather was cool and clear with clouds on the eastern horizon. The survey was initially run up the wash from 3:50-5:40 a.m., and then down the wash from 5:40-7:00 a.m., using two altimeters each run. The time of each altitude measurement was noted also.

The elevation of each point was established by the formula:

\[
Elev = Elev_{BM_3 o} + \left[ Elev_{GP_{alt}} - Elev_{BM_{alt}} \right] + \left[ (\Delta Elev_{BM_3 o + BM_3 o} - \Delta Elev_{BM_{alt} + BM_{alt}}) \times \left( \frac{\Delta t_{BM + GP}}{\Delta t_{BM + BM}} \right) \right]
\]
where

$\text{Elev}_{BM_{30}}$ is the elevation of the closest benchmark as established by third order leveling

$\text{Elev}_{GP}$ is the elevation of the gravity point as established by the altimeters

$\text{Elev}_{BM}$ is the elevation of the benchmark as established by the altimeters

$\Delta \text{Elev}_{BM_{30} \rightarrow BM_{30}}$ is the difference in elevations between two benchmarks, as measured by third order leveling

$\Delta \text{Elev}_{BM_{alt} \rightarrow BM_{alt}}$ is the difference in elevations between two altimeters benchmarks, as measured by the altimeters

$\Delta t_{BM+GP}$ is the amount of time from the benchmark to the gravity point

$\Delta t_{BM+BM}$ is the amount of time between benchmarks.

The elevation change between benchmarks as measured by the altimeters generally differed from the numerical difference of the elevations shown on the benchmarks. This discrepancy was considered a kind of "instrument drift" and it was distributed between the intervening gravity points according to time elapsed between the measured point and the benchmark as compared to the total time elapsed between benchmarks. This is the purpose of the third term in the equation.

The gravity survey was performed on Oct. 16, 1981 and again on Nov. 1, 1981 using a LaCoste and Romberg Model G Geodetic Gravimeter, instrument number G174. The time spent from base station to base station was 8.02 hours for the first survey and 7.70 hours for the second survey. Because of the length of time involved in the surveys, the gravity of point 16 was measured at the beginning and at the end of each survey. The instrument drift rates calculated between these two
measurements was compared with the drift rate from base station to base station. For each survey, the instrument drift rate measured on the site was very similar to that calculated for the entire survey.

The raw data (gravity values of field and base stations, elevations, time of measurement, latitude and longitude) were input into several computer programs developed by the Laboratory of Geophysics, University of Arizona. The first of these, XGRAV, corrects the gravity measurement for instrument drift, corrects for earth tide effects, calculates the observed and theoretical gravity for the survey point and determines the Free Air Anomaly and Simple Bouguer Anomaly for the station. The results of XGRAV are shown in Tables 1 and 2.

The output file from XGRAV is input into the next program TER99.F10, which formats the data for the terrain correction program, TERMAP. This program computes the terrain effect of mountains and valleys around the gravity station for a distance of 167 km, based on a map digitized for elevations of approximately 150' centers, over the entire state. Within 2.60 km; the terrain corrections were estimated by hand using a Hammer Chart, based on a density of 2.67. The results of this, the Complete Bouguer Anomaly, are also shown in Tables 1 and 2.

The Complete Bouguer Anomaly values are reduced to Bouguer Residual Anomaly values in the program FRPTS. FRPTS defines the Regional Bouguer Anomaly for the state of Arizona, based on a two harmonic fourier trend surface of elevation, and then subtracts the Complete Bouguer Anomaly values to obtain the Residuals.

The Residual Bouguer values are next input, together with their
distance along the survey line, into the program ITMODX. Because Putnam Wash is not exactly straight, the survey points were projected perpendicular to the "best-fit" line for the survey, and the intercepts were used to determine the distances along the line. ITMODX is an iterative two dimensional gravity model program, which computes depth-to-bedrock values below an alluvial valley based on gravity data.

The program first corrects for the regional trend of the anomaly values of the survey. It does this by relating the residual anomaly values of the survey points to their distance along the survey line. A line is then defined through the endpoints of this curve and the deviations of this curve from the line are used for the depth-to-bedrock determination. To do this, the program divides the survey line into a number of vertical rectangular prisms, whose centers are the gravity survey points. It assigns a density contrast value \( \rho_{\text{alluvium}} - \rho_{\text{bedrock}} \) to each of the prisms, computes the gravity effect for all the prisms, and determines the depth-to-bedrock based on the Bouguer Slab Formula. It then compares this gravity profile with the observed gravity profile, from which new residuals are derived. The program then densifies each of the prisms if needed, calculates a new depth to bedrock, and computes the gravity effect for the prisms again. This program loop is run ten times or until a specific residual limit is exceeded. The program also prints the residual and depth-to-bedrock values and constructs gravity and depth-to-bedrock profiles. As the density contrast between these consolidated fanglomerates and the underlying granite was less than that generally assigned to alluvium and bedrock, the program was modified
Table 1. Gravity Values, Putnam Wash Traverse, Run #1

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slightly to determine a depth-to-bedrock based on lower density contrast values.

Results and Discussion

The first run of ITMODX with data from the first survey clearly indicated that a large bedrock high existed in the central part of the profile extending from approximately stations 5 to 11 (Fig. 52). Furthermore, the depth-to-bedrock profile, when drawn to true scale, did not agree with certain geologic conditions that needed to be met: the depositional western contact of the granite fanglomerate probably dips about 15° eastward, as deduced from the dips mapped by Krieger in this vicinity. The initial run of ITMODX indicated a dip of only about 9° for this contact. This indicated that the density contrast between bedrock and granite probably needed to be reduced in order to obtain a deeper basin.

As a result of this run, all calculations from elevations to latitude were rechecked and the gravity survey was run again. The second survey, utilizing the same elevations as the first survey, yielded very similar results (compare Tables 1 and 2).

In addition, a number of samples of sandstone conglomerate and granite were collected along the traverse and the density of each was measured using a Jolly Balance. The results of the measurements (Table 3) indicate that the density contrast should more properly be about (-0.2 gm/cc). These results are somewhat misleading because the more unlithified samples of conglomerate could not be collected.

ITMODX was modified to calculate depth-to-bedrock on the basis of given
Fig. 52. Initial Run of ITMODX Model.
Table 3. Densities of Rocks Along Putnam Wash

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**Average** 2.44 ± 0.12

| Ruin Granite                        | 183.15              | 292.65           | 2.67                    |
| Ruin Granite                        | 226.20              | 364.90           | 2.63                    |
| Ruin Granite                        | 270.50              | 439.35           | 2.601                   |

**Average** 2.63 ± 0.03
density values, and it appears that a density contrast of -0.25 gm/cc fits the geology better and agrees reasonably well with the measured density values (Figs. 53 and 54).

Several attempts were made to reduce the magnitude of the gravity high in the center of the basin by varying the density contrasts of the prisms (see Appendix A). In general, however, this was to no avail and the gravity high remained in all ITMOD models.

The best fit ITMOD model for this traverse (Fig. 54) indicates the following:

1) The Putnam Wash basin may be two sub-basins.
2) The westernmost basin is about 1500 feet deep, while the easternmost basin is about 1000 feet deep.
3) The bedrock in the gravity high area may actually outcrop, or at least come very close to the surface.
4) There is a sense of upward concavity to the eastern halves of both sub-basins.

