AGS FIELD TRIP

SPRING 1984

[Tertiary tectonics of the San Manuel - Kearny
region, central Arizona: April 13-15, 1984
Stanley B. Keith]

DAY 1

INTRODUCTION

by
Stanley B. Keith

This AGS field trip is designed to be a kind of a companion trip to the 1983 Spring AGS Field Trip. The 1983 Spring trip looked at evidence for Laramide orogeny in the Tucson region emphasizing the relationship between low angle thrusts that moved in various directions and various generations of plutons, the entire scenario being part of a progressive sequence of Laramide compressive deformation. The 1984 Spring trip looks at the next younger part of the geologic record, the middle Tertiary. Whereas most workers agree that the Laramide was a time of compressive deformation of major dimension, many of those same workers agree that the middle Tertiary was a time of extensionally produced deformation. The most spectacular structural manifestation of mid-Tertiary deformation is of course the detachment faults which are widespread and many of which will be visited within the next two days. I am of the opinion however that the tectonic story for the mid-Tertiary deformation is not necessarily one of extension and one of the goals of this field trip will be to point out evidence for other kinds of middle Tertiary tectonics such as folding, strike slip faulting, reverse faulting, and, in particular, reverse drag on many of the mid Tertiary detachment structures. Consequently, my emphasis on the field trip will be to look at and interpret the middle Tertiary rock sequences and associated structures through a compressive tectonic model, although I admit that evidence for extension does exist. On the other hand Steve Naruk will undoubtedly interpret many of the structures that we'll see in the Kearny area on the second day as evidence of extensional deformation whereas I will interpret those same structures as evidence of compressive deformation. If nothing else, the participants on the field trip should have an entertaining time.

The first day will be led by myself and we will visit classical middle Tertiary geology that has a long history of description by numerous workers in the area of the San Manuel porphyry copper system of Laramide age. The first stop on the first day will begin at the base of the middle Tertiary sequence of rocks which depositionally rests on the 1400 b.y. Oracle Granite. The base of the middle Tertiary section consists of a volcaniclastic fluvial sedimentary sequence overlain by a thick pile of volcanics which interfingers upwards into a 10,000 foot thick sequence of fanglomerates and coarse clastics with occasional beds of arenite and tuff. As we will see later in the day, this sequence is overlain by the younger San Manuel formation which is also a thick, dominantly conglomeratic, package of middle Tertiary rocks that is also at least 10,000 feet thick. The middle Tertiary stratigraphic sequence that will be seen is involved in various ways with different kinds of structures that developed during the depositional history of each sequence and also after the deposition of each sequence ceased. The second and third stops will examine the parts of the section where the first stop leaves off. We'll also get a good look at the San Manuel fault that has had a history of different structural interpretations. One interpretation, detachment led to the discovery of the fault offset portion of the San Manuel porphyry copper system.

The second days trio will examine two more detachment faults similar to the San Manuel fault. One will be at Camp Grant Wash where participants will see an excellent exposure of the Camp Grant Wash detachment fault and will review evidence not only for the obvious normal juxtapostion of upper plate over lower plate rock units but evidence in the Oracle Granite of joint systems that have been folded over in a reverse drag sense within the structure suggesting reverse movement on the fault that perhaps predates the obvious normal movement. In the central Tortillas another detachment fault structure named the Smith Wash fault by Kreiger (1974) will be examined. The Smith Wash fault also has obvious evidence of normal movement and normal juxtaposition of upper plate Tertiary tilted conglomerates over lower Apache Group but participants will also see that lower plate Apache Group rocks have been folded in a reverse drag sense immediately beneath the Smith Wash fault. Thus again phenomena at this locality suggests an earlier reverse drag history on what many observers regard as a straight forward detachment fault.

The main part of the second day is a visit to tilted sequences of middle Tertiary mud flows and fluvial conglomerate assemblages in the Hackberry Wash area west of Kearny, AZ. In this area Medora Kreiger led an AGS field trip in about 1972 to the spectacular occurrences of megabreccia that are interleaved with the tilted middle Tertiary clastic sequences. In addition to the megabreccias, the basal contact of the middle Tertiary section with Apache Group and lower Paleozoic rocks will be examined with an eye to determining whether this contact is depositional or a fault. The Tertiary structural interpretation of the Tortilla Mountains is strongly constrained by the nature of this contact.

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ROAD LOG

Day 1 - by Stanley B. Keith

Begin road log at milepost 79 which is also the 1st Avenue (Tangerine Road)/Oracle Highway intersection.

Milepost 79

As we proceed up the highway for the next several miles an excellent view of the Pusch Ridge portion of the Santa Catalina Mountains may be seen. The cliffs in Pusch Ridge are comprised of various leucocratic sills of the Eocene peraluminous Wilderness granite complex. The large ridge capping cliffs are portions of what have been described by Keith and others (1980), as the main range sill of the Wilderness granite. As we drive northward several spectacular spires of 2 mica granite within the main range sill complex can be observed. The sill will thicken northward and then begin to roll over into a northward dip until we will be able to see the roots of the main range sill in the Cargadera Canyon area. Below the main range sill are several thinner layers of light colored material which are lower sills in the Wilderness granite sill complex. The intervening dark layers are mostly 1.4 billion year old deformed megacrystic granites within the forerange gniess complex, that have been lit par lit injected by light layers of the Wilderness sill complex. Lesser components of the darker layers are the 1.65 billion year old Madera granodiorite gneiss and recrystallized 1.7 billion year old Pinal schist.

Milepost 81.4 - Bridge over Canada del Oro wash

After crossing the bridge the road will ascend up on to the higher terrace levels of the late Tertiary valley fill sequence.

Milepost 82.6

The Tortolita Mountains are in view from the 9:00 to 11:00 position.

Milepost 83

An excellent view of the western portion of the Santa Catalina Mountains from the 1:00 to 6:00 position. At the 2:30 position we can see the upper Romero Canyon drainage. Here, the thicker portions of the main range sill complex occupy almost all of Romero Canyon and continue onto Cathedral Peak at the 2:45 position. Layering within the sill complex is flat at Cathedral Peak but north of Romero Canyon it begins to dip moderately steeply to the north.

Milepost 84

A good view of the Cargadera Canyon drainage. The steep dipping layers of cliff formers of the Wilderness granite sill complex abruptly end along a contact marked by the break in slope below the ridge. This slope break marks the approximate position of an intrusive contact described by Keith and others (1980), between the peraluminous 2 mica-bearing Wilderness granite complex of middle Eocene (44-51 m.y.) age and the mid-Tertiary (26 m.y.) Catalina quartz monzonite pluton of the Catalina intrusive suite defined by Keith and others (1980). Intrusion of the Catalina Suite marks the final consolidation of the so-called batholith complex which occupies 75% of the crystalline core of the Santa Catalina/

Rincon/Tortolita "metamorphic core complex" beneath the regional Santa Catalina low-angle fault zone. The Catalina quartz monzonite member of the Catalina Suite make up all of the outcrops north of Cargadera Canyon along Samaniego Ridge which is at the 1:00 to 3:00 position.

Of regional interest is the fact that the Catalina quartz monzonite pluton and the Catalina batholitic suite in general are the same age as the sediments and volcanics that we will be viewing in today's main field trip stops. It is significant that the final uplift, consolidation and deformation in the crystalline core complex in the Santa Catalina/Rincon /Tortolita "metamorphic core complex", occurred at the same time as the deposition of several thousands of feet of sediment and volcanics north of the complex.

Milepost 86

We enter the outskirts of the rapidly enlarging town of Catalina. The Tortolita Mountains west of Catalina are in good view from the 8:00 to 11:00 position. The prominent white scar in view in the eastern Tortolita Mountains is a marble quarry which is developed in metamorphosed roof pendants of Permian Concha limestone within a large northeast trending dike-like mass of Catalina quartz monzonite. North of the quarry are older rocks including Laramide (71 m.y., Rb/Sr), Chireon Wash granodiorite and many light colored 2 mica aplopegmatite dikes, apophyses of the Darrio Canyon 2 mica granite complex which is probably Eocene in age. Both of these plutonic suites are intruded to the south of the marble mine by 26 million year old Catalina suite plutons. The mine and surrounding rocks lie within the crystalline core of the Tortolita metamorphic plutonic complex or "metamorphic core" complex.

Milepost 90.5 - Oracle Junction. Veer right onto Highway 77 branch bearing northeast for Oracle.

Milepost 92

The northern Santa Catalina Mountains are at 1:00 to 3:00. The large conical hill at the 2:30 position marks the north end of the Rice Peak Ridge. Note a v-shaped notch just south of the conical hill. This marks the trace of the Mogul fault which trends west-northwest through the notch and continues westward under the alluvium just north of our position. The Mogul fault is the main structural boundary of the north end of the Santa Catalina metamorphic core complex. The fault trends west-northwest, dips steeply south and juxtaposes 1.42 billion year old Oracle Granite to the north against Apache Group and Oracle Granite with some Paleozoic to the south. The current position of rocks on either side of the fault indicates normal movement, with Paleozoic and Apache Group downthrown to the south against Oracle Granite to the north.

However, intriguing new structural developments that resulted from the recent Phillips-Anschutz test hole 30 miles to the northwest in the northern Picacho Mountains suggest the Mogul fault could have major reverse movement of middle-Tertiary age. The Anschutz-Phillips hole was collared north of the west-northwest trending North Star fault which is structurally similar to the Mogul fault in the northern Santa Catalina Mountains. The Anschutz-Phillips drill hole penetrated 10,500 feet of

Oracle Granite north of the fault and pierced an apparent low-angle fault above a radiometrically reset (25 to 30 m.y. K/Ar) crystalline terrain which resembles the crystalline terranes in the Tortolita and Santa Catalina complexes. In effect, the drill hole penetrated a profound low-angle fault structure that separated upper plate Oracle Granite from lower plate radiometrically reset crystalline rocks that apparently contained low-angle mylonite fabrics.

The low-angle structure penetrated by the Anschutz-Phillips drill hole cuts 47 m.y. old 2 mica granite which outcrops in probably lower plate mylonitic tectonized basement at the surface south of the west-northwest striking North Star fault zone. Thus juxtaposition of upper and lower plate lithologies across the North Star fault zone require at least 12,000 feet of vertical north side down movement. Because the low-angle structure penetrated by the Anschutz drill hole appears to cut a 47 m.y. old peraluminous granite, this movement must be post-47 m.y. in age.

By analogy, the Mogul fault and the Oracle Granite north of the Mogul fault would also be upper plate, and could rest allocthonously above deformed tectonized basement in the lower plate perhaps 10,000 feet below our current position. In this view the Apache Group-Paleozoic section south of the Mogul fault would be upthrown lower plate rocks against upper plate Oracle Granite which is downthrown. Because of its southward dip, the Mogul fault would actually be a reverse fault rather than a normal fault and would have at least 12,000 feet of vertical separation.!! By temporal analogy with the North Star fault zone, the reverse movement on the Mogul fault would be late Oligocene in age and would coincide with the K-Ar late Oligocene cooling ages in the crystalline core of the Santa Catalina/Tortolita metamorphic complex. Thus, subsurface geology as established by the Anschutz drilling may completely force resynthesis of apparently simple-looking surface geology. The Anschutz drill hole data has recently been published by Ryfe and Robinson (1982) in AGS Digest XIII. These data have profound implications for the presence of regional low-angle faulting in the Basin-Range of Arizona. A structural cartoon of the geology discussed above is shown in Figure 1.

Milepost 96

A good view of Black Mountain at 9:00. Black Mountain is mostly Oracle Granite, slightly reset in terms of potassium/argon dates. The south flank of Black Mountain is a prominent west-northwest trending topographic escarpment that perhaps represents an erosional expression of a slightly offset continuation of the Mogul fault. Black Mountain is in the same structural block that we are just now crossing into, a block dominated by Oracle Granite that from the last road log entry may well be allocthonous. The road cuts ahead will be shallow veneer alluvium that is mostly composed of boulders and grus of Oracle Granite. These will give way, as we travel to the north past milepost 97, to an extensive bedrock pediment cut on the Oracle Granite. This granite is basement to the mid-Tertiary section we will examine later today.

Milepost 98 - Bedrock pediment of Oracle Granite.

The regional pedimented topography is locally traversed by a northeast trending rhyodacite porphyry dike swarm that is probably Laramide in age and is regionally related to the porphyry copper systems. One node of porphyry copper mineralization occuring along this dike swarm is the San Manuel porphyry copper system. We will be cross over an offset portion of this deposit to get to the middle Tertiary stratigraphy that will be the subject of today's field trip.

Milepost 100

Continue straight ahead on new Highway 77 for Mammoth/Winkleman. Mt. Lemmon, the high summit of the Santa Catalina Mountains is in view at 3:00. In the Oracle area are many excellent spheroidal weathering boulders of Precambrian granite on the Oracle pediment. The Oracle pediment is regionally extensive and occupies most of the Tortilla Mountains, a collection of low hills and ridges that extend for about 50 miles to the north-northwest between Oracle, Arizona and the Gila River west of Riverside-Kelvin.

Mile 101.5

The road cut on the right contains the only fresh outcrop of Oracle Granite for miles. As the pediment is deeply weathered it is difficult to get good geochemical and isotopic samples. Consequently this road cut has been sampled by many investigators over the years. A 1.44 billion year uranium lead-zircon date from this road cut was reported by Shakel, Silver and Damon (1977).

Mile 102.5

Oracle Granite crosscut by darker colored rhyodacitic northeast trending Laramide dikes related to the porphyry copper event.

Mile 104.6

Greenish outcrops near here are of Precambrian diabase intruded into Oracle Granite. The body strikes northwest and dips about 40° northeast. This attitude is parallel to that of the younger Precambrian Apache Group which depositionally overlies Oracle Granite in the northern Black Hills about 8 miles north of our position.

Milepost 105

A sharp left turn onto old San Manuel-Oracle highway. Begin new cumulative mileage. Road cuts along the road for the next half a mile or so are in weathered Oracle Granite.

Mile 0.3

The rounded hill at 12:00 is in conglomerates of the basal San Manuel formation resting unconformably on Oracle Granite. The contact is at mile 0.5. Note the characteristic outcrop expression of the San Manuel granite clast conglomerate, which comprises rounded hills containing isolated large rounded boulders of Oracle Granite weathering out of a buff- colored sedimentary matrix. Stream transport directions from imbricated cobbles within this lower part of the San Manuel section indicate paleodrainages flowing to the northeast.

Mile 1.1

Better exposures illustrating the bedding and the textural character of this granite clast conglomerate facies of the San Manuel formation.

Mile 1.7

At 11:45 the 6 head frames of the San Manuel underground porphyry copper mine complex are visible. To the northeast across the San Manuel valley are the northwest trending volcanic Galiuro Mountains(3:00 to 11:00). Saddle Mountain at 11:00 marks north end of the Galiuro range.

Mile 2.1

The road cuts of San Manuel conglomerates contain a much more heterogeneous assortment of clasts which variously include Apache Group, Laramide granodiorite porphyry, some of which are mineralized and a good component of Oracle Granite.

Mile 2.3

A good view of the San Manuel copper smelter complex at 2:30.

Mile 2.5

Another good view of the Table Mountain area of the northern Galiuros behind the head frames of the San Manuel mine. The prominent cliffs in the upper Table Mountain area are the Holy Joe volcanic member and the Table Mountain andesite member of the Galiuro Volcanics. Holy Joe andesite is dated at about 26 million years. The Table Mountain andesite which is the uppermost cliff former has yielded a K-Ar whole rock date of 21 million years as reported by Scarborough and Wilt (1979). These ages correspond with the middle and upper parts of the Cloudburst section as established by Bill Weibel (1981). The Cloudburst Formation will be the main object of today's field trip.

Mile 3

The clast size in the San Manuel conglomerate is getting noticeably smaller, there are more fine grained fluvial interbeds and the clasts continue to be heterogeneous.