Three geologic possibilities may account for the gravity high (Fig. 54):

1) Bedrock (granite or schist) may actually be fairly close to the surface in the center of the traverse.
   In this case, two other geologic possibilities are present:
   a) Two low-angle listric basal discontinuities may be present.
   b) The bedrock may be a large basement fold of some type, possibly associated with the Cowhead Well fault.
2) A mass of fairly dense material may be present in the center of the basin.
Fig. 53. "Best-fit" ITMODX Model.
Fig. 54. Observed Gravity, ITMODX Model, and Three Postulated Basement Geometries to Account for the Observed Gravity
Model 1a is geologically possible in that Krieger has mapped and inferred two basins by low-angle "gravity slide" faults in the northern part of the Putnam Wash Quadrangle (see cross-section A-A', Kreiger 1974c). Both faults dip west and separate San Manuel Formation from granite and schist. According to her cross-sections, she shows the two faults as one fault, which has been repeated by high-angle faulting. According to her map, however, the western contacts of each basin (San Manuel on older rocks) are mapped in many places as depositional (the contacts are solid and no fault has been inferred in these places). Based on the geology around the San Manuel Mine where the low-angle normal fault displaces pre-Miocene rocks and where the western contact between San Manuel and Oracle granite is depositional (Creasey 1967; Lowell 1968)—the two fault traces mapped by Krieger (1974c,d) may actually represent two faults—both of which pass beneath the western San Manuel/older rock contacts and which necessarily offset the older basement rocks.

Model 1a is also attractive in that the displacement of the San Manuel fault near the mine is about two miles. The displacement of the Camp Grant fault, as shown by Krieger, is about six miles. If this basin is actually underlain by two faults, the displacement on each would only be about three miles each, roughly, which is more comparable to the displacement of the San Manuel Fault to the south.

Model 1b is also feasible in that the location of the fold is in an area in between two range-bounding normal faults which lie along the same trend: the west dipping Cowhead Well fault to the south which dies
northward in the vicinity of Putnam Wash and another unnamed east-dipping normal fault which bounds the Tortilla Mountains on the east, which dies southward before Putnam Wash. Viewed this way, the Cowhead Well fault and its northern counterpart are one fault system, and the center part of the Putnam Wash area is an area of "scissoring" or inflection. The gravity high of this area may be reflecting a fold or bedrock high which is part of the Tortilla Mountains.

The positive lobe of the gravity high may also be accounted for by density inhomogeneities in the bedrock beneath the basin, as shown in Model 2 (Fig. 54). At least two rock types in the area of the traverse (Pinal Schist, Precambrian diabase) are probably denser than the Ruin Granite assumed to lie below the San Manuel Formation, and various combinations of density and size of these rock bodies within the Ruin Granite could conceivably account for the positive lobe. An interpretation based strictly on one low-angle normal fault and density inhomogeneities would seem to ignore some of the structural features which are compatible with Models 1a and 1b. Hence Model 2 is not as attractive for explaining the positive lobe observed on the gravity profiles.
CHAPTER 5

GEOLOGY OF THE HIGHWAY 77 ROADCUT EXPOSURES

Because of their excellent exposure, the roadcuts of Highway 77, located 3½ miles southwest of Mammoth, afforded a unique opportunity to study the geometry, kinematics and strain involved in mid-Tertiary tilting of the San Manuel Formation. Three roadcuts just west of the San Manuel Fault were mapped in detail (1" = 20'). For the most part, these cuts are roughly normal to the strike of the beds and faults, so that true views of these planes can be observed. The roadcuts were mapped with a Brunton and tape, and a stadia board was placed on the outcrop to estimate vertical distances.

**Stratigraphy**

The interbedded arkosic sandstones and fanglomerates exposed here are part of the undifferentiated member of the San Manuel Formation of Heindl (1963). The rocks are light grey brown to medium brown, thin to thick bedded, clast-supported and tuffaceous. Volcanic fragments, Precambrian and Paleozoic sediments, quartz monzonite and clasts of other fanglomerates are abundant. The maximum clast size exposed is about 12 inches. As derived from imbricate pebble orientations, the paleocurrents represented in these roadcuts flowed southwest, with a vector mean S37W (Fig. 55).
Fig. 55. Paleocurrents in the San Manuel Formation, Highway 77 Roadcuts.
Structural Geology

The roadcut exposures are located just west of the San Manuel fault, which is covered by artificial fill along the highway. The fault is well exposed in Cottonwood Wash, ½ mile to the south. Physically, the fault here more resembles the Camp Grant fault than it resembles the San Manuel fault exposed in the southwest flank of the Black Hills. There is no chloritization, brecciation or foliation developed in the lower plate rocks, and unaltered tilted sediments rest atop a phyllonite (Fig. 56). Perhaps this discrepancy is due to the type of upper plate rocks involved in the deformation. In this area semi-lithified sandstones and fanglomerates are the upper plate rocks, as in the Camp Grant-Putnam Wash area, whereas the upper plate rocks of the southwest flank of the Black Hills are strongly lithified fanglomerates and andesites of the Cloudburst Formation. This discrepancy may also reflect the depth of faulting; the chloritized part of the fault in the southwest flank of the Black Hills may have formed deeper than that near the roadcuts. This effect is compatible with models developed by G.H. Davis for low-angle normal fault systems (Davis, 1982).

The structure of the upper plate rocks in these roadcuts is a distributed normal fault system in which the dip of bedding is antithetic to the dip of the faults (Fig. 57). The bedding of the San Manuel Formation dips fairly uniformly to the northeast. Figure 58 is a contour diagram of dips measured during profile mapping. The
Fig. 56. The San Manuel Fault in Cottonwood Wash
The fault is the shallow dipping lineation in the right center part of
the photo. Note several low-angle normal faults in tilted sediments,
left side of photo. Note person for scale to left of center.
Fig. 58. Lower Hemisphere Equal-Area Contour Diagram of Poles to Bedding, Highway 77 Roadcuts
maximum is N37W, 42E. In general the faults dip to the southwest at about 48°, a fairly low angle. A contour diagram of poles to the faults (Fig. 59) roughly defines a great circle: this may reflect the arcuate trace of the San Manuel fault in this vicinity. A few of the faults dip steeply to the northeast (Fig. 57).

Striations were observed on 14 fault planes, and form a fairly tight cluster on a stereonet, with a maximum of 34°, S35W (Fig. 60). Phyllonites, similar to those observed in Camp Grant Wash, were observed in six faults in the roadcut exposures (Fig. 61). Cleavage in the phyllonites of faults is indicative of normal movement on these fault planes and a fabric of oriented cobbles is often developed adjacent to these faults (Fig. 62). Of the total number of faults observed, 34 have apparent normal offset, 11 have apparent reverse offset, and no decision could be made about three. The apparent offset could be measured on the smaller faults by correlating distinctive beds on either side of the fault. Distinctive markers were not apparent across some faults, but the offset could be estimated by comparing gross packages of beds across the fault. It was generally difficult to estimate the offset across faults containing the phyllonitic clay gouge. As a result, only minimum estimates of the offsets could be made on these faults. If the beds of the hanging wall and footwall did not contain marker beds, and the phyllonite indicated normal offset, the minimum offset was estimated as the exposed fault length. If a marker bed was observed on one side of the fault, but not the other, the minimum offset was estimated from the marker to end of the exposed
Fig. 59. Lower Hemisphere Equal-Area Contour Diagram of Poles to Faults, Highway 77 Roadcuts
Fig. 60. Lower-Hemisphere Equal Area Contour Diagram of Striations, Highway 77, Roadcuts
Fig. 61. Photos of Two Low-Angle Normal Faults in the Highway 77 Roadcuts
Note the phyllonite zone in each photo and the oriented cobbles in a zone adjacent to the fault.
Fig. 62. Close-up of Phyllonite Zone (note cleavage) and Oriented Cobbles
fault length.