Mile 3.3

Turn left onto dirt road for Black Hills ranch. We are now in the area of the Purcell window, having crossed a fault contact between the San Manuel formation and Oracle Granite. This area overlies the west end of the Kalamazoo porphyry copper deposit, the faulted half of Magma's San Manuel deposit displaced 8000 feet west on the San Manuel fault. Discovered in 1965 by J. David Lowell and Quintana Minerals, the deposit was subsequently sold to Magma Copper. Prior to this discovery, published accounts of movement history on the San Manuel fault suggested right lateral strike slip (Creasey, 1965), reverse (Wilson, 1957 and Heindl, 1963) and down dip (Steele and Rubly, 1947 and Schartz, 1953). Quintana's drilling established the older workers were correct. The Kalamazoo system lies approximately 4000 feet beneath us.

Mile 3.6

A northeast trending dike probably related to the San Manuel/Kalamazoo system. The hill at 1:00 contains an erosional remnant of rhyodacite porphyry presumed to be of late Oligocene age as mapped by Bill Weibel. Much of the geology that we will see today has been drawn from his 1981 M. Sc. Thesis at the U of A.

Mile 3.7

An adit into Oracle Granite, perhaps exploring a small occurrence of copper mineralization in the outer halo of the now tilted Kalamazoo orebody to the south and beneath us.

Mile 4.2

Contact between Oracle Granite and the fanglomerate member of the Cloudburst formation (the reddish colored outcrops on the west side of the tributary wash). Weibel has mapped the contact where the road crosses the contact as a fault, but most of the contact along this western margin of the Oracle Granite lies concealed beneath stream gravels in this tributary to Tucson Wash.

Mile 4.3

A good exposure of flat lying fanglomerate member of the Cloudburst formation on the west side of the wash.

Mile 4.5

A small saddle in the ridge containing fanglomerate member of the Cloudburst formation. The conical hill at 12:00 is a rhyodacitic volcanic intercalated within Cloudburst fanglomerate, according to Weibel. Creasey (1965) mapped a small intrusive but Welbel's more recent mapping establishes that it is better interpreted as volcanic.

Mile 4.7

Bear a sharp right through a gate down into Tucson Wash. After entering Tucson Wash, bear a left up the wash.

Mile 5.4

All outcrops on both sides of the wash between here and where we entered the wash are in Cloudburst fanglomerate. Ahead at 11:00 to 12:00 the reddish brown outcrops are in the volcanic member of the Cloudburst formation.

Mile 5.9

The lower slopes of the hills to the west of the wash are in Cloudburst fanglomerate member which here strikes northeast and dips steeply south, depositionally overlying the volcanic member of the Cloudburst which here consists of andesitic breccia, in the upper 1/2 of the hill.

Mile 6.1

Bear right onto and continue up a tributary to Tucson Wash.

Mile 6.2

Excellent outcrops of Cloudburst andesite breccia on the right. Ahead and to the left are fanglomerates of the San Manuel formation dipping to the southwest. These are in the hanging wall of a northwest-striking major fault that juxtoposes San Manuel formation conglomerates against the volcanic member of the Cloudburst formation. The fault is shown by Wiebel to dip 65° to the southwest. This same Red Rock fault brings San Manuel formation in contact with Oracle Granite at the Purcell window.

Mile 6.5

Turn right onto pipeline road. We will proceed northwest across pedimented outcrops of the volcanic member of the Cloudburst formation.

Mile 7.1

At a "45" sign along the pipeline, the road will cross the approximate position of a Cloudburst/Oracle Granite contact. This has been mapped as a thrust fault by Creasey. An outcrop of this contact just north of here will be seen later on the first traverse. It looks quite depositional in character. The field trip will park for the first traverse by the gate where the two pipelines join.

Stop 1: Traverse through the Cloudburst Formation
and exposures of the San Manuel fault

After leaving the parking area, proceed due east to the contact between the Cloudburst formation and the Oracle Granite. As you leave the parking area you will be in highly grussified outcrops of Oracle Granite.

Point A: Oracle Granite Cloudburst contact

Gullies in this area contain excellent exposures of the Cloudburst/Oracle Granite contact. The Cloudburst/Oracle Granite contact has been mapped by Creasey (1964) in the San Manuel quadrangle just to the east as a low angle fault contact. On the Creasey (1964) regional map (Plate 3), the contact at Point A is also shown as a low angle thrust fault contact. We can see at this location that the contact is probably depositional in character. Evidence for the depositional character includes the fact that the Oracle Granite immediately beneath the contact shows a reddish color indicative of paleoweathering and that it grades up smoothly into the sedimentary sequence with no evidence of shearing. In addition, the immediately overlying sedimentary sequence contains a large component of decomposed Oracle fragments.

Interpretation of the basal mid-Cenozoic contact as a fault is widespread in USGS mapping throughout the San Pedro valley. To the north, as will be seen tomorrow, this contact is mapped as a high angle normal fault; here, the contact has been mapped by the survey as a low angle fault contact. In both cases other workers have regarded these contacts as depositional in character (e.g. Schmidt, 1971, U of A PhD, dissertation).

Point A to Point B

After inspecting the contact at Point A proceed northward towards a low ledge of rocks about 1/4 mile to the north which will be Point B. Between Point A and Point B we will cross through a 150 foot thick sequence of fluvatile volcaniclastic sedimentary rocks containing abundant clasts of the immediately overlying Cloudburst volcanics as well as clasts of Oracle Granite. There are also a few quartzite clasts along with some porphyry clasts. These sediments interfinger upward into the base of the Cloudburst volcanic section and at Point B we will see an outcrop of basalt which has been dated at 28 m.y. (K/Ar).

Point B: Basaltic units at the base of the Cloudburst volcanic member of the Cloudburst formation.

In the immediate vicinity of Point B one can notice several near vertically standing, light brownish weathering, flaggy volcanics about 100 feet above the base of the sedimentary sequence that we just passed through. A freshly broken surface is black betraying the basaltic composition. A chemical analysis of one of these rocks (see Table 1) shows that it is indeed an alkali basalt. All of the chemical data that will be discussed here and at subsequent stops were obtained by Bill Rehrig and myself in the Spring of 1977. Rocks from this unit were very fresh (see petrographic descriptions in Table 1) and yielded dateable material for the K/Ar whole rock technique. We submitted a sample of the basalt to the U of A geochronological laboratory under the administration of

Paul Damon. They obtained a 28.3 ± 0.3 m.y. K/Ar whole rock date which they published in Shafiqullah and others (1978). Because of the regional significance of this date, a confirmatory date was obtained on a second sample of this same basalt unit from Geocron Labs. This sample yielded a K-Ar whole rock te of 27.8 ± 1.4 m.y. (Rerig (1977), personal communications). Analytical data for this second date are provided in Table 2. The geochronological data provide an absolute age constraint for the base of the middle Tertiary sequence of about 28 m.y. in the area of San Manuel. The date was also regionally significant because the Cloudburst sequence was regarded by some past workers to be late Cretaceous in age and correlated with the Williamson Canyon volcanics in the Winkleman area to the northeast which are indeed late Cretaceous in age.

As we walk up through the volcanic sequence, those that have seen both rock sequences will see that there are a number of textural similarities between the two. Thus, it was an easy correlation to make on the basis of petrography. However, much of the USGS stratigraphy that has been subsequently determined for the San Pedro valley was unfortunately based on the assumption that the Cloudburst sequence that we are standing on is Cretaceous in age. The San Manuel formation which rests unconformably on this sequence became the basal mid-Tertiary stratigraphic unit in the San Pedro valley and was correlated widely with sections of mid-Tertiary sequences further to the north that will be seen during Day 2. However, our work and that of Bill Wiebel (1981) established that the Cloudburst formation is unequivocally late Oligocene in age and should correlate with the Hackberry formation of Eberhard Schmidt (1971) in the Kearny area. Unfortunately, because of their assumptions about the Cloudburst formation the USGS correlated the San Manuel formation with Eberhard Schmidt's Hackberry formation. A better correlation would be to equate Schmidt's Hackberry formation with the Cloudburst formation as defined by Heindl (1964) and Weibel (1981). The San Manuel formation is better correlated with the Big Dome formation as defined by Kreiger, Banks and Cornwall (1973) in the Kearny area. In effect, the USGS has correlated the San Manuel formation with the wrong mid-Tertiary unit. As a result of this miscorrelation it is suggested here that the San Manuel formation should be restricted to the local exposures in the San Manuel area. All other units north of San Manuel, which are called San Manuel on USGS maps, should be considered suspect until it can be proven that they are indeed San Manuel in age, that is 21 m.a. to 14 m.a. It is also suggested that the Hackberry formation terminology of Eberhard Schmidt (1971) is a perfectly good term and should be retained for the exposures in the Kearny region beneath the Big Dome formation of Kreiger and others (1974), and also that it should be correlated with the Cloudburst formation at San Manuel as redefined by Weibel (1981). A suggested correlation scheme is shown on Figure 1.

Point B to Point 1

From Point B to Point 1 we will proceed eastward traversing stratigraphically upward through a several thousand foot thick sequence of basaltic to andesitic volcanics. As can be seen from Table 1, the volcanic sequence gets progressively silicic upward so that before Point 1 is reached the andesitic part of the Cloudburst volcanic section will be exposed. Sample #2 on Table 1 is a chemical analysis of a typical andesitic flow unit between Point B and Point 1. Many of the andesitic flows have aphanitic bases that grade up into scoriaceous vesicular zones near the tops of each individual flow. There are literally hundreds of flows, each individual flow being 5 to 30 feet thick as we progress upward through the Cloudburst section.

Point 1

Conglomerate unit intercalated within the volcanic member of the Cloudburst formation. Stream exposures in the area of Point 1 contain excellent outcroppings of the approximately 100 to 150 feet thick conglomerate unit intercalated within the Cloudburst volcanic member. Clasts within the conglomerate unit contain mostly well-rounded cobble-sized to small boulder-sized Oracle Granite with minor amounts of Dripping Spring quartzite, possibly Troy quartzite clasts and lesser amounts of possible Laramide age granodiorite porphyry. The clast content and imbrications within this unit suggest stream flow from the west.

Point 1 to Point 2

From Point 1 we will continue eastward down Cloudburst wash through the upper part of the Cloudburst volcanic member. The upper part of the Cloudburst volcanic member becomes progressively more intermediate in composition with andesitic materials giving way to the dacitic materials. The outcrop color changes from the darker reddish browns to lighter buff colored units that betray the more silicic compositions. Also the textures of the flows become more fragmental in character as compared to the more scoriaceous nature of the andesitic flow units. Sample CB6 shows major element oxide chemistry on one of the andesite flow units approxiately 200 meters stratigraphically above the conglomerate unit.

Sample CB7 is from a more felsic unit approximately 600 meters stratigraphically above the conglomerate unit. Near the top of the volcanic member the more siliceous volcanics begin to interfinger with fluvially deposited conglomerates and arkoses of the fanglomerate member of the Cloudburst formation. Near the middle of the fanglomerate member Bill Weibel has mapped a fairly siliceous lens of dacitic composition. Creasey (1964) mapped part of this as a dacite to rhyolite plug but Weibel's mapping has shown that it is more reasonably interpreted as part of a flow within the mainly fluvially deposited clastics of the fanglomerate member. Chemistry for the dacitic and rhyolitic parts of the volcanics taken from Creasey (1964) and Krieger (1968) are also shown in Table 1. Krieger (1968) also reports a date of 22.4 m.y. on one of the rhyolitic dikes that is probably related to the Cloudburst magmatic event. This data taken in conjunction with the data reported by Weibel (1981) and Shafiqulla and others (1978) shows that the Cloudburst magmatic event began about 28 to 29 m.y. ago and terminated approximately 22 m.y. ago. This is the same age range as the dates obtained for the Galiuro volcanics about 30 miles northeast of our present position on the northeast side of the San Pedro valley. However, the chemistry of the Cloudburst volcanics and associated rhyolite plugs and dikes is quite different from that of the Galiuro rocks. Figure 1 is a K_2O/SiO_2 variation diagram that shows the Cloudburst volcanics are considerably more potassic. The K57.5 index of the Cloudburst volcanics is approximately 4.0 whereas the K57.5 index of the Galiuro volcanics is approximately 2.6 to 2.8. Thus the chemical data indicate that the Cloudburst volcanics are part of a metaluminous alkalic magma series whereas the Galiuro volcanics are a metaluminous alkali-calcic magma series.

Twenty-two million year old rhyolitic phases of Cloudburst magmatism are also closely associated with gold-copper-fluorine-lead-zinc mineralization at Tiger about 2 miles northeast of Point 2. The association of 13 to 28 m.y. old gold-copper-fluorine mineral deposits with metaluminous alkalic magmatism, and high angle faults (also local low-angle faults) is common in southern Arizona. The younger alkalic gold deposits (18 to 13 m.y. old) tend to occur west of the oligocene-miocene gold systems.

Point 2: Fanglomerate units of the upper fanglomerate member of Cloudburst formation.

At Point 2 the Cloudburst becomes dominantly a fanglomerate. This member is a fining-upward sequence of fluvially deposited conglomerate with some mudflows. Just downstream, observe the radical changes in clast makeup between adjacent or nearby conglomerate beds. Weibel (1981) has shown that the current direction was from west to east. However, the conglomerates appear very immature, indicating a nearby source for most clasts. As we proceed down the wash to Point 3, sedimentary structures in the fanglomerate are well exposed. Note the channel about 200 yards below Point 2.

Point 3: Arenite unit within the Cloudburst fanglomerate member at McKinney Dam.

This unit is a medium grained arkose and contains crossbeds (Weibel, 1981) indicating west to east transport. In the outcrop we will see, an eastward transport direction is suggested by a very planar set of crossbeds conformably overlying fanglomerate at the base of the unit.

Point 3 to Point 4

Proceed north from Point 3 through the washes and cholla for 0.4 miles to the contact between Cloudburst volcanics and fanglomerates and Oracle granite. The dip and strike of the contact can be inferred from its surface trace. The nature of the contact is not apparent here but we are on what past workers all agree is the outcrop trace of the San Manuel fault. Veins and aplites in Oracle Granite sub-parallel to the Cloudburst contact suggest that pre-San Manuel fault weakness planes in the Oracle Granite may have influenced the location of younger movement(s). Also, the San Manuel fault zone may have been a partial source for volcanics of the Cloudburst formation. The volcanic section noticeably thins southward away from the fault in the hanging wall block and also thins away from the San Manuel fault zone in the footwall block. Dike- like masses of andesite in the Signal Peak area seemingly intrude parallel to the fault just south of its outcrop trace in the hanging wall block.

Point 4 to Point 5

Traverse west along the trace of the San Manuel fault for about 0.5 miles to Point 5. Note the unsheared travertine developed along the fault. At Point 5, the fault, or strands of the fault, are well exposed in washes and in some small pits which prospect apparent exotic copper mineralization. The travertine and exotic copper suggest significant fluid flow and hot spring activity along the structure.

The dip here is steeper than normal for the San Manuel fault. This may be related to a local change in strike from west-northwest to northwest as the fault skirts the north side of Signal Peak. Slickensides on Signal Peak are directed down the dip of the structure, at S45°W. The age of normal movement on the San Manuel fault is constrained by the fact that the fault displaces 15 to 20 m.y. San Manuel formation in a normal sense.

We will now proceed south to Cloudburst Wash, a distance of about 800 feet. Once there, turn west and retrace the earlier part of the traverse to the vehicles. Drive back down Tucson Wash to Point 5, just below the Black Canyon Ranch.

Stop 2 (Point 5): Black Canyon Ranch fault zone (lunch stop).
Excellent slickensides exposed in the most westerly outcrops on the south side of the wash. They indicate dip slip, strike slip, and combined movements on Weibel's Black Canyon Ranch fault. At this point, the fault juxtaposes Cloudburst fanglomerate against Cloudburst fanglomerate. Weibel reports older dip slip and younger strike slip. There may be a reduction in the proportion of Oracle Granite clasts within the Cloudburst fanglomerate member to the north of this fault zone.

Point 5 to Point 6
We will retrace our course to the pavement just past the Black Canyon gate and windmill, then turn east and park at Point 6.