The excellent exposure of the roadcuts allows an estimation of the minimum amount of extension of the San Manuel Formation at that location. As stated before, the estimate is a minimum because the normal offsets on the faults with phyllonite gouge may be severely underestimated. On the other hand, the deformation in these roadcuts may be fairly intense and the extension of the rocks as viewed in these outcrops may be abnormally great as compared with the rest of the San Manuel Formation. Furthermore, because all of the faults did not have striations, the absolute net extension for the roadcuts could not be calculated. Instead, the extension was obtained by summing the horizontal component of the apparent offset for each fault in the roadcut. (Using this scheme, normal faults add to the horizontal extension and reverse faults detract from the extension.) Hence, this amount of extension represents an approximation to the absolute horizontal extension and represents a semi-axis of the strain ellipsoid of this system along the direction of the roadcut. The actual direction of maximum elongation is probably represented by the modal direction of plunge of the striations, S37W. From east to west, the extensions shown by the roadcuts are a minimum of 14 percent, 28 percent, and 9 percent. If all the areas of poor exposure and the areas between roadcuts are disregarded, this section of fanglomerates has been horizontally extended by 17 percent minimum.

In addition to having been extended, the San Manuel Formation has also been apparently thickened by distributed normal faulting (Fig. 63). This apparent thickening can be measured by comparing the apparent thick-
Fig. 63. True Thickness of Rock Versus Apparent Thickness of Rock Due to Successive Normal Faults.
ness (i.e. the thickness measured if all faults are ignored) to the true thickness (the thickness measured if a given horizon is successively downfaulted by the amount of apparent offset on the faults). For the three profiles, the minimum apparent thickening was measured at 1.35, 1.63, and 1.34 times the measured thickness. If all areas of nonexposure are disregarded, the total apparent thickening for these three profiles is 1.44 times the true thickness.

Undoubtedly, two phases of faulting are represented in these roadcuts: a middle-Tertiary episode related to the rotation of the gravels and a late-Tertiary episode related to the formation of the San Pedro Graben. I feel that most of the faults shown on the profiles are mid-Tertiary listric(?) normal faults. These roadcuts are on the western flank of the San Pedro Graben, and late Tertiary faults in this area would probably be high angle northeast dipping faults. Because the preponderance of faults mapped in the profiles dip shallowly south-westward, they are more likely to have been caused during the middle Tertiary episode. The northeast dipping faults may be late Tertiary or they may be middle Tertiary antithetic faults.
Southern Black Hills

**Cloudburst Detachment.** In the southern Black Hills, at least two low angle faults have been mapped: the Cloudburst detachment and the San Manuel fault. The Cloudburst detachment, as shown on the maps and cross-sections of Creasey (1965), has placed younger (Oligocene) sediments and volcanics of the Cloudburst Formation atop 1.4 b.y. granodiorite and quartz monzonite (Fig. 17). This detachment dips $10^\circ$ east and the beds in the upper plate dip more steeply east at $25^\circ - 75^\circ$ (Fig. 64). Although Creasey (1965) has interpreted this fault as a thrust, the cross-sections he has drawn are remarkably similar to those of younger on older low-angle normal faults, as shown by Davis and Hardy (1981), Anderson (1971), Davis and others (1980), and Dokka (1981), Anderson (1971), Davis and others (1980), and Dokka (1981). In fact, Krieger (1974a) has reinterpreted this fault as a gravity slide fault.

The dip direction of the Cloudburst discontinuity at first seems enigmatic in comparison to that of other low-angle normal faults in the area. Similar, but opposite, geometries are apparent in the Graham Mountains to the east of the Galuiros, however. Here, the Eagle Pass detachment dips shallowly westward into the Sulphur Springs Valley and...
Fig. 64. Lower Hemisphere, Equal-Area Contour Diagram of Poles to Bedding Above the Cloudburst Detachment Data from Creasey (1965).
separates Precambrian quartz monzonite from overlying Miocene sedimentary and volcanic rocks which dip more steeply westward.

Davis and Hardy (1981) observed that the Eagle Pass detachment is a trough-like feature and that fault drag features along the northwest side of the trough indicate that the direction of translation of the upper plate rocks was to the northeast. This is also consistent with the concept of antithetic rotation of these rocks in this locality. Similarly, the Cloudburst detachment, according to Creasey's map, is also trough-like: the northwest side dips 45°SE, while the southwest side dips 10°NE (Fig. 17). Furthermore, a slight change in the strike of the upper plate rocks near the northwest side of the detachment to a more northerly direction may indicate southwest translation of the upper plate rocks, which is consistent with the concept of antithetic rotation of these beds. Davis and Hardy (1981) have proposed that the Eagle Pass detachment has been rotated to its present westerly dip by subsequent deeper listric faulting and/or arching of the Piñaleno Mountains. Furthermore, they have proposed that a similar kinematic mechanism operated on both sides of the Galiuros contemporaneously, but in different directions. Based on the similarities in geometries between the Cloudburst detachment and other low-angle normal faults, I would interpret this detachment as a low-angle normal fault, as Krieger (1947a) has done, which originally dipped horizontal or west, and on which Oligocene volcanics and sediments were rotated to easterly dips. Subsequently, the detachment and the upper plate have been rotated easterly by deeper listric faulting and/or uparching in the Black Hills, similar to the interpretation of Davis and Hardy (1981).
Heindl (1963) cites drill hole evidence that the Cloudburst Formation extends beneath more recent sediments of the San Pedro River Valley. Heindl's cross-sections show the Cloudburst Formation as extending to the Galiuro Mountains, an interpretation which is not untenable given the lithologic similarity, the contemporaneity and the spatial proximity of the Galiuro Volcanics and the Cloudburst Formation. Hence, the Cloudburst Formation as observed in the southern Black Hills may actually be a basinal facies of the Galiuro Volcanics which has been translated westward and rotated eastward by the Cloudburst detachment and/or deeper listric faults.

San Manuel Fault. The San Manuel Fault bounds the top of the San Manuel orebody. During exploration for the offset portion of the orebody, J.D. Lowell made a structure contour map of the fault and observed several rolls plunging down dip. He interpreted them as mullions indicative of normal-slip movement. Based on this observation, an area two miles southwest of the orebody was drilled, and the Kalamazoo orebody was intersected on the first drill hole. Subsequent work by Lowell (1968) on the similarities of alteration zones surrounding each orebody conclusively demonstrated that the Kalamazoo and San Manuel orebodies were portions of a single orebody offset by normal faulting. The Kalamazoo orebody has been offset approximately 8000 feet, 25°-30°, S55W (Lowell 1968).
Deeper Rotational Faults. In addition to these faults, another low-angle detachment surface may be present at depth in the southern Black Hills. First, as stated earlier, the dip of the Cloudburst detachment may indicate this. Second, the San Manuel orebody was probably a vertical pipe-like body when it was formed (Lowell 1968). Since then, the axis of this body has been inclined to about $65^\circ$ from vertical and also rotated to the east. If most of this tilting is middle Tertiary, then the timing of this rotation with respect to movements of the Cloudburst detachment and San Manuel fault, is contingent upon assumptions of the original dip of the Cloudburst and San Manuel faults (Fig. 65). If for example, the Cloudburst detachment originally dipped $55^\circ$ west, all of this $65^\circ$ of rotation could have happened between movements of the Cloudburst and San Manuel faults. If both faults originally dipped $45^\circ$ west, then $20^\circ$ of rotation followed San Manuel faulting, $35^\circ$ occurred post-Cloudburst and pre-San Manuel faulting and $60^\circ$ occurred pre-Cloudburst faulting. If the Cloudburst detachment was originally flat, then $55^\circ$ of rotation occurred before the Cloudburst detachment and may not be related to middle Tertiary rotational deformation. Obviously, no one unique solution exists. The trace of this deeper detachment, in the context of this interpretation, must lie to the east of the easternmost outcrops of the Cloudburst and west of the less rotated outcrops of the Galuiero Volcanics. It may be buried by late Tertiary sediments of the San Pedro River Valley.
Fig. 65. The Timing of Rotation of the San Manuel/Kalamazoo Orebody With Respect to Major Black Hills Faults.