Stop 3 (Point 6): Purcell Window and Cloudburst-San Manuel exposures south of the Black Canyon fault zone.

Laramide porphyry dikes and local structurally controlled alteration here may be related to the Kalamazoo deposit. We will walk east through greatly thinned Cloudburst fanglomerate which lies directly on pre-Cloudburst basement of Oracle Granite and Laramide intrusive rocks. There is no volcanic member.

Point 7

At Point 7 are good exposures of Weibel's 'Oct' tuff unit. It is an excellent marker, and has been dated by Weibel at 22.5 m.a. by K/Ar on sanidine. The tuff provides the structural data with which to evaluate Cloudburst age tectonic features north and south of the Black Canyon Ranch fault zone. South of the fault zone the entire Cloudburst formation is less than 600 feet thick. No volcanic member is present. North of the fault zone over 5500 feet of Cloudburst formation with a thick northward thickening volcanic member is present. These data suggest local relief possibly related to movements on the Black Canyon fault at the beginning of and during Cloudburst time.

To the east, Cloudburst fanglomerate is overlain by San Manuel formation. The change is signalled by a light gray rather than tan to reddish color to the soil, and by the characteristic large Oracle boulders weathering out of the San Manuel formation. The contact is not exposed here, but has been mapped by Weibel to the north as disconformable but generally concordant.

TABLE 1

CHEMICAL DATA FOR CLOUDBURST VOLCANIC MEMBER LAVAS AND POSSIBLY RELATED SILICIC INTRUSIONS

Sample	CB-2	CB-4	CB-6	CB-7	1a	1b	W-10	1c
SiO_2	50.16	53.56	53.74	59.56	53.7	66.7	76.2	77.2
TiO_2	1.0	1.4	.69	.77	.93	.64	.18	.10
Al_2O_3	13.4	15.1	15.3	15.7	15.8	16.2	12.8	12.9
Fe_2O_3	10.2	8.6	6.9	5.0	6.5	3.2	.87	.56
FeO					.88	.11	.12	.05
MgO	10.0	2.8	6.0	2.6	5.4	.60	.25	.20
MnO	.16	.07	.11	.10	.16	.02	.05	.04
CaO	9.9	6.4	6.9	2.0	4.0	1.7	.72	.46
Na_2O	2.3	3.9	3.4	4.7	3.2	4.4	3.0	2.7
K_2O	1.6	2.9	1.8	4.6	4.6	4.4	4.5	5.1
P_2O_5	.435	.513	.171	.382	.32	.20	.02	.02
L.O.I.					4.8	2.09	1.0	1.33
Total Oxides	98 6	05.24	95.01	95.41	100.29	100.26	100.	100.66

Sample Descriptions[2]:

CB-2 Two pyroxene alkali basalt flow 200 feet above base of Cloudburst volcanic member. Pilotaxitic groundmass; 1% secondary biotite; 10% of pyroxene is serpentine and Fe oxides; otherwise very fresh. This sample (UAKA-77-61) yielded a K-Ar whole rock date of 28.3 ± 0.63 m.y.

CB-4 Pyroxene (?) andesite flow 1500 feet above base of Cloudburst volcanic member. Felty groundmass of elongate randomly oriented plagioclase surrounded by equigranular magnetite, pyroxene?, and quartz; Pyroxene? replaced by magnetite; about 25% of magnetite is oxidized, otherwise very fresh.

CB-6 Pyroxene basalt flow 2500 feet above base of Cloudburst volcanic member. Strongly trachytic groundmass composed of elongate plagioclase, tiny pyroxene grains, and minor K-feldspar; Pyroxene altered to Fe amphibole and minor FeO.

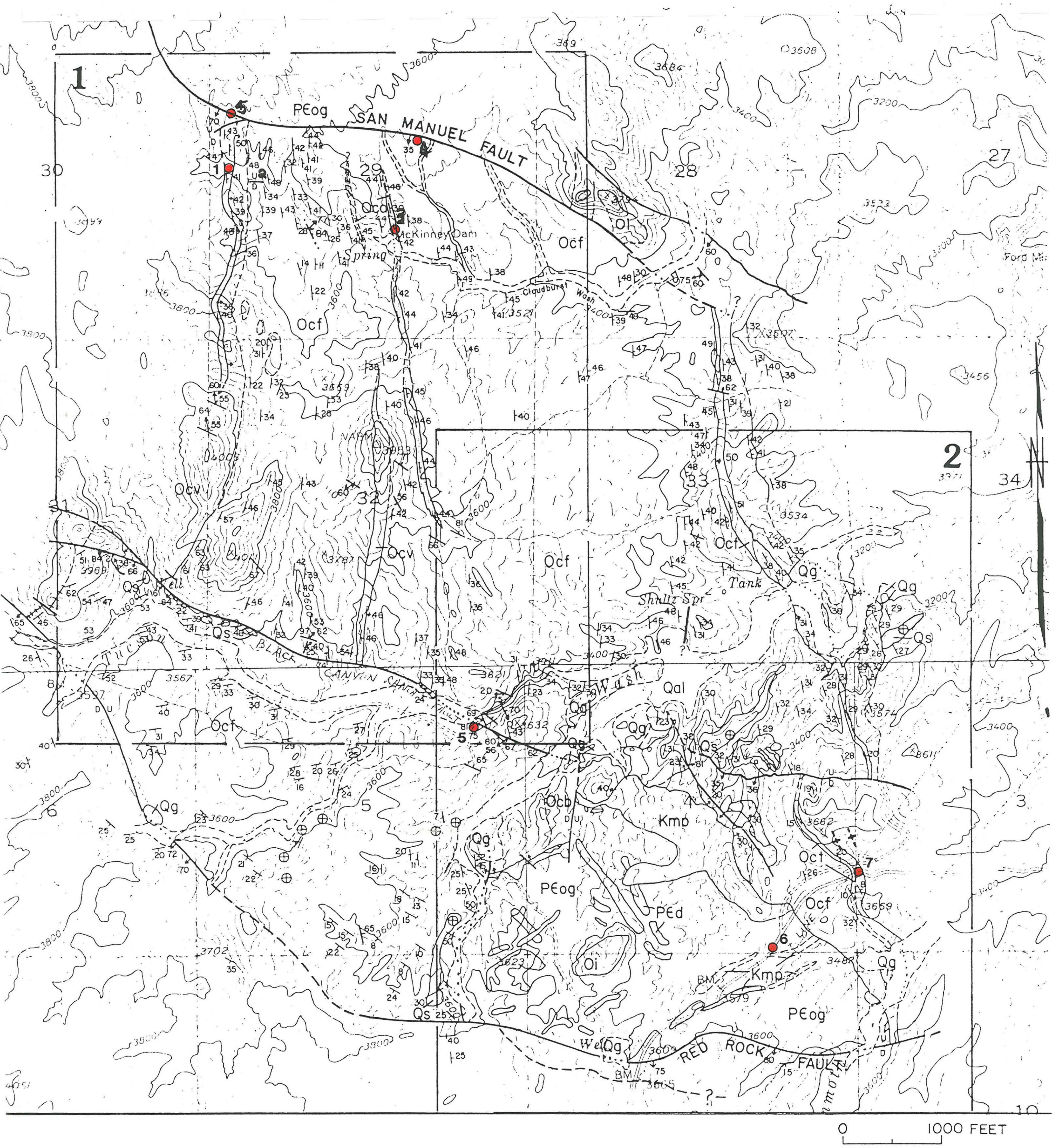
CB-7 Fine-grained latite-andesite flow 3100 feet above base of Cloudburst volcanic member. Pilotaxitaic groundmass with some K-feldspar; 5% of rock vesicular with silica filling in vesicules.

1a Cloudburst composite lavas (Table 4, col. 1, Creasey (1964))

1b Intrusive rhyodacite (Table 5, col. 1, Creasey (1964))

W-10 Rhyolite dike, Putnam Wash Quadrangle, Krieger (1974); Sample yielded K-Ar biotite date of 22.3 ± 0.7 m.y.

1c Intrusive rhyolite (Table 6, col. 1, Creasey (1964))



EXPLANATION

QUATERNARY

Qal — Alluvium

Qg — Gravel

Qs — Sacaton Formation

Mr — Intrusive rhyolite

Msm — San Manuel Formation (Undifferentiated)

TERTIARY

Oi — Intrusive rhyodacite

Oct, Ocb, Ocf, Oca, Ocv — Cloudburst Formation

Oct, tuff, volcanic breccia and tuff breccia, interbedded with granitic boulder conglomerate; clastic portion of volcanic breccia dated at 22.5 ± 0.5 m.y. (K-Ar, sanidine), this report. Ocb, basal facies rich in monzonite porphyry clasts. Oca, arenite unit, volcanic arenite to lithic arkose. Ocf, fanglomerate unit, chiefly muddy conglomerate. Ocv, volcanic flows, agglomerate, and breccia; andesite and rhyolite in the fanglomerate unit; andesite from lower volcanic unit dated at 28.3 ± 0.7 m.y. (K-Ar, plagioclase) by Shafiqullah and others, 1978.

CRETACEOUS(?)