The sequence is dependent upon assumptions of initial dip of the faults.

Sequence 1

a) emplacement of ore body
b) Cloudburst detachment develops with a $55^\circ W$ dip
c) Orebody and detachment rotate $65^\circ$ eastward
d) San Manuel fault develops with a $25^\circ W$ dip

Sequence 2

a) emplacement of ore body
b) $10^\circ$ of eastward rotation
c) Cloudburst detachment develops with a $45^\circ W$ dip
d) system rotates $35^\circ$ eastward
e) San Manuel fault develops with a $45^\circ W$ dip
f) orebody and both faults rotate $20^\circ$ eastward

Sequence 3

a) emplacement of orebody
b) $55^\circ$ of eastward rotation
c) Cloudburst detachment develops with a flat dip
d) $10^\circ$ of eastward rotation
e) San Manuel fault develops with a $25^\circ W$ dip
Fig. 65. The Timing of Rotation of the San Manuel/Kalamazoo Orebody With Respect to Major Black Hills Faults.
Kinematics and Timing of Upper Plate Structures. The nearly homoclinal dip of the San Manuel Formation and the faults observed in it seem to be geometrically and kinematically coordinated with each other and with the San Manuel fault. The faults observed in the roadcuts are part of a distributed west-dipping normal fault system, in which the western blocks are progressively downthrown, along an extensional axis of about S37W. Similarly, the San Manuel fault is a normal fault with a net displacement in a S55W direction. In addition, the contour diagram poles to faults in the roadcuts shows an arcuate trend (Fig. 59). Measurements of the dip the San Manuel fault, derived from the map of Creasey (1965), and my own measurements in the area near the roadcuts also plot on a stereonet as an arc with a similar trend (Fig. 66). The similarity of trends of these arc implies that the faults observed in the roadcuts tend to parallel the San Manuel fault, but are about 25° steeper. This geometric relationship implies that the roadcut faults developed as a result of movement on the San Manuel fault.

The strike of the San Manuel beds in the area of Creasey's map generally approximates the strike of the San Manuel fault nearby (Fig. 17). A pi diagram of bedding also shows a conical pattern that reflects the arcuate nature of the fault trace (Fig. 66). Furthermore, the strike of beds, as mapped by Creasey, is nearly orthogonal to the net slip direction as deducted by Lowell in the San Manuel-Kalamazoo ore bodies area (Fig. 66), which is consistent with the concept of anti-thetic rotation of these beds along a basal detachment. The fact that
Fig. 66. Lower Hemisphere Equal-Area Projection of Poles to Bedding in the San Manuel Formation in the Mammoth Quadrangle and Poles to the San Manuel Fault

The conical pattern probably reflects the arcuate trace of the San Manuel fault. Bedding measurements are taken from Creasey (1965) and fault plane attitudes were taken from Creasey (1965), my own observations and from three-point solutions of the fault as mapped by Creasey.
the strike of bedding of the Cloudburst Formation and the strike of the San Manuel fault diverge substantially (Fig. 17) may indicate that the Cloudburst was tilted in response to the Cloudburst detachment and subsequently downfaulted along the San Manuel fault.

It is difficult to prove that the upper plate normal faults are the mechanical means for achieving the tilt seen in the sediments. Within the San Manuel Formation, the dip of faults and beds are antithetic to each other. The strike of the maximum of the pi diagram of poles to faults (N26N) is similar to the strike of the maximum of the pi Diagram of poles to bedding (N37W), although qualitatively there seems to be more variation in the fault attitudes than in the bedding attitudes however (compare Figures 59 and 60).

The Cloudburst Formation has probably undergone a similar antithetic rotation as the San Manuel Formation. Numerous normal faults were observed during mapping in the southwest flank of the Black Hills. Most of these faults seem to be late Tertiary. Some normal faulting occurred before San Manuel faulting however, as a result of movement on the Cloudburst detachment. The deformation of the Cloudburst has included a type of low-angle normal fault displacement similar to block-glide landsliding, which occurred before Late Tertiary. The similarity of the slip line direction for this allochthon (about S48W) with that of the San Manuel fault (S55W) suggests that both faults occurred contemporaneously.

Frost (1979) has given evidence that tilted mid-Tertiary gravels in the Whipple and Buckskin Mountains were deposited contemporaneously
with movement on the basal discontinuity. To assess this possibility in the southern Black Hills, the outcrop area of the Cloudburst and San Manuel Formations was divided into a series of domains (Fig. 34). The numerical values of the dips measured by Creasey (1965) and myself were then arithmetically averaged and these averages were plotted as a function of the distance from the base of the Cloudburst to the center of the domain. The averages of dips from four domains above the Cloudburst detachment were also plotted as a function of the distance from the center of the domain to the west edge of the detachment. These graphs indicate that there is a distinct lessening of dip with younger stratigraphic position (Fig. 67). Hence, in a gross way, rotation may have occurred contemporaneously with deposition throughout Cloudburst/San Manuel time. In fact, the disparity of dips between the lower and upper Cloudburst has been portrayed by Creasey (1965) as an "onlap" of fanglomerates on volcanics (see Creasey, 1965, plate I, cross-section B-B).

The zones of oriented cobbles developed adjacent to some of the larger west-dipping normal faults in the San Manuel Formation may also indicate penecontemporaneous deposition. The fact that faulting in the San Manuel Formation never cuts cobbles, and that the cobbles have rotated such that their long axes approximate the dip of the fault plane implies that the matrix of the fanglomerates was not extremely lithified at the time of deformation.
the folding adjacent to Cowhead Well fault has lessened the amount of dip.

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**Fig. 67.** Plots of Average Dip Versus Stratigraphic Position for Domains in the Cloudburst and San Manuel Formations. Data from Creasey, 1967 and Hansen, this report; See Fig. 34 for location of domains.
Summary. In the southern part of the Black Hills, the geometries of bedding and structures suggest that antithetic eastward rotation of bedding was accomplished by successive downfaulting to the southwest along a low-angle distributed normal fault system. This fault system is probably limited to the upper plate rocks and the faults probably either end at or sole into the basal San Manuel fault. Within the San Manuel Formation, the rotation of bedding and the net extension as a result of the fault system are geometrically coordinated with and probably resulted from normal faulting along the San Manuel fault. The Cloudburst Formation above the San Manuel fault has also been rotated antithetically to eastward dips, but has probably been involved in two episodes of low-angle normal faulting. The upper plate of Cloudburst Formation may have also been deformed by low-angle normal faulting, similar to large block-glide landsliding. The progressive shallowing of average dip with higher stratigraphic position in the Cloudburst and San Manuel Formations suggests that rotation, probably as a result of low-angle normal faulting was contemporaneous with deposition. Finally, there is some evidence for a third west-dipping rotational normal fault below the orebodies, as both the orebodies and the Cloudburst detachment seem to have been rotated eastward. The timing of this movement with respect to other middle Tertiary structural movements is not clear.

Camp Grant-Putnam Washes

Low-Angle Normal Faults. The middle Tertiary sandstones and fanglomerates of the San Manuel Formation in the Camp Grant-Putnam Wash
area have been rotated eastward along a west-southwest dipping imbric­cate normal fault system, similar to the San Manuel Formation in the Southern Black Hills. The faults sole into or stop at the basal Camp Grant Fault, which dips 20° SW and displays fracture cleavage indicative of normal movement.

Krieger (1974a,c) attributed the dip of sediments in this area to gravity sliding and antithetic eastward rotation along the Camp Grant Fault. She felt that this rotation was a true "thin-skinned" process and her cross-sections show that faulting is limited to the interface between fanglomerate and granite and that it did not involve movement of granite across granite. In the Tortilla Mountains, fifteen miles northwest of Putnam Wash, Krieger (1974a) interpreted the steep easterly tilt to the development of a Miocene monoclinal fold in the basement rocks. The monoclines, more properly termed homoclines because they lack flat "upper" limbs, consist of steep east-dipping upper Precambrian sediments and 1.4 b.y. granites. The lowermost Miocene fanglomerates are in high-angle fault contact with steeply tilted Precambrian rocks, according to Krieger (1974b) and Cornwall and Krieger (1975). Schmidt (1971) also mapped this area in detail and felt that this contact was depositional and only locally faulted. Krieger, Cornwall and Schmidt all noted a "fanning" in the dips of Miocene fanglomerates, which indicate Miocene penecontemporaneous deformation. Although Krieger (1974c) does not detail the kinematics of rotation in the Putnam Wash area, presumably her interpretation would be similar to that given for the Tortilla Mountains (Krieger 1974a).
The geology of the Camp Grant–Putnam Wash area is similar to that of the Mammoth quadrangle. In both areas, early Miocene tilted fanglomerates are depositional on granite in the west and separated by a low-angle normal fault in the east. Because the San Manuel fault has been demonstrated to offset basement rocks, I would assert that a similar basement-involved low-angle normal fault mechanism operated on the rocks of the Camp Grant–Putnam Wash area, and that a low-angle normal fault passes beneath basement rocks on the west side of the Putnam Wash Quadrangle. In other words, if the sediments are tilted in response to low-angle normal fault movement and if tilted sediments are depositional on basement rocks, then the basement rocks must have been involved in the rotational faulting event.

The gravity surveys in Putnam Wash indicated that a large buried bedrock high probably exists in the center of the traverse. To explain this bedrock high, two geologic possibilities are apparent: either two low-angle faults exist, or one exists which has been subsequently upwarped along the Cowhead Well fault. The first possibility is favored because mid-Tertiary tilted fanglomerate is in depositional contact with basement rock in several areas in the southwestern part of the Winkleman quadrangle and northwestern part of the Putnam Wash Quadrangle (Points 1 and 2, Fig. 34). This hypothesis is objectionable because no low-angle fault surface was found from the south end of Krieger’s Camp Grant fault(?) (Point 3, Fig. 34). Downfaulting along the Cowhead Well fault could conceivably obscure the trace further to the south. This objection would be alleviated if the western fault
ceased movement before the eastern fault did. This might cause the central bedrock block to subside with a deposition contact above it (Fig. 68). In the area near the top of the bedrock high where some unconformities might be expected in NWk, sec. 10, T.1S., R.15E. (Krieger 1974c,d) has mapped some lenticular units in the San Manuel Formation, which may support this concept. Alternatively, the system could be viewed as a high-angle fault system that has been rotated antithetically by a deeper rotational fault (Fig. 69). In either case, the movement of the eastern fault is younger than the western fault.

Some additional evidence, albeit tenuous, for a deeper rotational fault exists also. The Younger Precambrian sediments at the mouth of Putnam Wash dip steeply (40°-60°) in a direction similar to the San Manuel beds further upstream. Some of the formations in this packet, such as the Dripping Springs Quartzite and the Pioneer Shale, seem strongly rotated in comparison to their counterparts across strike in the Galiuros (45° Putnam vs. 15° Galiuros). Others, such as the Martin Formation dip approximately the same in both localities. Schmidt (1971, p. 227) first noted that the eastward tilt of these pre-Cenozoic rocks in Putnam Wash may be a part of general eastward tilt on the west side of the San Pedro River Valley. Furthermore, if the San Manuel orebody is underlain by a rotational detachment surface, the entire Black Hills block may be underlain by a rotational detachment. In the absence of known mid-Tertiary tilted sediments in the San Pedro River Valley to the east, this conclusion must be regarded as tenuous.
Fig. 68. Hypothetical Development of a Depositional Contact Above the Western Low Angle Normal Fault in the Putnam Wash Area. Sequence of events: a) development of two faults; b) rotation on eastern fault; c) infilling of sediments; and d) erosional denudation.
Fig. 69. Alternate Mode of Development of a Bedrock High by Rotation Along a Deeper Rotational Fault. Sequence: a) development of graben and associated fanglomerates; b) rotation and denudation of the graben.
It is tempting to correlate the western fault (the "Camp Grant fault(?)" of Krieger, 1974c,d) with the San Manuel fault. Both have similar displacements (roughly three miles, western fault, vs. two miles, San Manuel fault) and similar trends (Fig. 34) and they exist on opposite sides of the Cowhead Well fault. Furthermore, inception of movement began on both at roughly the same time. Weibel (1981) dated a rhyolite tuff at the top of the Cloudburst Formation at $22.5 \pm 0.5$ my and also dated the basal basalt flow of the San Manuel Formation at $22.1 \pm 0.5$.

If this correlation is correct, the Camp Grant fault is the eastern fault. It begins one mile south of Camp Grant Wash, trends northeast for three miles to Putnam Wash, is offset one mile west in Putnam Wash along a tear fault and continues north for $2\frac{1}{2}$ miles until it is buried under recent basin fill material. It is responsible for the steeply tilted east facing homocline consisting of diabase, Pioneer Shale and Dripping Springs Quartzite that trends north-northwest through the Winkleman Quadrangle, and for the San Manuel Formation, which dips east at $25^\circ$.

The rotation implicit in the dips of the San Manuel Formation here cannot account for the discrepancy of dips between the Dripping Springs Formation in the homocline and similar rocks across the San Pedro River Valley. The homocline dips roughly $60^\circ$ NE and the Dripping Springs across the valley dips roughly $13^\circ$ NE, while the San Manuel
dips about 28°. Hence, about 20° of tilt must be accounted for—
either by rotational faulting or some other structural event.

**Kinematics of Upper Plate Rocks.** Although the kinematic relations
between bedding, minor faults and the basal detachment in the Camp
Grant Wash study area are not as evident as those of the San Manuel area
to the south, there are certain similarities. Bedding dips northeast­
ward and is antithetic to the majority of faults observed in the fanglo­
merates. The strike of the maximums of pi diagrams to bedding and fault
planes are similar, but not parallel (Figs. 44 and 45). Generally, the
faults dip steeper than the Camp Grant fault, and no faults within the
fanglomerates were observed to cut the Camp Grant Fault.

Contrary to the apparent dip slip relations between the San Manuel
fault and the San Manuel Formation, the Camp Grant fault appears to cut
obliquely across the strike of bedding, in the detailed study area.
This suggests that the motion on the Camp Grant fault was some combina­
tion of dip slip and tear movements. This movement does not appear to
be reflected in the dips of bedding adjacent to the fault, however
(Fig. 31) and this may be because the cross-bedded nature of the sand­
stones in the area obscures evidence for tear fault movement.

Presently, two theories have been suggested to explain the kinematics
of rotation of fanglomerate beds such as these. The foremost theory is
that tilt occurred by rigid body antithetic rotation by normal slip along
curviplanar concave up (listric) faults, which sole into the basal detach­
ment. The other hypothesis holds that the tilt may have occurred as the
fanglomerates slipped normally along a basal discontinuity with concomitant dislocation along normal faults that end at the basal discontinuity, similar to tilt of books on a bookshelf.