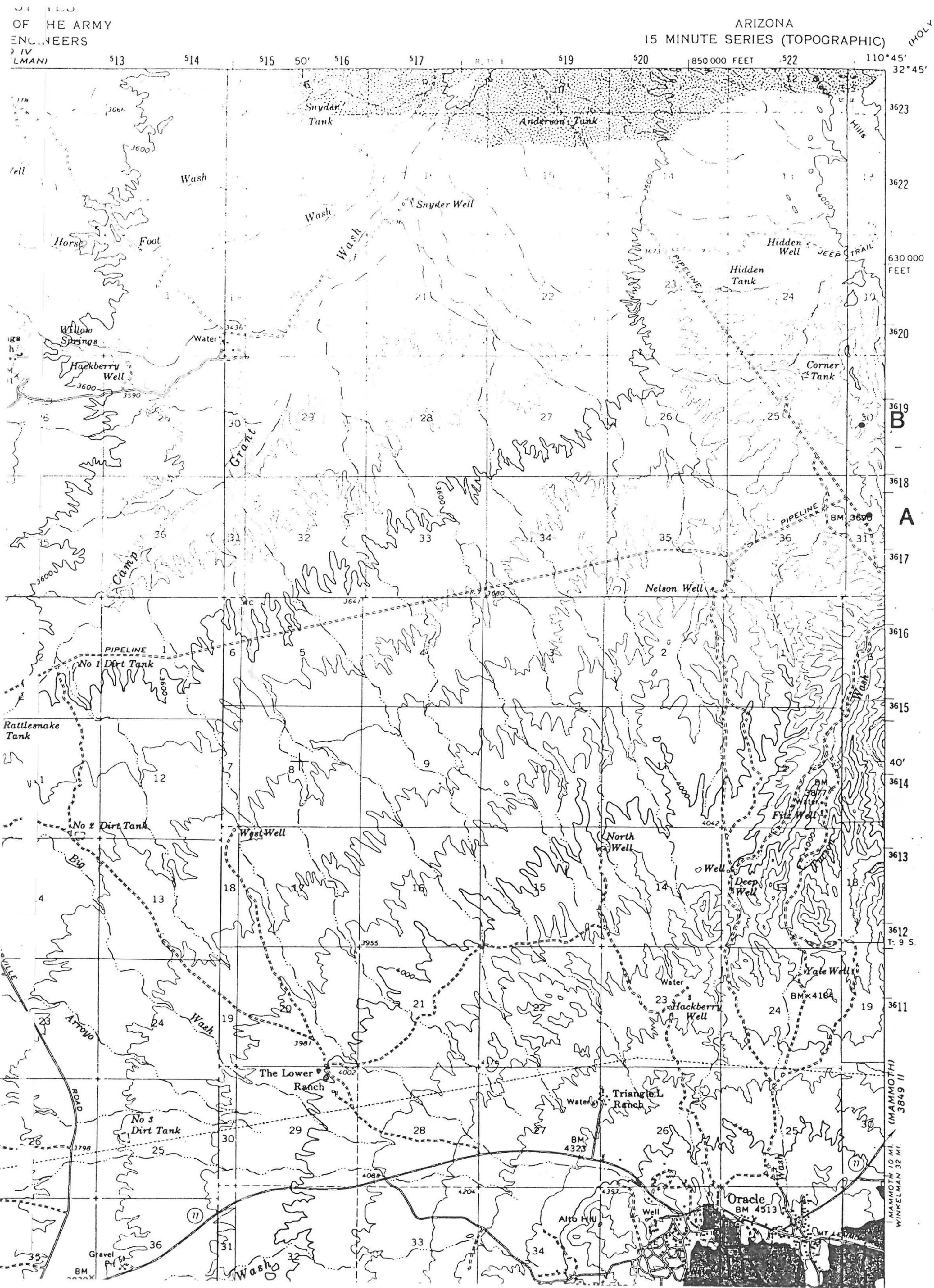
Kmp — Monzonite porphyry

PRECAMBRIAN

PЄd — Diabase Dikes and sills

PЄog — Oracle Granite Quartz monzonite

3 ● Field Trip Location



OF THE ARMY
ENGINEERS
ARIZONA
15 MINUTE SERIES (TOPOGRAPHIC)
850 000 FEET
110°45'
32°45'
630 000 FEET
40'
T. 9 S.
Snyder Tank
Anderson Tank
Hills
Wash
Snyder Well
Horse Foot
Hidden Well
JEEP TRAIL
Hidden Tank
PIPELINE
Willow Springs
Water
Hackberry Well
Corner Tank
Grant
B
A
BM 3690
Camp
Nelson Well
PIPELINE
No 1 Dirt Tank
Rattlesnake Tank
BM 3877
Water
Fitz Well
No 2 Dirt Tank
West Well
North Well
Well
Deep Well
Big
Yale Well
Water
Hackberry Well
BM 4164
Arroyo
The Lower Ranch
ROAD
Triangle L Ranch
No 3 Dirt Tank
BM 4323
Oracle
BM 4513
Alto Hill
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Gravel Pit
Wash
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WINKELMAN 32 MI.
(MAMMOTH)
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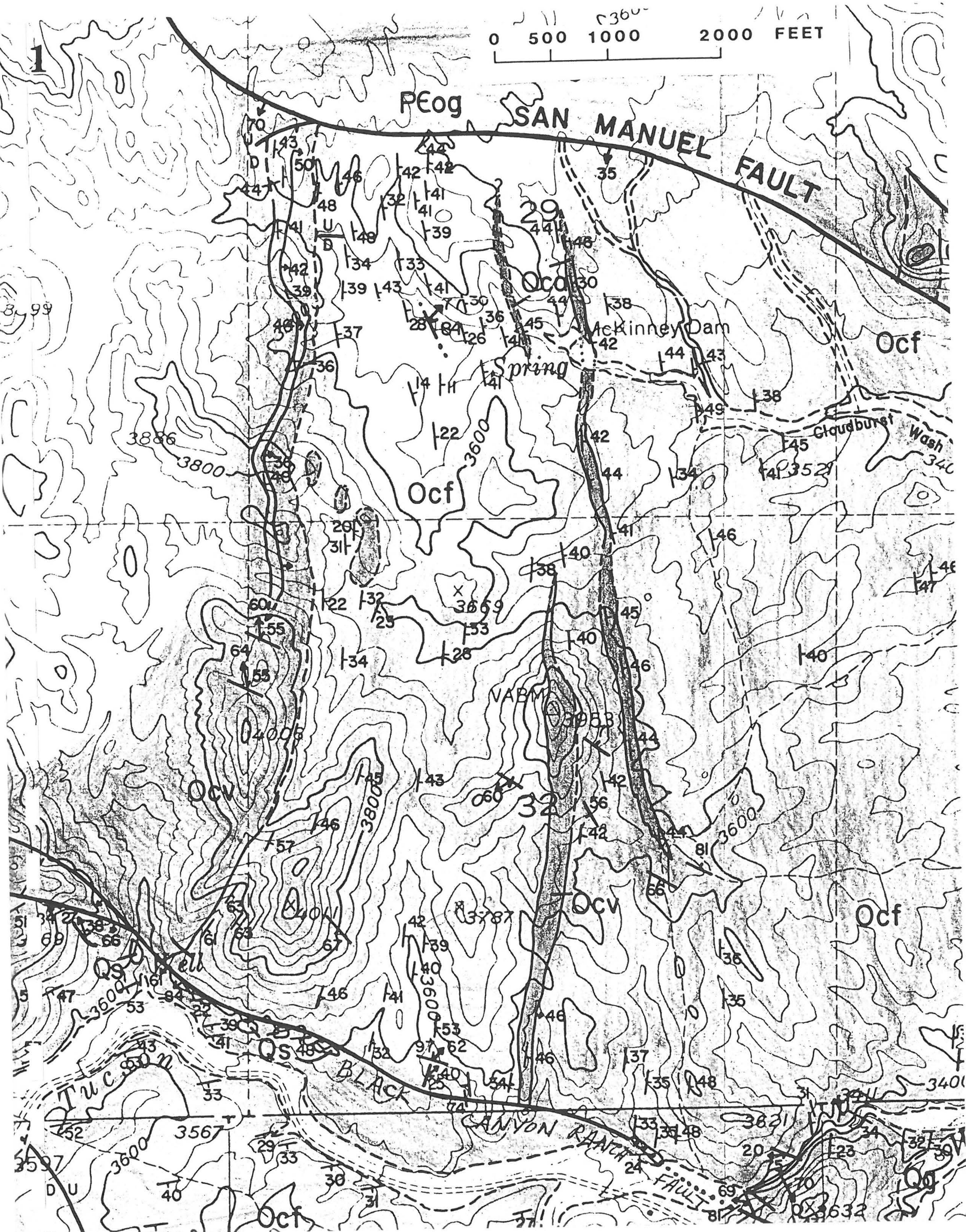
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SAN MANUEL FAULT
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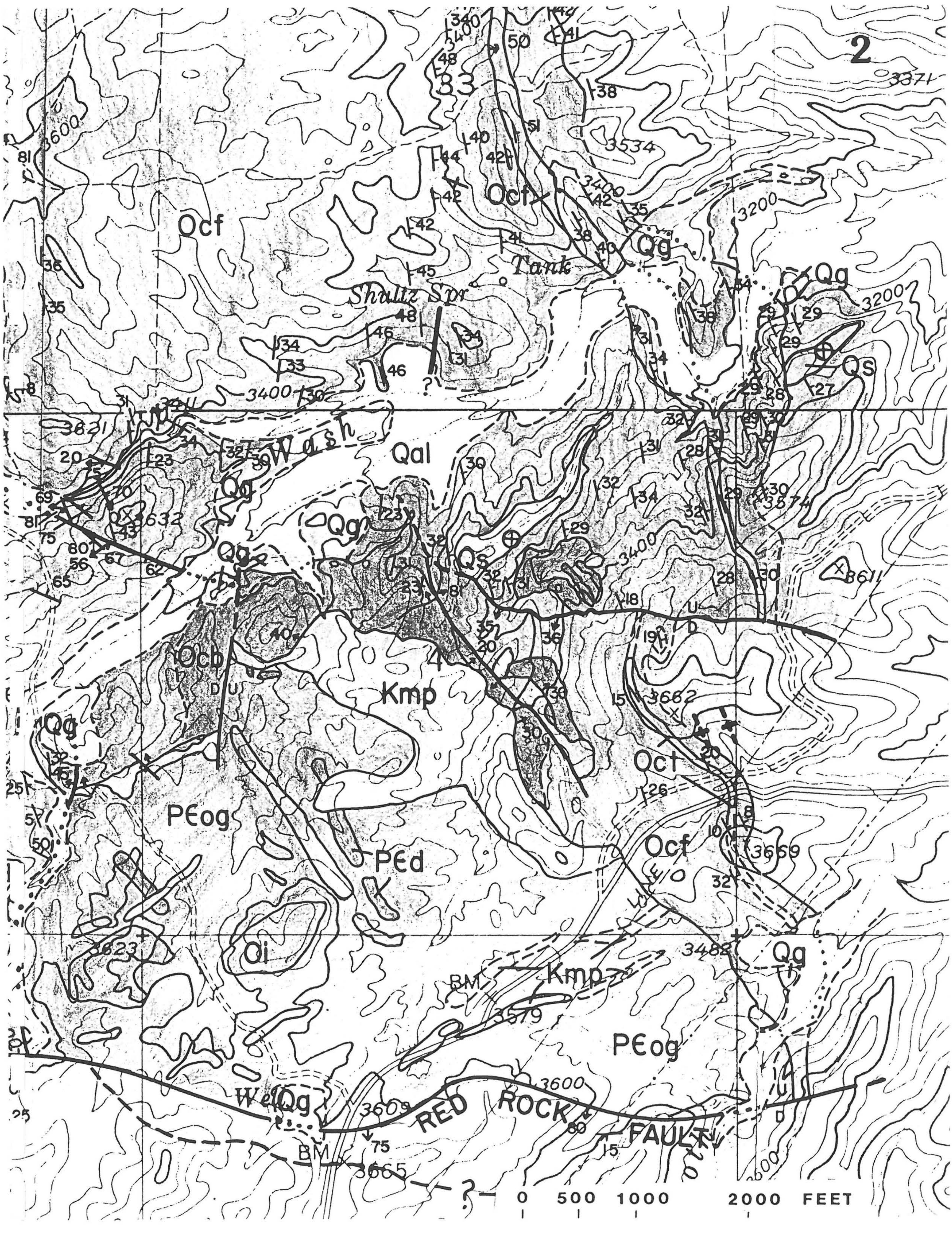
McKinney Dam
Spring
Cloudburst Wash
Tucson
BLACK CANYON RANCH FAULT
VABM


2
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DEPOSITIONAL HISTORY AND GEOLOGY OF THE CLOUDBURST FORMATION NEAR MAMMOTH, ARIZONA

by

William Lee Weibel

A Thesis Submitted to the Faculty of the

DEPARTMENT OF GEOSCIENCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

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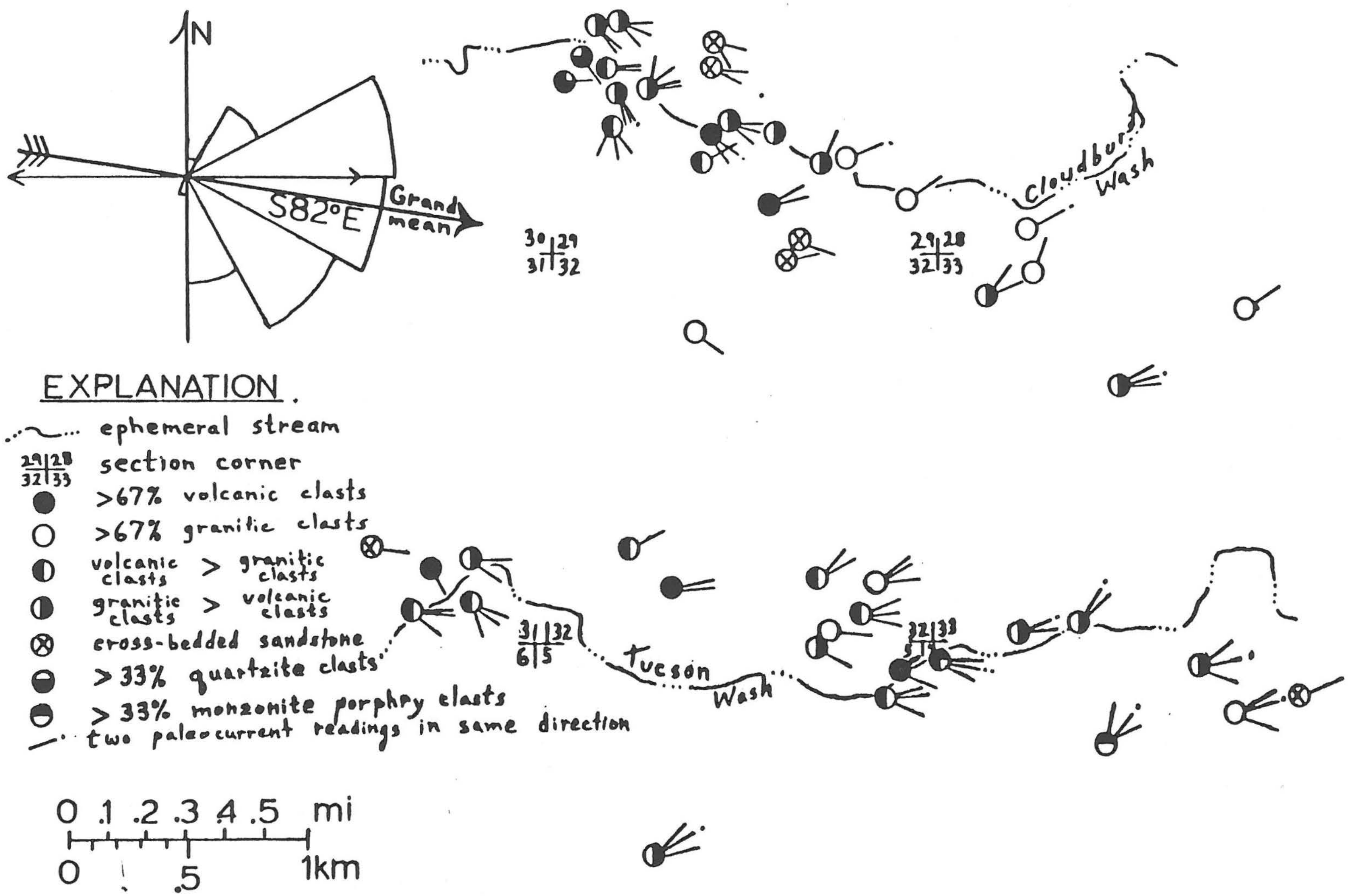

Figure 9. Paleocurrent directions and rosette

same general direction as did granitic fragments. The ubiquitous presence of Laramide monzonite porphyry clasts and the overall paleocurrent pattern necessitates that outcrops of the porphyry be included in the Late Oligocene paleogeography west of the area.

Isotopic Age Dating

Potassium-argon dating conducted for this study enabled the absolute age of the bulk of the Cloudburst Formation to be bracketed. The possibility that basalt flows of the basal San Manuel Formation in the Putnam Wash Quadrangle (Krieger, 1974) are correlative with Cloudbursts basaltic andesite flows in the Cloudburst volcanic unit was also tested to establish the chronologic relationship of the two formations on a more regional scale.

Sampling, crushing, and sieving of San Manuel basalt by the author was followed by the concentration of groundmass plagioclase by the Laboratory of Isotope Geochemistry at The University of Arizona. The isotopic age of the basalt was found to be 22.1 ± 0.5 m.y.; thus it is Early Miocene in age.

Datable material was later discovered after a thorough search of the tuff unit just beneath the top of the Cloudburst Formation. The larger fragments from a rhyolitic cobble breccia were sampled, crushed, and sieved by this author prior to the separation of sanidine, also by the Laboratory of Isotope Geochemistry.

The age of these rhyolitic cobbles must be greater than or equal to that of the unit from which they were derived. Cross-bedded tuff just north of the locality where dated samples were collected suggest that paleostreams emanated from the west-southwest during sedimentation of this stratigraphic marker. The isotopic age of the Cloudburst tuff unit determined by the K-Ar method (sanidine) is 22.5 ± 0.5 m.y. Thus the majority of the Cloudburst Formation accumulated between 29 and 22 million years ago. A revised stratigraphic column is shown in Figure 10.

Comparison of the age of this uppermost Cloudburst tuff (22.5 m.y.) from this map area with the new age (see above) for basal San Manuel volcanics (22.1 m.y.) exposed about 20 km away suggests that the contact between the Cloudburst and San Manuel Formations does not represent a a significant hiatus. Figure 11 demonstrates the chronological relationship of the Cloudburst Formation to the San Manuel Formation and the Galiuro Volcanics (Cooper and Silver, 1964) including the new K-Ar mineral ages. The data conclusively show that the Galiuro Volcanics are chronologically equivalent to the Cloudburst Formation. Perhaps the Hells Half Acre Tuff (part of the Galiuro Volcanics)

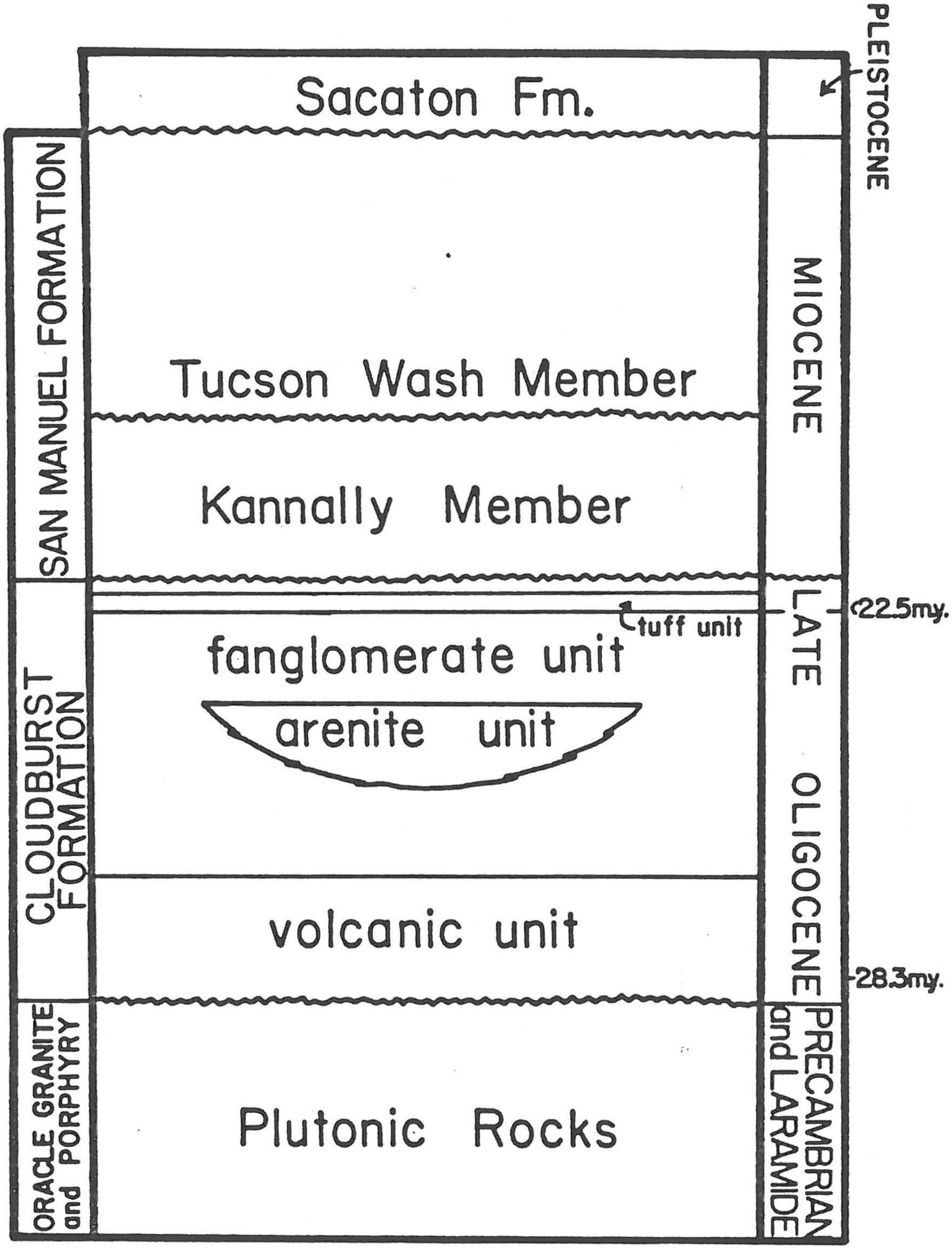

Figure 10. General stratigraphy of the Black Hills

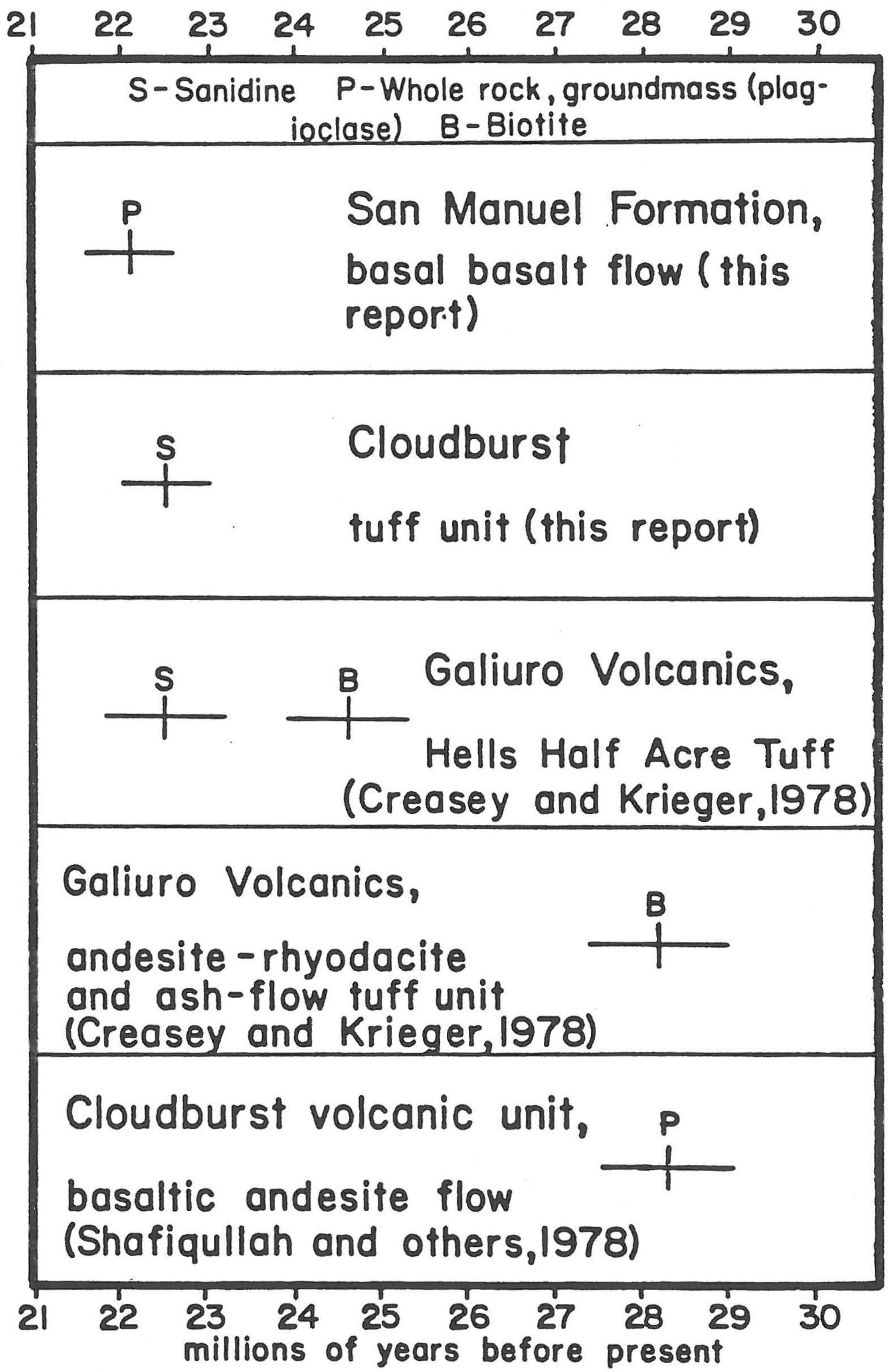

Figure 11. Comparison of K-Ar ages from mid-Tertiary formations in southeastern Arizona

is both lithologically and chronologically equivalent to the Cloudburst tuff unit.

CONCLUSIONS

The Cloudburst Formation accumulated in an intra-arc basin during Late Oligocene time. Large composite alluvial fans growing on the flanks of mountainous areas were chiefly composed of granitic and volcanic debris that was transported toward the southeast and perhaps later to the northeast in debris-flow lobes, stream channels, and as sheetflood deposits. The San Manuel Formation disconformably overlapped the Cloudburst Formation concordantly beginning in the Early Miocene. Oxidizing depositional conditions and the diagenesis of ferrous compounds colored the majority of the Cloudburst fanglomerate unit red or brown. Calcite is the most common cementing material, but many muddy deposits are compacted without notable cement. Silica filled pore spaces primarily in the volcanic conglomerates and arenites.

Post-depositional tectonic activity was primarily extensional; the strata were first inclined generally eastward to form a homocline. The tilting was probably accomplished by means of listric normal faults active during Early Miocene time east of the study area. The San Manuel fault later displaced the resultant homocline, shifting the upper plate about 2.5 km southwest along a low-angle, essentially planar surface. High-angle normal faults trending north to west further deformed the homocline during the Basin and Range period deformation. The supposed "angular unconformity" reported by Heindl (1963) and Creasey (1965, 1967) is instead a major high-angle normal fault.

The isotopic ages of the upper part of the Cloudburst Formation in the map area and the lowest part of the San Manuel Formation about 20 km northwest were determined to be 22.5 ± 0.5 and 22.1 ± 0.5 million years, respectively. The chronologic range of Cloudburst sedimentation is thus bracketed between 29 and 22 million years, and the oldest San Manuel deposits must be younger than 22.6 million years in age. Thus the Cloudburst Formation is not Late Cretaceous-Early Tertiary in age, as thought by previous workers (e.g., Krieger and others, 1973; Creasey, 1965, 1967) but is instead Late Oligocene in age as surmised by Heindl (1963) and Schmidt (1971). The data indicate that San Manuel deposition began soon after Cloudburst deposition ended; the contact displays less than 100 m relief.

Chronological correlation of the Cloudburst Formation with the Galiuro Volcanics exposed on the east side of the San Pedro Valley and the Hackberry formation (Schmidt, 1971) near Hayden can be made with confidence because of K-Ar mineral dates. Creasey and Krieger (1978) described a thick sequence of calc-alkalic volcanics in the Galiuro Mountains ranging in isotopic age from 29 to 23 million years. This chronologic range fits not only the Cloudburst Formation but also approximates the range of cooling ages (28 to 21 m.y.) first reported by Damon and others (1963) and later affirmed by Creasey and others (1977) for plutonic and gneissic rocks extensively exposed in the Rincon and Santa Catalina Mountains to the south and west of the study area. This chronology is also coeval with the emplacement of large syntectonic plutons of quartz monzonite, termed the Catalina suite of plutons by Keith and others (1980), now exposed in portions of the Rincon, Santa Catalina, Tortolita and Picacho Mountains of central southeastern Arizona.

Extensive differential vertical uplift was also experienced during the Late Oligocene within a north-northwest-trending belt now partially exposed in the Rincon, Sanga Catalina, Tortolita, Tortilla, Picacho Mountains, and Black Mountain, as well as in the Black Hills. The Cloudburst Formation most likely accumulated as a sedimentary response to this thermotectonic uplifting as it developed during Late Oligocene time, from about 29 to 22.5 m.y. ago. Subsequent erosion of nondeposition was probably brief, and was followed by a transition to dominantly sandy, more rounded conglomerates of the Early Miocene San Manuel Formation.

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Economic Geology
Vol. 63, 1968, pp. 645–654

Geology of the Kalamazoo Orebody, San Manuel District, Arizona

J. David Lowell

Abstract

An exploration project initiated by Quintana Minerals Corporation in 1965 has resulted in the discovery of the faulted segment of the San Manuel orebody. The project was based on a new interpretation of the geology of the San Manuel orebody which assumed that an original cylindrical orebody with concentric alteration zoning had been first tilted approximately 70°, then bisected by the flat San Manuel normal fault into the lower plate San Manuel orebody and an upper plate Kalamazoo orebody.

The deep drill holes of the Kalamazoo project provide an unusually good cross section of porphyry copper wall rock alteration. Vertical mineral and alteration zoning effects down the original vertical axis of the deposit are also exposed because the vertical axis is now nearly horizontal and within drilling depth of the ground surface.

Introduction

In the period 1943–1947, exploration projects were carried out in the San Manuel area by the U. S. Bureau of Mines and Magma Copper Company which resulted in the development of the San Manuel underground block-cave mine which is now in production at a rate of 41,000 tons per day.

Mining claims covering the area immediately west of the San Manuel orebody were staked in 1946 by Frank F. Salas, R. A. Buzan, H. G. Buzan, and W. C. Buzan of Mammoth, Arizona. These claims were optioned to Martha Purcell in 1946, and in the period of 1947–1958 seven churn drill holes ranging in depth from 1,400 to 2,950 feet were drilled by Mrs. Purcell. These holes did not intersect ore and no further deep exploration was attempted prior to the Quintana Minerals Corporation project which began in August, 1965, and which is described in this report.

The Kalamazoo deposit is in Sections 3, 4, 9, 10, T 9 S, R 16 E, Pinal County, Arizona, and it is seven miles east from Oracle, Arizona (Fig. 1).

The writer is indebted to Corbin J. Robertson and Ronald B. Thompson who participated in the exploration planning of this project and to a number of other individuals who contributed to its execution and management. Petrographic work by J. M. Guilbert was used as a basis for rock and alteration classifications.

A paper being prepared by the writer and J. M. Guilbert for publication in Economic Geology will compare the characteristics and genesis of the lateral and vertical alteration-mineralization zoning at San Manuel-Kalamazoo with those of a number of other porphyry copper deposits.

Acknowledgment is gratefully made to Quintana Minerals Corporation for permission to publish information developed during the Kalamazoo project.

Geology of the San Manuel District

The geology of the San Manuel area has been described by Steele and Rubly (1947), Schwartz (1953), Pelletier (1957), Creasey (1965), and Thomas (1966).

Precambrian quartz monzonite of the Oracle granite batholith in the San Manuel area was intruded in Laramide time by swarms of monzonite porphyry dikes and irregular monzonite porphyry masses. The rock classified as monzonite porphyry can be subdivided into a range of rock types including quartz latite porphyry, quartz monzonite porphyry, monzonite porphyry, biotite dacite porphyry, and probably other rock types. Some of these appear to be

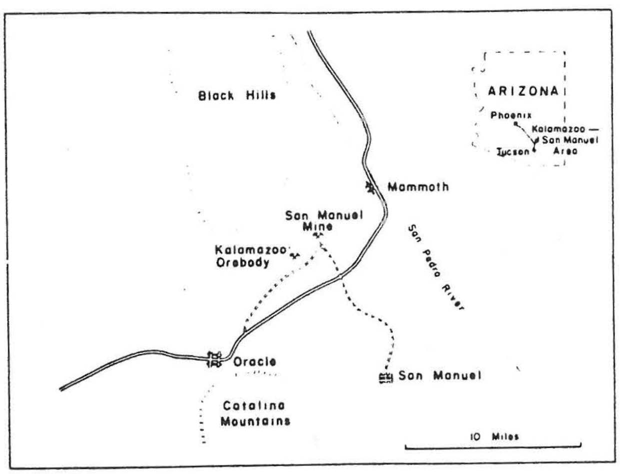


Fig. 1. Location map San Manuel District, Arizona.

slightly later than others, but all are closely related in time and all are apparently pre-ore in age. A few diabase dikes are also present in the Laramide-age dike swarms. Closely related in time with this Laramide intrusive activity was a pulse of porphyry copper-type mineralization that produced the San Manuel-Kalamazoo orebody and its associated concentric hydrothermal alteration zones. The axis of the hydrothermal flowage system seems to have been centered in the middle of one of the monzonite porphyry dike swarms.

Following emplacement of hydrothermal mineralization and alteration, district-wide structural displacements occurred that produced northeasterly tilting and probably resulted in relative elevation of the block which included the San Manuel-Kalamazoo orebody. Erosion cut into this block exposing a small corner of the orebody, and attendant supergene activity produced a thin chalcocite enrichment blanket. At this time the long axis of the orebody may have dipped at an angle of about 65° (Fig. 2). Subsequently, andesitic flows interbedded with detrital sediments and pyroclastics were deposited on this surface. Further igneous activity following the sedimentation resulted in the emplacement of andesite and rhyolite dikes.

The older Tertiary conglomerate unit in the Kalamazoo area has been correlated in published mapping (Creasey, 1965) with the Cloudburst formation of the Mammoth-St. Anthony area two miles to the northeast. The Cloudburst was considered by Creasey to be of post-San Manuel ore, but pre-Mammoth-St. Anthony ore age. Evidence for its post-San Manuel ore age in the Mammoth-St. Anthony area is not entirely convincing. However, the lowest conglomerate unit at Kalamazoo does appear to be of definite postore age; it is less well indurated than the Cloudburst formation and may be considerably younger. It may correlate (Watson, 1967) with the Pantano and Mineta formations of southern Arizona, which are considered to be late Oligocene or early Miocene.

Further tilting, averaging perhaps 15°, followed deposition of the lower conglomerate. It seems likely that tilting was accompanied by renewed elevation of the fault block since the block was again beveled by the erosion surface on which the Gila Conglomerate was later deposited. A third stage of about 30° of tilting moved the Gila Conglomerate into its present inclination and brought the long axis of the San Manuel-Kalamazoo orebody into a 20° west-dipping attitude. As seen on Figure 2, the San Manuel fault then diagonally bisected and offset the orebody into two pieces: the San Manuel and the Kalamazoo. It is uncertain whether the San Manuel fault displacement occurred before or after the last stage of tilting, but the fault has several characteristics commonly associated with low-angle faults including a thick gouge-breccia zone, a rolling fault plane surface, and braiding. It seems likely that the San Manuel fault displacement followed final tilting and that the present 25°–30° dip of the fault represents its original attitude. The fault divided the originally cylindrical San Manuel-Kalamazoo orebody into two mirror-image halves, and the upper (Kalamazoo orebody) half was moved in a down-dip, S55°W direction, about 8,000 feet. Imbricate displacements apparently occurred on overlying San Manuel fault strands which have resulted in one Kalamazoo ore section locally overriding another.

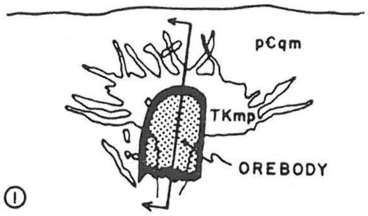
A system of high-angle, northwest-trending faults later produced relatively small, mostly normal fault displacements in both halves of the original orebody, and erosion stripped most of the Gila Conglomerate from the east end of the present San Manuel orebody. This erosion cycle developed extensive leaching and oxidation in the upper part of the San Manuel orebody with limited chalcocite enrichment beneath the oxidized zone. The lower portion of the San Manuel orebody and all of the Kalamazoo orebody were protected from oxidation by thick sections of capping. Erosion in the most recent cycle of erosion has exposed windows of pre-ore rock in the vicinity of both San Manuel and Kalamazoo (Fig. 3). A small area of the San Manuel orebody that had been exposed by erosion led to the original exploration of the area.

The original, unfaulted orebody, as defined by an 0.5% copper limit, has the general shape of a somewhat flattened or elliptical (in cross section) cylinder at least 7,700 feet in long dimension (along the axis of the cylinder) and from 2,500 to 5,000 feet in diameter. The top (east end after tilting) of the cylinder may have had a rounded shape with the bottom (west end after tilting) probably being somewhat irregular in shape. The orebody, like many porphyry copper deposits, had a poorly metallized core or "low-grade center." The wall thickness of the ore shell surrounding the low-grade center varied from about 100 to 1,000 feet. Mineralization and alteration form approximately coaxial cylindrical zones (Fig. 4).