Generally, the faults were observed to be planar in cross-section, and the some faults were observed to end at the Camp Grant Fault (Fig. 33). Many of the faults approach the basal discontinuity at a very shallow dip, however, and because the faults are never exposed for more than 100 feet, the fault segments observed may only be small parts of broad curviplanar surfaces. A hint of upward concavity can be seen in the left low-angle fault of Figure 33. Finally, the depth-to-bedrock profiles generated during the gravity surveys indicate that the basal detachment surfaces (that is, the right sides of the two basins shown in Figure 53) may also be concave upward.

Various kinds of drag features were usually observed adjacent to the low-angle faults. These features include fabrics consisting of oriented cobbles up to several feet thick, fault drag structures and horses which have been "plated" against faults. Because the faults are often observed to be planar, some of the strain involved in rotation against these flat surfaces may be taken up by rotation of cobbles within the matrix and creation of drag structures adjacent to the normal faults in these fairly plastic fanglomerates.

Summary. The middle Tertiary fanglomerates and sandstones of the Camp Grant-Putnam Wash area have been rotated to 20° to 30° eastward dips along a low-angle, west-dipping imbricate normal fault system.
The faults in this system may be listric and some of the rotational strain may have been accommodated by the development of oriented cobble zones and drag features adjacent to the faults. The faults do not appear to extend below the Camp Grant fault. Cleavage within the Camp Grant fault zone shows evidence of repeated normal movement and offset. This detachment may actually be two low-angle normal faults, based on a gravity profile to determine depth to bedrock and an analysis of geologic mapping of area done by Krieger (1947c). The westernmost detachment dips roughly 10° west, is listric, and is tenuously correlated with the San Manuel fault. The eastern discontinuity, the Camp Grant fault, dips 10° to 14° west, is also listric and may be younger than the western discontinuity, based upon the depositional contacts observed in the San Manuel Formation in the vicinity of where the trace of the western fault should be.

**Late Tertiary Kinematics**

The late Tertiary high-angle faults block out the ranges and basins and give the area its final structural style.

On the eastern side of the range, the faults are largely covered by late Tertiary-Quaternary alluvial fans. In the southeastern part of the Mammoth Quadrangle, the largest high-angle fault is known as the Mammoth fault and it strikes N40W and dips 50° to 75° northeast. According to Creasey (1965) the movement on the Mammoth fault was dominantly dip slip, east side downthrown, with displacement 40 to 200 feet. A number of faults parallel the Mammoth fault and an en echelon buried fault or set of faults further northeast of the Mammoth fault
probably bounds the northeast side of the Black Hills. The San Pedro River Valley is fairly shallow in this area, less than 800', as shown on the depth-to-bedrock maps of Oppenheimer and Sumner (1980).

The west-dipping Cowhead Well fault is the western and southwestern range front fault of the Black Hills. It extends from the southern Black Hills north to Putnam Wash (Fig. 34). Two miles north of Putnam Wash, on the same trend, Krieger (1974c,d) has mapped another high-angle normal fault, which dips east.

A number of folds are associated with the Cowhead Well fault. These are generally broad upright folds and their proximity to the fault suggests that they probably resulted from movement along the fault. The trend of the anticline-syncline pair in the southwest flank of the Black Hills in the Cloudburst Formation is parallel to the fault, and suggests that the folds resulted from simple drag along the fault. The existence of an antiform, as expressed by the trace of the San Manuel fault, may indicate that some actual uplift of the Black Hills block has occurred, rather than mere down faulting of the Camp Grant basin.

Along the southwest flank of the Black Hills, movement along the Cowhead Well fault is expressed in the San Manuel Formation in four folds. A fault drag syncline is evident from exposures in the northernmost part of the Oracle Quadrangle and from exposures in Tucson Wash about one mile southwest of the fault. Near Tucson Wash, the syncline trends east and eventually intersects the Cowhead Well fault and 1 3/4 miles to the east (Fig. 34). Two other anticlines in the southwest flank of
the Black Hills trend obliquely to the fault. These anticlines occur at location of changes in strike of the Cowhead Well fault and may reflect dip slip movement on two adjoining obliquely oriented segment of the faults.

A number of folds associated with the Cowhead Well fault occur in the Putnam Wash area where Krieger (1974c) indicates the fault dies. I view this area as an area of inflection between the Cowhead Well fault and the unnamed east dipping normal fault on trend to the north. Physiographically, this area may be separated into four quadrants. The boundaries of these quadrants are the Cowhead Well-unnamed fault trend and a line roughly normal to this through the point where the Cowhead Well fault dies. The rocks of the northwest and southeast quadrants consist dominantly of pre-late Tertiary basement rocks, whereas the rocks of the northeast and southwest quadrants contain more late Tertiary-Quaternary basin fill material. In the area of inflection, the dominant structures are: synclines (N7E trend) in the northeast and southwest quadrants and anticlines (N20W trend) in the northwest and southeast quadrants. This configuration of folds might be expected due to drag from movements along the faults north and south. A simplified block diagram illustrating this concept is shown in Figure 70. In this way, the Cowhead Well and unnamed fault are viewed as segments of a large scissor fault, with its inflection in the Putnam Wash area, which relatively uplifts the Black Hills and Tortilla Mountains and imparts the final structural appearance to this area.
Fig. 70. Simplified Block Diagram of Late Tertiary Faults and Folds in the Putnam-Camp Grant Wash Area.
CHAPTER 7

MIDDLE-LATE TERTIARY DEVELOPMENTAL MODEL OF THE BLACK HILLS

The purpose of this section is to suggest a conceptual model for the development of middle-late Tertiary structural and stratigraphic features of the Black Hills, which integrates the mapping and observations of Heindl (1963), Creasey (1967), Krieger (1974), Weibel (1981) and this study. The model is based on a palinspastic reconstruction of cross-sections A-A' and B-B', Figure 17. The diagrams proceed from middle Tertiary time (approximately 25 m.y. ago) to the present, but are keyed to structural events, rather than a sequential time sequence. Some of the events, such as rotation and deposition probably proceeded simultaneously, but these are presented separately to aid in conceptualization.

The following assumptions were made in this model:

1) The Cloudburst detachment and San Manuel fault are low-angle normal faults.

2) The Cloudburst detachment originally dipped 35° west and has been rotated to its present attitude along a rotational fault to the east.

3) The San Manuel fault displacement is 8,000' downdip.

4) The original dip of sediments was zero.

5) The San Manuel Formation is limited to the hanging wall of the San Manuel fault.

In addition, there are the following unknowns in the model.

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1) The location and number of rotational (listric?) faults that sole into the Cloudburst and San Manuel faults is unknown.

2) The displacement of the Cowhead Well fault is unknown. Simple projection of the base of the San Manuel Formation on either side of the fault, into the fault in the southern Black Hills indicates that it may be about 6,000 feet.

An explanation of each diagram follows.

Figure 71a. Deposition of the lower Cloudburst in a half-graben. The half-graben is suggested by the easterly dip of the Cloudburst and the nearly level dip of the Cloudburst detachment.

Figure 71b. Deposition of the upper Cloudburst fanglomerates and rotation of the lower Cloudburst volcanics. The rotation of the lower member with respect to the upper member is suggested by a difference in the average dips between the two (Fig. 67).

The formation of the extensive granitic megabreccia deposits of the upper Cloudburst Formation, above the Cloudburst detachment, occurred during this time. This may have resulted from oversteeping of the hanging wall block during rotation and subsequent landsliding, as Schmidt (1971) has proposed for the megabreccias of the Tortilla Mountains.

Weibel (1981) determined that source rocks in the upper Cloudburst were dominantly granitic with lesser amounts of volcanics, and that paleocurrents during deposition were directed easterly.