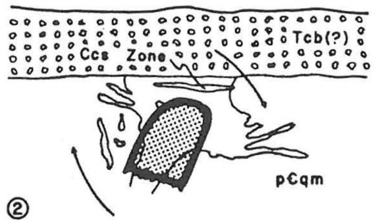
Figure 5 is a longitudinal geologic section of the Kalamazoo orebody and the overlying northeast-dipping Tertiary sediments. Figure 6 is a cross section illustrating the bisected hollow cylindrical shape of the orebody and shows a cross section of the mullion structure in the San Manuel fault zone

Mineralization

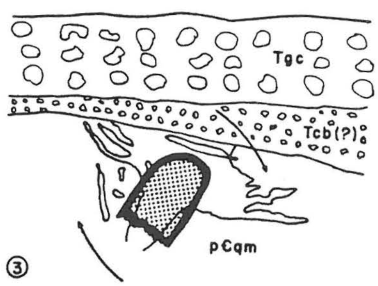
Ore mineralization is about equally distributed between coarse-grained Precambrian quartz mon-



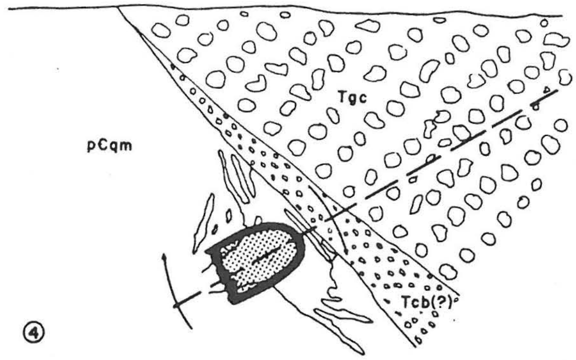
1. Precambrian quartz monzonite (pCgm) was intruded by a Laramide age monzonite porphyry (TKmp) dike swarm. A hollow cylindrical or pipe-shaped orebody with dimensions of approximately 8,000 × 3,500 feet was formed. It was probably nearly vertical and centered on the monzonite dike swarm. (Section line shows position of Figure 7.)



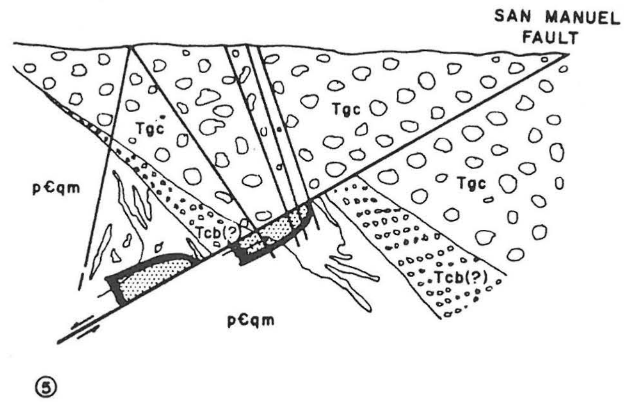
2. Tilting of the orebody was followed by erosion, then deposition of conglomerate and interbedded volcanics (Tcb?). A thin chalcocite blanket (Ccs) was formed at the water table.



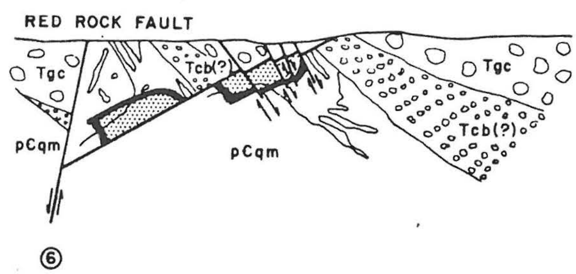
3. Continued tilting was followed by erosion of conglomerate and quartz monzonite and deposition of middle Tertiary Gila Conglomerate (Tgc).



4. Orebody is now at a flat angle due to continued tilting. An erosion surface is cut on the tilted quartz monzonite and Gila Conglomerate. Incipient San Manuel fault is formed.



5. Upper portion of orebody is displaced approximately 8,000 feet down the dip of the San Manuel fault. Some imbricate displacement may have occurred in the Kalamazoo segment.



6. High-angle normal fault displacements produced small offsets in the San Manuel orebody and a large displacement on the Red Rock fault west of the Kalamazoo orebody. Erosion exposed intrusive rocks and a corner of the San Manuel orebody and produced oxidation and limited chalcocite enrichment in the upper portion of the San Manuel orebody.

FIG. 2. Schematic drawings showing possible origin of Kalamazoo orebody.

zonite and Laramide monzonite porphyry host rocks. Ore in the Precambrian quartz monzonite tends to be slightly higher in grade.

Primary ore minerals in the San Manuel-Kalamazoo orebody are pyrite, chalcopyrite, molybdenite, and rare bornite. Oxide copper minerals, principally chrysocolla, have been developed in the upper portion of the San Manuel orebody. Chalcocite is common in the lower portion of the oxide zone and near the top of the chalcopyrite mineralization in the San

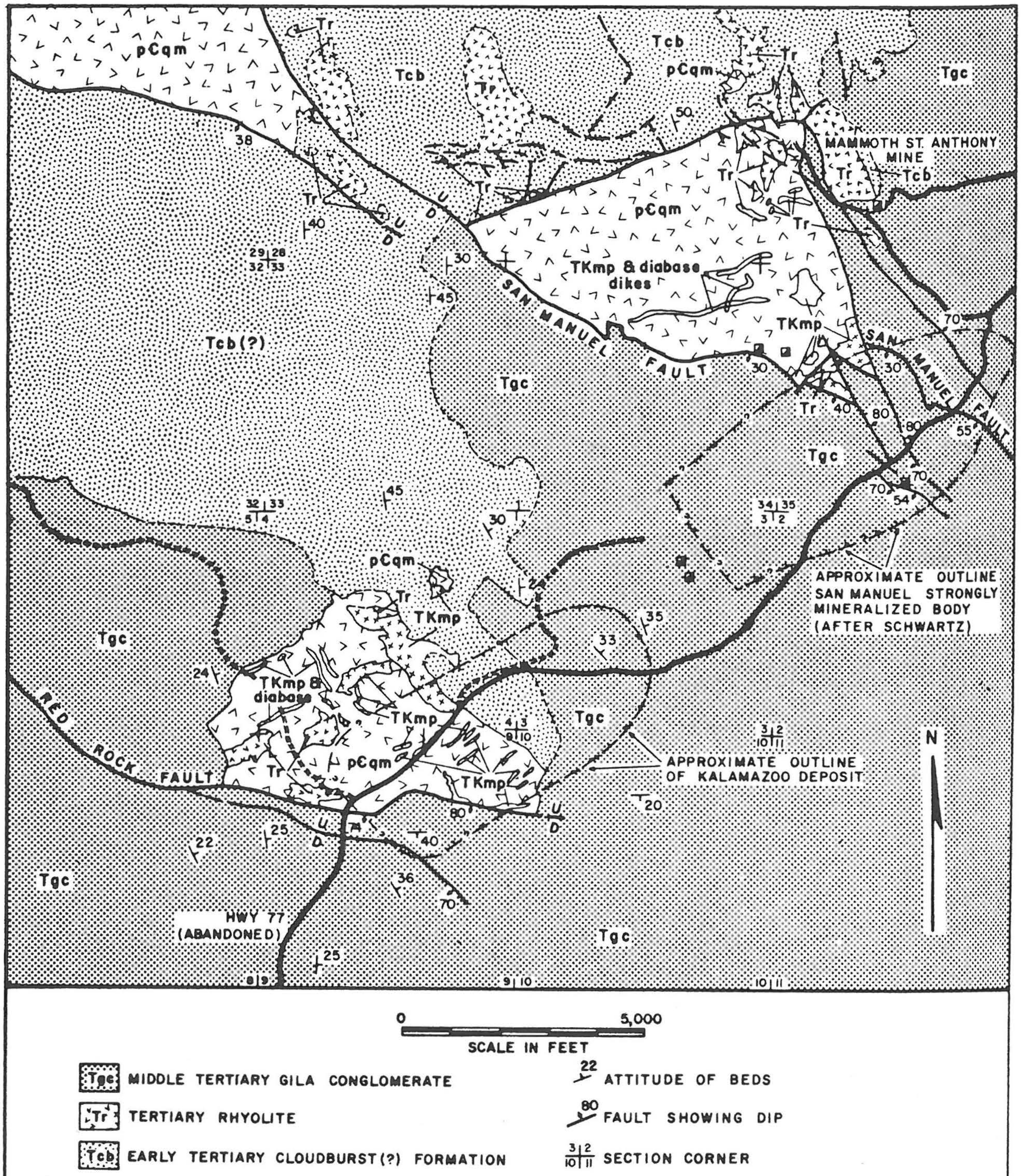


FIG. 3. Geologic map of the San Manuel area.

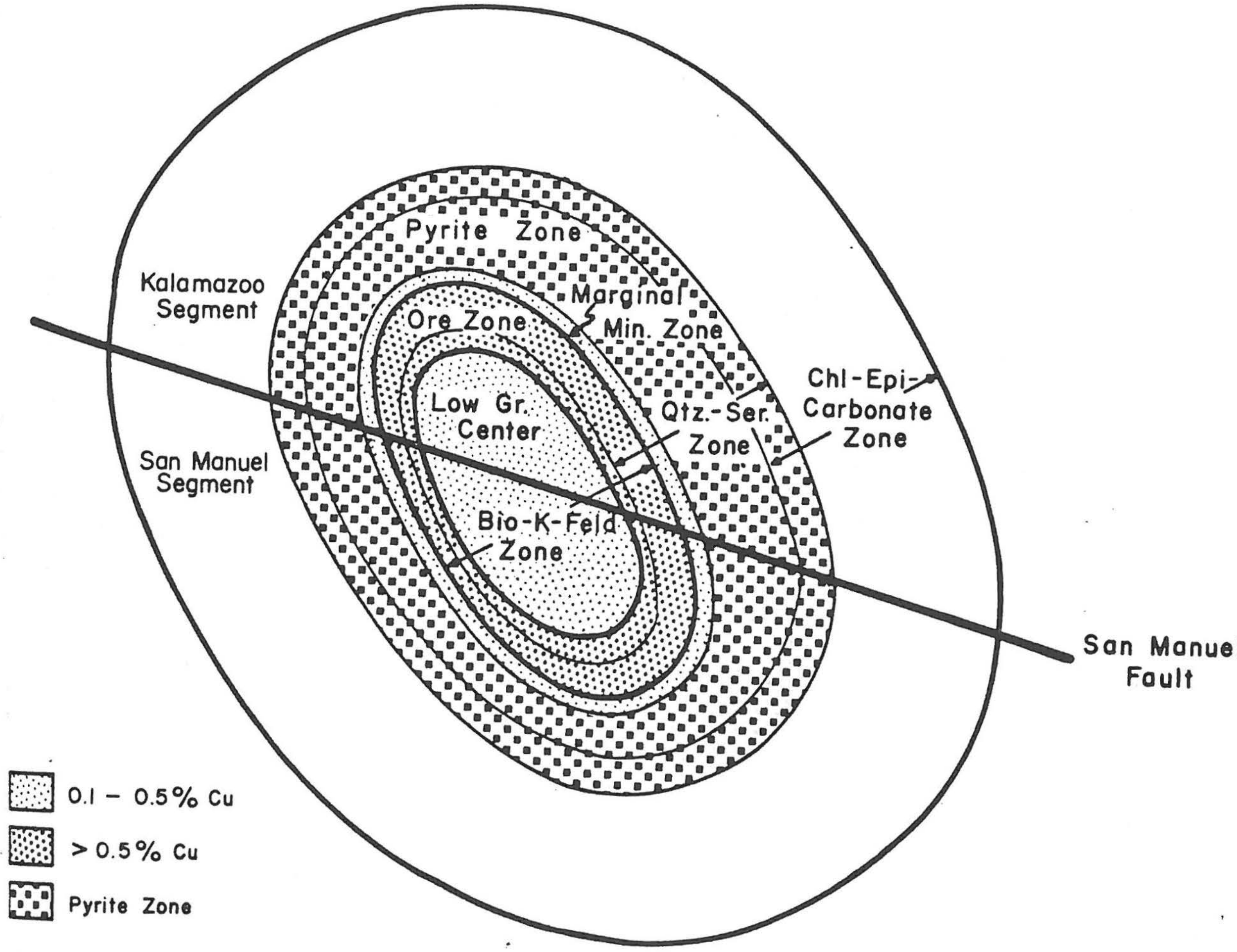


FIG. 4. Schematic horizontal plan showing alteration and mineralization zones.

Manuel orebody, but both chalcocite and oxide minerals are absent in the Kalamazoo.

Zones of Mineralization (Fig. 4).—1. The low-grade center zone averages about 2,600 feet in diameter and about 0.3% Cu in grade. Total sulfide content is low with a pyrite-to-chalcopyrite ratio of about 1:2.

2. The ore shell averages about 600 feet in thickness and ranges in grade from 0.5%–1.0% Cu. The pyrite-to-chalcopyrite ratio is about 1:1.

3. The marginal mineralization zone which surrounds the ore shell averages about 200 feet in thickness and ranges in grade from 0.1%–0.5% Cu. The pyrite-to-chalcopyrite ratio is about 10:1.

4. The pyritic zone that surrounds the marginal mineralization zone ranges in thickness from about 1,000–1,500 feet and ranges in grade from 0.01%–0.10% Cu, averaging about 0.03% Cu. It contains from 6%–25% pyrite by weight, averaging about 10% pyrite.

Total volume of sulfide minerals increases progressively from the center of the concentric mineralization-alteration system out to a point of maximum sulfide content in the inner portion of the pyritic zone. Outward beyond this point sulfide content progressively decreases. Copper content increases progressively from the center of the system out to a point of maximum copper grade in the center of the ore shell, then decreases by steps to the outer margin of the zone of marginal mineralization. Beyond this point copper rarely occurs as recognizable copper minerals, and the 0.01%–0.10% Cu content of the pyritic zone is probably included in the crystal structure of the pyrite.

Alteration

Alteration zones in this deposit, as in most porphyry copper deposits, are rather poorly defined and overlapping. Various host rocks respond in different ways to alteration solutions to produce

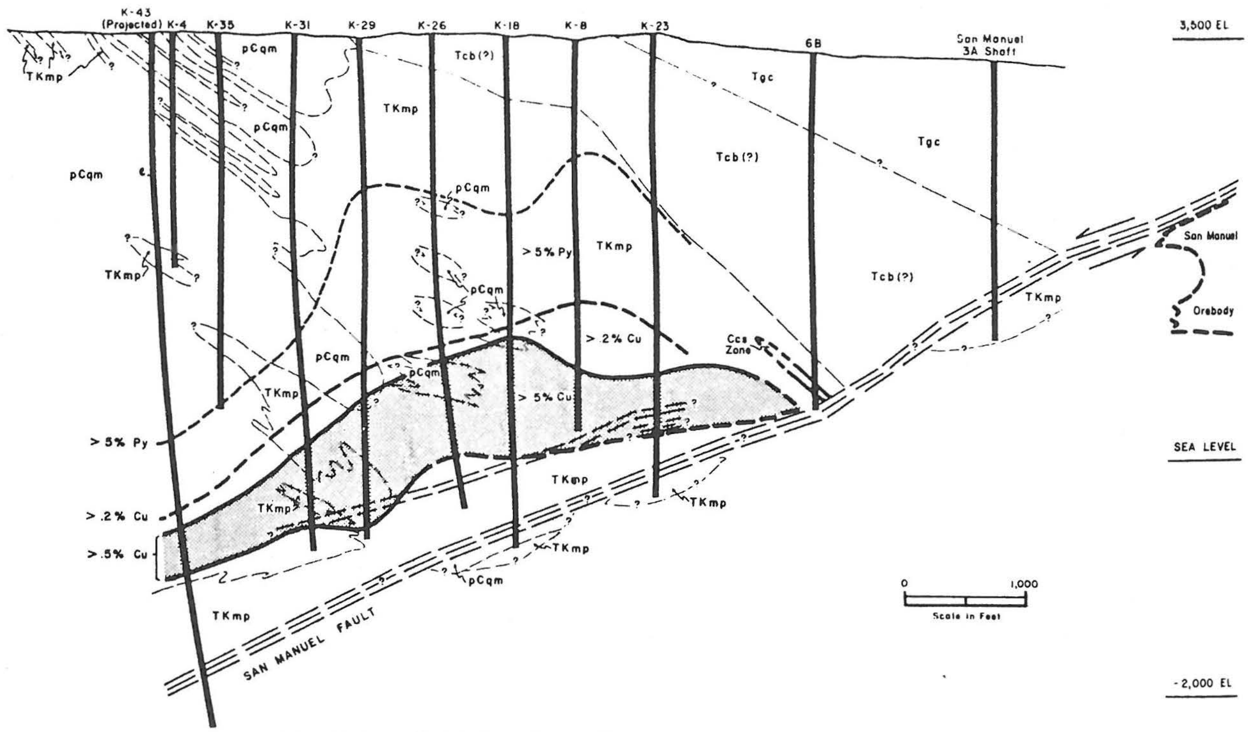


FIG. 5. Longitudinal section of Kalamazoo orebody looking northwest.

somewhat different alteration products within the same zone. Alteration zones are more clearly defined here than in most porphyry deposits, however, because the original San Manuel-Kalamazoo orebody had unusually uniform boundaries and a well-developed symmetrical configuration. This probably resulted from the fact that alteration and mineralization affected intrusive host rocks that were of generally similar chemical composition and of essentially isotropic fabric.