Figure 71c. Faulting of the upper plate. The best correlation marker between the Cloudburst Formation above the Cloudburst detachment and that above the San Manuel fault seems to be the change from volcanics of the lower section to fanglomerates of upper section. When this break
is projected to the San Manuel fault in both areas, the displacement is greater than 8,000 feet. Rather than increase the displacement of this fault, one large listric normal fault was added instead. In reality, many such faults of lesser magnitude probably displace the Cloudburst Formation and account for this discrepancy.

Figure 71d. Rotation of the system. This is necessary to rotate the Cloudburst detachment to an easterly dip. A stage of rotation was chosen here because there is a difference in average dips between the San Manuel and Cloudburst Formations. This tilt is presumed to have been accomplished by a deeper rotational fault which shoals to the east. If the Cloudburst detachment were listric, further tilting of the upper plate rocks and shallowing of the detachment may have been accomplished by rotation of the strata downward along the fault, but this probably would have created a distinct angular unconformity between the Cloudburst and San Manuel Formations, and is contrary to what Weibel (1981) observed.

Figure 71e. Movement of the San Manuel fault. The lower member of the San Manuel Formation (Kannally) has roughly the same clast constituency as the upper Cloudburst (Weibel 1981), and paleocurrents are in a similar direction (this study). Weibel (1981) suggested that movement along the San Manuel fault was accomplished during deposition of the upper member (Tucson Wash) of the San Manuel Formation. At least some of this detritus must have come from the footwall of the San Manuel Fault, as southwest directed paleocurrents were measured along the Highway 77 roadcuts adjacent to the trace of the San Manuel Fault. Movement on the Camp Grant fault also probably occurred at about this time (Fig. 72a).
Figures 71f and 72b. Tilting. This tilting brings the San Manuel Formation to an average dip of 20° east and brings the Cloudburst detachment to its present attitude. Erosion occurred from the late Miocene to early Pliocene.

The flat dip of the San Manuel and Camp Grant faults may represent the deeper levels of listric faults or this dip may have been achieved by rotation backward along deeper rotational faults. The latter concept is preferred, because the dips of bedding of the San Manuel Formation in this area are fairly shallow, (average about 25°), and I would expect the bedding dips to be much steeper if these shallow faults represent the deeper levels of listric faults.

Figures 71g and 71h. Development of high-angle faults and erosion to present topography. This basin forming event created the Quiburis Formation. The displacement on the Cowhead Well fault (about 10,000 ft in the location of this cross-section) seems large. This displacement can be reduced somewhat if any of the wedge shaped rock units of the Cloudburst or San Manuel Formations are thinner in the west than depicted, or if a distinct angular unconformity between San Manuel Formation and Cloudburst Formations exists (thus thinning the section and reducing the possible displacement of the Cowhead Well fault) perhaps beneath more recent sediments in Camp Grant Wash. This would thin the section and reduce the displacement of the Cowhead Well fault. Another possibility is that another low-angle fault may have denuded the section previous to San Manuel deposition.

Perhaps the most striking feature of this model is the tremendous thicknesses of mid-Tertiary volcanics and sediments deposited in the
Fig. 71. Conceptual Sequence of Events in the Structural Development of the Southern Black Hills, Mid-Tertiary to Present.
Fig. 71 (cont'd)
Fig. 72. Conceptual Sequence of Events in the Structural Development of the Camp Grant—Putnam Wash Area, Mid-Tertiary to Present.
half-grabens. The exposed outcrop width of the Cloudburst Formation is about 13,600 feet. Assuming an average dip of 35°, the thickness of the Cloudburst is 7,800 feet. This thickness is probably an apparent thickness, which is thicker than actual due to successive normal faulting and repetition of section.

Weibel (1981) suggested that the Cloudburst Formation is time equivalent to the Galiuro Volcanics. Furthermore, he suggested that the tuff at the top of the Cloudburst Formation (date 22.5 ± 0.5 m.y.) may be the same as the Hell's Half Acre tuff (dated by Creasey and Krieger, 1978, at 22.5 ± m.y.). As far as can be ascertained, no measured section through the Galiuro Volcanics has been published. From mapping done by Krieger (1968) in the Holy Joe Peak Quadrangle, 15 miles northeast of the Black Hills, however, the thickness of the Galiuro Volcanics from their base to the Apsey conglomerate, which is the unit overlying the Hell's Half Acre tuff, is 700-800 feet (see Krieger, 1968, cross-section B-B', through the Table Mountain Area). If the Cloudburst Formation has been apparently thickened by twice its original amount, it is still nearly five times thicker than the same time-equivalent section in the Galiuros. This indicates to me that the Cloudburst Formation accumulated in a subsiding basin located to the west of the present Galiuro Mountains.

In the Rincon Mountains to the south, Lingrey (1982) has proposed that middle Tertiary sediments and volcanics accumulated in half-graben basins formed as brittle responses to a ductile shear zone at depth.
This shear zone dipped shallowly southwest and the tectonic transport direction of the upper plate was to the southwest. The culmination of this shear zone was to the west of the present crest of the Galiuros, and the deeper manifestations of this shear zone produced the foliated and lineated gneisses of the Santa Catalina-Rincon-Tortolita metamorphic core complex.

Although metamorphic carapace rocks or extensive areas of distinctly lineated and foliated gneisses were not observed in the Black Hills, the timing of deposition and the kinematics of translation and rotation agree well with scheme of tectonic evolution proposed by Lingrey for the Rincons. Accumulation and rotation of Cloudburst and San Manuel volcanics and sediments occurred from about 29 to about 18 m.y.a. This is similar to Lingrey's phase II deformational period (26-17 m.y.a.), in which unmetamorphosed allochthonous rocks, including the Oligocene-Early Miocene Mineta Formation, were emplaced over previously deformed metamorphic rock. The translation directions of middle Tertiary rocks in the Black Hills and in the Rincons are also similar. In the Rincons the translation direction of the basal detachment fault was southwest. In the Black Hills, the translation direction of the San Manuel fault was S55W (Lowell, 1968) and that of the allochthon in the lower Cloudburst was S48W. The maximum value of a stereonet plot of striations measured in the San Manuel along the roadcuts was S37W, and if dip of beds above the Camp Grant and Cloudburst detachments is indicative of the sense of translation along the detachment, as the dip of the San Manuel Formation above the San Manuel Fault appears to be, then the translation of these detachments is also to the southwest.
The San Manuel fault, Camp Grant fault and the Cloudburst detachment are part of a system of low-angle normal faults, which extend from the Black Hills north-northwest through the Tortilla Mountains. This system was first mapped and recognized by Krieger (1974a). These faults dip shallowly west, and middle Tertiary strata are rotated to easterly dips above them. Unlike the Rincon Mountains however, foliated and lineated gneisses are not immediately adjacent. Foliated and lineated gneisses are present, however, roughly twenty miles to the southwest, along the slip line direction of the San Manuel Fault. There, within the metamorphic core complexes of the Tortolita Mountains, Pichacho Mountains and Durham Hills, lineations interpreted to be the direction of extension (Davis 1980) are very similar to the slip line direction of the Black Hills low-angle normal faults.