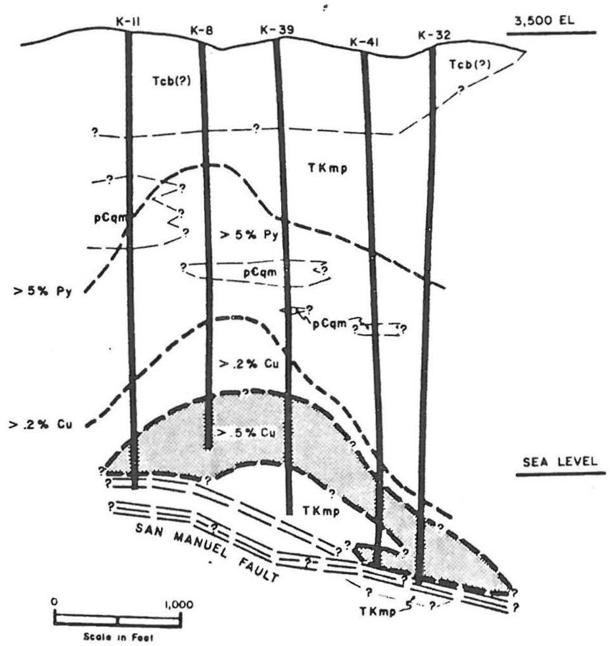


FIG. 6. Cross section of Kalamazoo orebody looking northeast.

Horizontal Alteration Zones.—These are zones distributed laterally in and around the orebody at a given depth at the time of ore formation. They consist of:

1. The inner alteration zone of the San Manuel-Kalamazoo orebody consists of biotite K-feldspar alteration (Fig. 4).

Several authors, especially Hemley and Jones (1964), have discussed the potassic alteration environment. Hemley and Jones delimit an environmental interface between K-feldspar and sericite stabilities consistent with late magmatic or early hydrothermal conditions in the K-feldspar-sericite-kaolin (pyrophyllite) system. Expansion of the system to include iron and magnesium should bring biotite, K-feldspar, sericite, and quartz into consideration, an assemblage increasingly often noted in porphyry copper deposits (Creasey, 1966) and assignable to the late magmatic-early hydrothermal "deuteric" environment. Such a biotite K-feldspar alteration assemblage with quartz, sericite, anhydrite, pyrite, chalcopyrite, and molybdenite generally constitutes the low-grade center and part of the ore shell of the Kalamazoo deposit. Conditions approaching those of wholesale remobilization of the porphyry concurrent with potassic alteration are suggested by coarsely vermicular and diffuse intrusive contacts between host rock and porphyry masses within the orebody.

It is certain in any case that this intense potassic alteration produced fresh-looking secondary minerals which led to the incorrect conclusion on the part of some previous workers that this alteration zone represented alteration weaker than that of the surrounding zones. The intense phase of biotite K-feldspar alteration tends to alter monzonite porphyry to a coarser-grained rock that somewhat resembles in texture the fresh Precambrian quartz monzonite. This alteration is not nearly as obvious as other alteration effects in the surrounding quartz-sericite zone which represent weaker hydrothermal conditions but more obvious destruction of rock textures.

At depth the biotite K-feldspar zone is partly replaced by a core of quartz-sericite-chlorite ± K-feldspar alteration as will be discussed later in this paper. This assemblage appears to represent a high-temperature environment in which sericite, chlorite, and minor carbonates appear.

2. A zone of quartz-sericite alteration generally includes all of the marginal mineralization and pyritic zones and overlaps the biotite K-feldspar alteration in the outer part of the ore shell. Sericite tends to be more abundant in the inner part of this zone with clay minerals and hydromica becoming more abundant towards the margins of the zone. In the inner portion of this zone, rock textures have been largely destroyed. The zone contains sections of spectacular, pervasive pyrite mineralization in which pyrite in some cases constitutes more than 20 percent by weight of the rock. Specularite is common towards the margins of the zone. A zone of hydrothermal magnetite mineralization appears to interfinger with and possibly replace this zone towards the west end (original bottom prior to tilting).

3. Surrounding and overlapping the quartz-sericite zone is a zone of propylitic alteration in which chlorite, epidote, and minor carbonates are developed. Pyrite content by weight averages 4 percent.

This zone gradually fades and may have a total thickness of 2,000 feet or more. The configuration of the alteration zone is apparently not related in detail to the distribution of monzonite porphyry bodies.

Vertical Alteration Zones.—The San Manuel-Kalamazoo orebody has unique genetic significance in the study of porphyry copper deposits because of the great length of the original vertical column of mineralization exposed. If the orebody has been tilted approximately 70° as postulated, then the west end represents ore mineralization which was originally about 8,000 feet deeper than the east end. Including mineralization in drill intercepts in the lower plate of the San Manuel fault below the Kalamazoo orebody, it is possible to partially reconstruct vertical mineral zoning changes over an original vertical column of 13,000 feet or more.

Figure 7 is a schematic section that illustrates vertical zoning relationships interpreted for the original San Manuel-Kalamazoo orebody. Concentric mineralization and alteration zones were roughly cylindrical in shape, but several zones appear to have converged upward, and the overall configuration of the system may have been beet shaped with a restricted root in depth. The hydrothermal magnetite and quartz-sericite-chlorite ± K-feldspar zones occurred only near the bottom of the orebody, and little is known regarding their configurations.

1. The core of the concentric alteration system or low-grade center mineral zone grades upward from quartz-sericite-chlorite ± K-feldspar alteration to biotite K-feldspar.

2. The ore-shell mineral zone progressively transgresses upward across the contact of the biotite K-feldspar and quartz-sericite zones. The upper portion of the ore shell is entirely within the quartz-sericite zone. Chalcopyrite mineralization appears to grade from predominantly bleb and veinlet type at the bottom to predominantly fine-grained disseminated at the top.

3. The zone of marginal mineralization surrounding the ore shell grades from chlorite-sericite-magnetite at the bottom to quartz-sericite alteration through most of the length of the orebody.

4. Magnetite substitutes for pyrite to a large extent in the bottom portion of the pyritic zone. Sericite content appears to decrease with the decrease in pyrite downward and to increase with the increase of pyrite content upward. The strongest pyrite mineralization was near the original top of the orebody.

5. Alteration surrounding the pyritic zone grades upward from disseminated and veinlet magnetite, chlorite, sericite, epidote at depth to chlorite, epidote, carbonate. Little is known of the general configuration of this zone because it has been partially destroyed by erosion and most of the present surface area is covered by postore formations. It seems likely that the overall configuration was beet shaped with a constricted root.

Geological Premises for Kalamazoo Project

The initiation of the Kalamazoo project was based upon the assumptions by the writer that (1) the San Manuel low-grade center and its potassic alteration represented the most, rather than the least, intense alteration zone present and, therefore, perhaps the

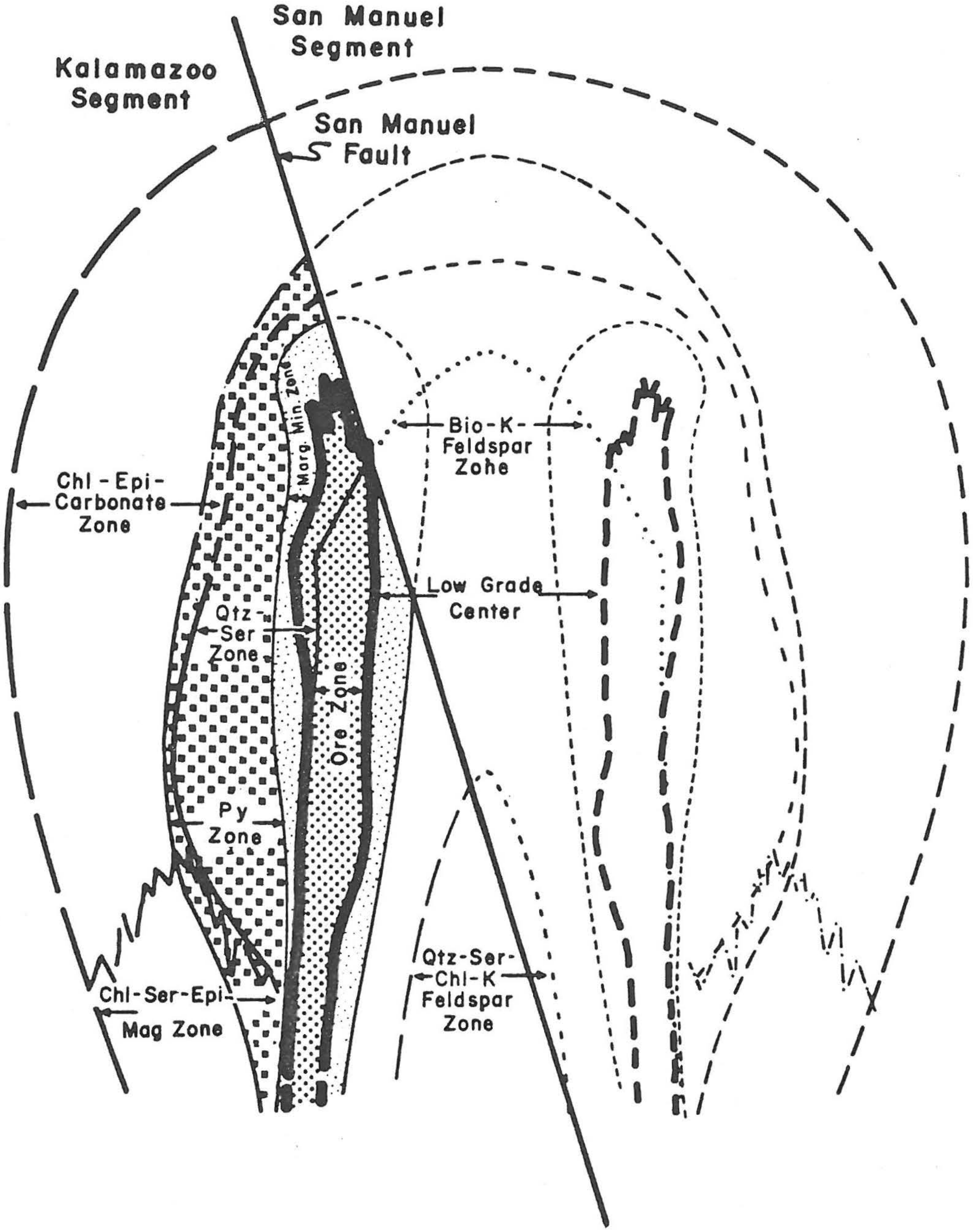


FIG. 7. Schematic section of San Manuel-Kalamazoo orebody showing vertical alteration and mineralization zones. Solid lines and shaded areas represent observed geology, and broken lines indicate extrapolated information. (See Fig. 2 for position of this section relative to final configuration of orebodies.)

core of an original cylindrical-shaped orebody, and that this original orebody would have had coaxial alteration and mineralization zones which would complete the cylindrical symmetry found truncated at San Manuel; (2) evidence existed for at least 45° of tilting of this cylindrical-shaped orebody and that it was reasonable to postulate additional tilting in pre-Cloudburst time so that the cylinder could have been originally in a near-vertical position typical of pipe-like porphyry copper deposits; and (3) the direction of displacement in the San Manuel fault could more logically have been in a down-dip direction as proposed by Steele and Rubly (1947) and Schwartz (1953) rather than having "had a domi-

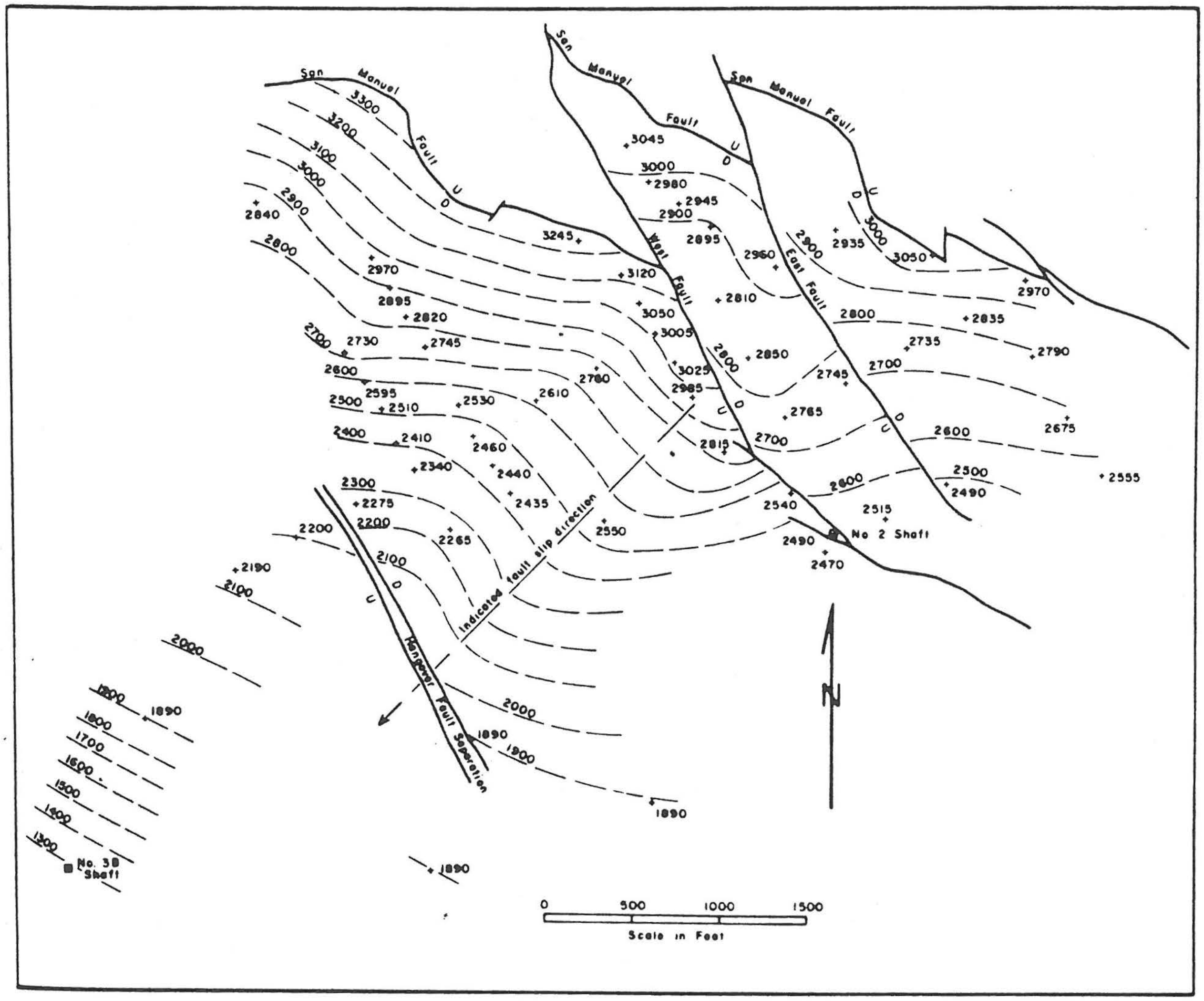


FIG. 8. Structure contour map of the San Manuel fault plane. Elevations are shown in feet above sea level.

nant component of right-lateral strike-slip movement" as postulated by Creasey (1965, p. 28) or having had reverse fault displacement as proposed by Wilson (1957) and Heindl (1963).