Schmidt (1971, p. 229-230) recognized the mirror symmetry of tilted rock formations on either side of the Dripping Springs Mountains to the northeast of the Black Hills. Precambrian and middle Tertiary formations tilt northeastward in the Tortillas, whereas Tertiary through Precambrian rocks tilt southwestward in the Mescal and Pinal Mountains. He states,

These four mountain ranges then appear to be part of or involved in a large-scale uplift-collapse structure that centers around the Dripping Spring-Galiuro mountain chain. The Tortilla Mountain block forms the western portion and the Mescal-Pinal Mountain block the eastern portion of this structure. It is inconceivable, however, that one is dealing here with a simple dome which stretches from the Tortilla Mountains in the west to the Pinal Mountains in the east. It is much more likely that the Tortilla Mountain block tilted independently of but simultaneously with and opposite to the Pinal Mountain block and that the centrally located Dripping Spring Mountains experienced intimate block faulting with several thousand feet vertical displacement but virtually no rotation. The observed features clearly developed in a tensional stress field characterized by east-northeast to west-southwest directed distention.
Indeed, near San Carlos Reservoir to the northeast of the Dripping Springs Mountains, Wilden (1964) shows cross sections which depict several low-angle detachment surfaces which place younger rock on older rock, and which involve large thicknesses of southwest tilted Tertiary volcanics and conglomerate in the upper plate.

Later, Davis and Hardy (1981), working independently of Schmidt, noted that the slip line directions of detached middle Tertiary continental and volcanic rocks were very similar to lineations developed in adjacent metamorphic core complexes on both sides of the Galiuros, but that the sense of rotation of the Tertiary strata on either side of the Galiuros was opposite. They suggested that Rincon-Galiuro-Pinaléño block could be envisioned as a megaboudin bounded by ductile shear zones on the southwest and northeastern sides of the Galiuros. Perhaps, if Schmidt's interpretation is correct, this megaboudin extends further to the northwest, and this system of west-dipping low-angle normal faults, of which the Black Hills detachments are a part, represent the shallower manifestations of the west flank of this megaboudin and of the middle Tertiary metamorphic core complexes to the southwest.
APPENDIX A

ITMODX VARIATIONS TO THE PUTNAM WASH GRAVITY SURVEY
1. ITMOD Run - Depth to Bedrock Calculated on the Basis on Variable Density Contrasts for each Prism.
2. **ITMODX Run** - Depth to Bedrock Calculated on the Basis of a Density Contrast of -0.20 for all Prisms.
3. **ITMODX Run - Depth to Bedrock Calculated on the Basis of a Density Contrast of -0.30 for all Prisms.**
4. ITMODX Run - Depth to Bedrock Calculated on the Basis of a Density Contrast of -0.35 for all Prisms.
5. ITMODX Run - Depth to Bedrock Calculated on the Basis of a Density Contrast of -0.20 for Center Prisms and -0.30 for all Other Prisms.
6. ITMODX Run – Depth to Bedrock Calculated on the Basis of a Density Contrast of -0.60 for Center Prisms and -0.30 for all Other Prisms.
REFERENCES


5 maps
Figure 3

R.15 E. R.16E.

GEOLOGIC MAP OF THE SOUTHWEST FLANK OF THE BLACK HILLS PINAL COUNTY, ARIZONA

EXPLANATION OF MAP SYMBOLS

- Alluvium
- Colluvium
- Alluvial fan deposits
- Unconsolidated basin fill gravels
- Unconformity
- Son Manuel Formation - alluvial sandstones and fanglomerates
- Cloudburst Formation - fanglomerate
- Light phase andesite
- Dark phase andesite
- Granitic monolithological sedimentary breccia
- Latite (?)
- Welded tuff
- Andesitic lapil deposit
- Andesite
- Unconformity
- Diabase dikes
- Aplite, pegmatite dike or quartz vein
- Ruin Granite
- Oracle Quartz Monzonite

- Holocene
- Plio-Pleistocene
- Quaternary
- Oligocene
- Tertiary
- Paleogene
- Mesozoic
- Cenozoic
- Paleozoic
- Precambrian

- Low angle normal fault
- Strike and dip of bedding
- Strike and dip of formation of the Cowhead Well Fault
- Strike and dip of formation of a Grandeur Fault
- Lateral and vertical exaggerations

SAN MANUEL FAULT

CAMP GRANT FAULT

COWHEAD WELL FAULT

SAN MANUEL FAULT

CLOUDBURST DETACHMENT
GEOLOGIC MAP OF THE LOWER PART OF CAMP GRANT WASH

Geology by J. B. Hansen, June, 1981 M.S. Thesis, Dept. of Geosciences, University of Arizona
GEOLOGIC STRUCTURES IN THE BLACK HILLS, PINAL COUNTY, ARIZONA

Explanation

- Fault, showing dip. Bar and ball on downthrown side.
- Thrust fault: teeth on upper plate.
- Low-angle normal fault, showing dip. Hachures on upper plate.
- Anticline, showing plunge.
- Syncline, showing plunge.

Sources of information used in this compilation

Krieger, 1974a
Krieger, 1974b
Krieger, 1969b
Creasey, 1965

Compilation by J. Hansen, 1982
MS Thesis, Dept. of Geosciences, University of Arizona
DETAILED GEOLOGIC PROFILES OF THE HIGHWAY 77 ROADCUTS

**East**

**Lowermost Roadcut**
- Gray phyllonite; F-N15W 60E; S-55W, S35W
- 0.5' normal offset; F-N30W 75E; S-40W, S45E
- Minimum offset; foliations parallel to fault developed in fanglomerate
- At least 2' minimum offset; note foliations parallel to fault
- Reverse fault (370'; F/N53VV 32W) with 20' offset
- Cleavage in phyllonite indicates normal fault
- 1' normal offset; F-N48W 78E
- 1.5' normal offset; F-N20W 85E
- 3' normal offset
- Fault is very oblique to profile; best guess on offset is 7' normal
to the fault are distinctly oriented parallel to the fault estimated minimum offset is the length of the fault; F-N52W 47W; S-30W, S39W
- Offset across this fault and phyllonite to the east is 26
- 5' offset; no orientation; normal fault drag
- 0.5' offset; no orientation

**Middle Roadcut**
- White phyllonite 26 minimum normal offset; F-N16W 37W; S-32W, S35W
- Pebbles and cobbles are vaguely parallel to the fault
- 12' normal offset; no orientation
- 25' normal offset; F-N70W 43W; S-43W, S37W
- 1' normal offset; F-N45W 85E
- Horizontal line
- 1.5' normal offset; F-N50W 58W; S-57W, S38W

**Uppermost Roadcut**
- 450' (apparent thickness)
- 335' (measured thickness) = 1.34
- 570' - 523' = 9.0%
- 1.5' reverse offset
- 1/2' white phyllonite
- 26 minimum normal offset; F-N16W 37W; S-32W, S35W
- Pebbles and cobbles are vaguely parallel to the fault
- 12 normal offset; no orientation
- 25 normal offset; F-N70W 43W; S-43W, S37W
- 1 normal offset; F-N45W 85E

**West**

**Lowermost Roadcut**
- Gray phyllonite; F-N15W 60E; S-55W, S35W
- 0.5' normal offset; F-N30W 75E; S-40W, S45E
- Minimum offset; foliations parallel to fault developed in fanglomerate
- At least 2' minimum offset; note foliations parallel to fault
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- 1 normal offset; F-N45W 85E

**INDEX MAP**
- R. 16 E. to San Manuel mine to Mammoth to Son Manuel

**EXPLANATION**
- Conspicuous plant
- F-N25W 55W (orientation of fault)
- S-52W, S40W (orientation of striations)
- B-N41W 35E (orientation of bedding)
- Key bed used to assess offset on faults
- Base of roadcut

**NET APPARENT THICKENING AND EXTENSION, ALL ROADCUTS**
- East 1.25 (apparent thickness)
- West 1.18 (measured thickness)
- Minimum horizontal extension = 1722 - 1469 = 17.2%

Geology by J. B. Hansen
JULY 1981
M.S. Thesis, Dept. of Geosciences
University of Arizona

Scale 1:20