Kalamazoo Exploration Project

Initial investigation involved reviewing the geologic and assay logs and drill cuttings samples from the old Purcell drill holes. It was found that four of these holes apparently penetrated from weakly pyritic propylitic alteration into a strongly pyritic, quartz-sericite zone at depth, and one hole apparently bottomed in mineralization typical of the San Manuel marginal mineralization zone. The geometry of these intersections together with the projection of the San Manuel fault plane approximately determined the position of the cylindrical-shaped Kalamazoo pyritic zone.

A geochemical soil survey was carried out in the pre-ore outcrop area of the Purcell claims. This survey produced a moderately well-defined copper and molybdenum anomaly which was later found to overlie the Kalamazoo orebody. The anomaly probably represents the outcrop of a cylindrical shell of comparatively copper-rich (±0.04% Cu) propylitic alteration. Assaying the soil samples for total Fe produced a less well-defined anomaly approximately centered on the orebody which is thought to represent the outcrop of a shell of pyrite mineralization within the propylitic zone but outside the strong pyritic zone. The geochemical survey was not diagnostic in itself but did serve as additional evidence for the location of the faulted segment.

Elevations of intersections of San Manuel drill holes with the San Manuel fault were compiled from U.S.G.S. Professional Paper 256 and were contoured by W. F. Chester and the writer in a structure contour map of the San Manuel fault. This map (Fig. 8) showed large ridges and valleys in the fault surface which formed a large-scale mullion structure consistent with dip-slip normal fault displacement. The Kalamazoo orebody was located by the first drill hole that was spotted according to the normal faulting interpretation and the other evidence cited.

The first Quintana Minerals Corporation drill hole penetrated through Gila Conglomerate and Cloudburst formation into monzonite porphyry with, first, propylitic and then quartz-sericite alteration. The hole passed from the pyritic and marginal mineralized zones into ore-grade mineralization at about 2,500 feet. From structural considerations it appeared that the axis of the Kalamazoo orebody might have an orientation of N57°E. A 600-foot rectangular drill grid on a N33°W and N57°E orientation was laid out centered on the first drill hole. The unique opportunity for extrapolating geology and symmetry of mineral zones from the San Manuel deposit has made it possible to intersect the Kalamazoo orebody with every hole completed to date.

Typical holes in the project were drilled to a depth of about 3,000 feet by the relatively cheap rotary drilling method. The rotary cuttings were assayed using a field analytical method and, when the assays reached 0.2% copper, coring was begun. The final intercept of approximately 1,000 feet which contains the marginal and ore zones was completed with NX wireline core drilling by the same drill rig. No casing was used. Holes were drilled with oil field type rotary drill rigs equipped with 95-foot masts, automatic bit pressure controls, and geolograph recorders. Drill operations in the project were planned and managed by the Quintana Minerals Corporation drilling department.

The Kalamazoo orebody has the shape of an overturned canoe, and the first ore block mined will be the relatively wide and flat canoe bottom. This ore block will be overlain by the marginal mineralization zone so that block-cave dilution material will contribute some values to the mill heads. The ore lacks any chalcocite enrichment but is also free of oxide copper content. The molybdenum content falls in the same range as in the San Manuel orebody, and the ore contains a small recoverable amount of gold and silver. The rock in the Kalamazoo orebody appears to be suited to block-caving mining under conditions similar to those found in the nearby San Manuel mine.

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TUCSON, ARIZONA,
March 18; April 20, 1968

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DAY 2

AGS 1984 SPRING FIELD TRIP

ROAD LOG

Day 2

Milepost 105

Log begins on Highway 77 at milepost 105, turnoff to the Day 1 area. For the next 3 1/2 miles the road cuts are in San Manuel Formation.

Mile 108.5

The San Manuel fault is well exposed in this road cut. San Manuel formation to the west is faulted against Oracle granite to the east on a structure dipping 40° west. The east flank of the Oracle outcrop is depositionally overlain by shallow dipping, white to gray conglomerates. These may be a facies of the Quiburis formation which is defined to include the flat lying lacustrine and/or overbank deposits which fill the floor of the San Pedro valley to the north and south and fluvatile distributaries. A date on interbedded glassy tuff in the Quiburis to the south yielded an age of 5.2 m.a., consistent with Hempilian mammal faunas described from this formation. Depth to pre-mid-Tertiary basement in the San Pedro valley rarely exceeds 1000 feet near the river but cover thickens significantly eastward towards the fault bounded west face of the Gailuro Mountains.

Mile 111.5 - Watch for radar

Town of Mammoth, founded by miners working the Mammoth, Collins and other veins of the mid-Tertiary gold mineralization of the Mammoth district

2 1/2 miles west. From here to Winkleman, road cuts mainly expose Pleistocene gravels unconformably overlying Quiburis formation, and young gravels (<30,000 years old) which fill older channels, forming the present "Aravaipa" surface.

Milepost 122 (approx.)

About 10 miles north of Mammoth is the turnoff to Aravaipa Creek. Due west is Putnam Wash which branches 2 miles west of the San Pedro to form Camp Grant Wash on the south. The Camp Grant fault, described in the introduction, is 2000 feet southwest up Camp Grant Wash. Gypsum is mined from beds in the Quiburis formation east and north of here. The cut on the hillside west of the San Pedro is in Escabrosa limestone, probably mined for flux.

Milepost 123 to 124 (approx.)

Fine grain, flat lying, thin bedded to laminate Quiburis formation is visible from the road.

Follow Highway 77 to Winkleman and turn west on Highway 177 to the turnoff to the Kennecott plant at Hayden. Park while someone gets a guard to open the bridge, and then proceed across the bridge and turn west.

INTRODUCTION

The Tortilla Mountains expose a series of strongly rotated fault blocks which are depositionally overlain by synkinematic middle Tertiary sediments (Figures 1 & 2). Each fault block consists of 1.4 b.y. old Ruin Granite, with minor inclusions of 1.7 b.y. old Pinal Schist, and minor intrusions of Precambrian diabase, Cretaceous quartz diorite, and Cretaceous and Tertiary felsic dikes. (The Western limits of the fault blocks are represented by west-dipping, low-angle normal faults which juxtapose Tertiary sediments with the underlying Precambrian granite.) These faults include the Ripsey Wash Fault, the Indian Camp Wash Fault, and the Camp Grant Fault.

The Eastern edges of the blocks consist of thin, approximately vertically dipping, northwest-striking remnants(?) of late Precambrian and Paleozoic sedimentary rocks. The contact between these sedimentary rocks and the Ruin Granite is depositional rather than tectonic. The sediments young to the east and occur in their original depositional sequence. Minor exceptions to this occur in the Winkleman quadrangle, where units are repeated by faults which, at least in their present configuration, dip eastward less steeply than bedding and effect high-angle, normal separation. Krieger (1974 b) interprets these faults as rotated Laramide thrust faults. The Precambrian and Paleozoic rocks are also cut by numerous east-northeast-trending high--angle faults. These produce both left-lateral and right-lateral apparent offsets, and typically do not extend into the overlying Tertiary sediments.

A small angular unconformityu separates the Precambrian and Paleozoic rocks from the overlying Tertiary San Manuel formation. Although Krieger (1974 a) and Cornwall and Krieger (1975 a,b) show this contact as a fault, Schmidt (1971), Krieger (1974 b), and original research show this contact to be an unconformity. The bedding at the base of the San Manuel formation typically strikes northwest and dips 60° to 80° eastward. Higher in the section the bedding dips decrease to approximately 30° east. In the southern part of the Kearny quadrangle the bedding defines several open, northwest-trending synclines and anticlines (Figure 3).

Lithologically, the San Manuel formation consists primarily of thinly bedded, medium to coarse-grained, maroon sandstones and conglomerates. The beds contain abundant dessication cracks and exceedingly few paleocurrent indicators. Krieger (e.g., 1974 a,b) interprets the formation as playa lake and alluvial deposits, and subdivides it into several members on the basis of both clast type and depositional environment.

MONOLITHOLOGIC MEGABRECCIAS

Several kilometer-scale lenses of monolithologic megabreccia occur within the lower San Manuel formation in Hackberry Wash. The breccia lenses are derived from various limestones, quartzites, and basalts or diorites. The breccia clasts are generally centimeter-scale in size, variably rounded and rotated. Despite the pervasive fracturing and rotation, however, there is no mixing of clasts of different rock types. Contact relations are commonly preserved, and the original depositional stratigraphy is also preserved in some of the breccias.

The breccias apprently represent catastrophic rockfalls and landslides which occurred early in the depositional history of the formation. The breccias apparently slid into place along a cushion of compressed air, conformable with the underlying deposits. Where the leading edge of one megabreccia lens is exposed, however, the underlying sediments are highly folded and deformed, suggesting that the breccia lenses were emplaced by ploughing into the still soft, underlying deposits (Cornwall and Krieger, 1978).

KINK FOLDS

The "dark playa deposit" member (Tsdp) of the San Manuel formation contains a peculiar style of kink fold. These are monoclinal kink bands which appear to represent a horizontal extension in terms of strain, and which require an extensional stress configuration as a condition of formation. The folds are on the order of a meter in size, and are very rarely related to faults. The fold axes trend northwest-southeast, and the fold axial planes strike northwest and dip subvertically (Figure 4). In Hackberry Wash, where the enclosing beds dip approximately 35° to the northeast, the folds typically face southwest; the middle limbs of the folds have been rotated an average of 30° towards horizontal. In the area located west of Hackberry Spring, where the enclosing beds dip approximately 40° to the southwest, the folds typically face northeast; the middle limbs of these folds also have been rotated an average of 30° towards horizontal. Thus the middle limbs of the folds are rotated in opposite directions in the two domains, but in both cases it is rotated back towards a subhorizontal position (Figure 5).

These folds do represent layer-parallel shortening. However, because the beds are inclined, and because the middle limb is uniformly rotated back towards horizontal, the folds are effecting horizontal extension. As shown schematically in Figure 6, the horizontal projection of the fold limb prior to folding (L_2 cos 30°), is shorter than the horizontal projection of the limb after folding (L_2).

If the folds initially formed in horizontal beds and later rotated to their present orientation, they would not represent horizontal extension. However, because the folds' asymmetries or vergences appear to be dependent on the present attitudes of the beds, the folds appear to have formed during or after the beds were rotated. If the folds formed in horizontal beds under a uniform stress confirugation (e.g., compression), they should have the same vergence regardless of the present orientation of the enclosing beds.

The stress configuration implied by these folds is also extensional. Both field and experimental studies show that kink folds require high layer-parallel shear stresses (Dewey, 1965; Reches and Johnson, 1976). More importantly, they show that the sense of shear associated with monoclinal kink bands is exactly opposite that which is normally associated with parasitic drag folds (Figure 7). Thus the "up-dip" vergence of the San Manuel kink folds indicates a normal sense of shear stress rather than a reverse sense (Figure 8). This, in turn, implies that the principal compressive stress was vertical, not horizontal, and that the stress field was extensional rather than compressive.

When combined with the surface and subsurface data shown in Figures 1 and 2, these analyses of the kink folds suggest that they formed in response to large-scale rotations along extensional faults. As the San Manuel beds were rotated through some critical dip inclination, the layer-parallel shear stress due to gravity exceeded some threshhold value required for the formation of kink folds, and subsequently produced the observed folds.

Experimentally, the formation of kink-style folds, as opposed to concentric-style, is favored by relatively high contact shear strengths and relatively thin, stiff beds (Reches and Johnson, 1976). The thinly bedded, coarse-grained nature of the San Manuel formation thus may explain why kink folds formed rather than some other style of fold.

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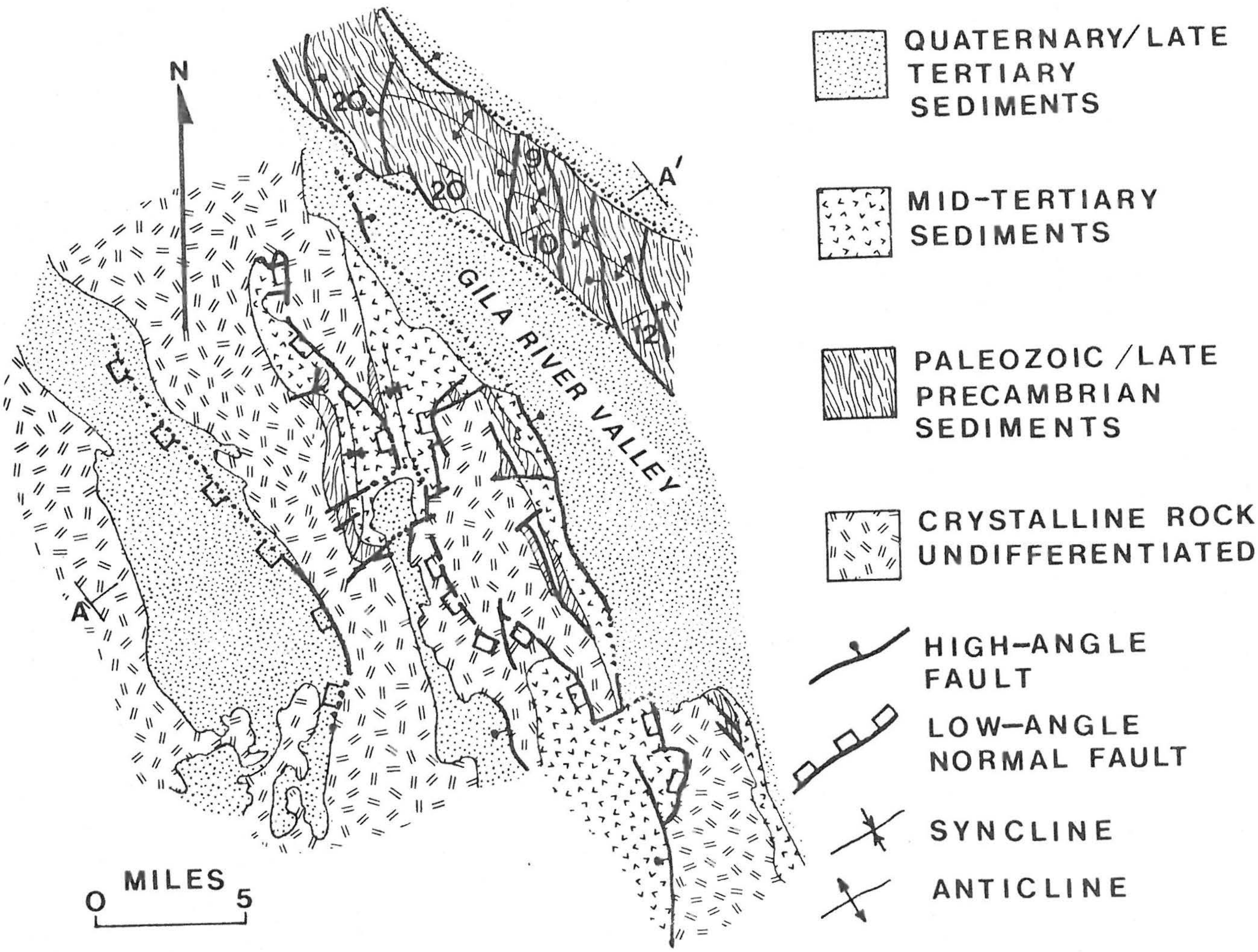


Figure 1. Simplified geologic map of the northern Tortilla Mountains and Dripping Spring Mountains.

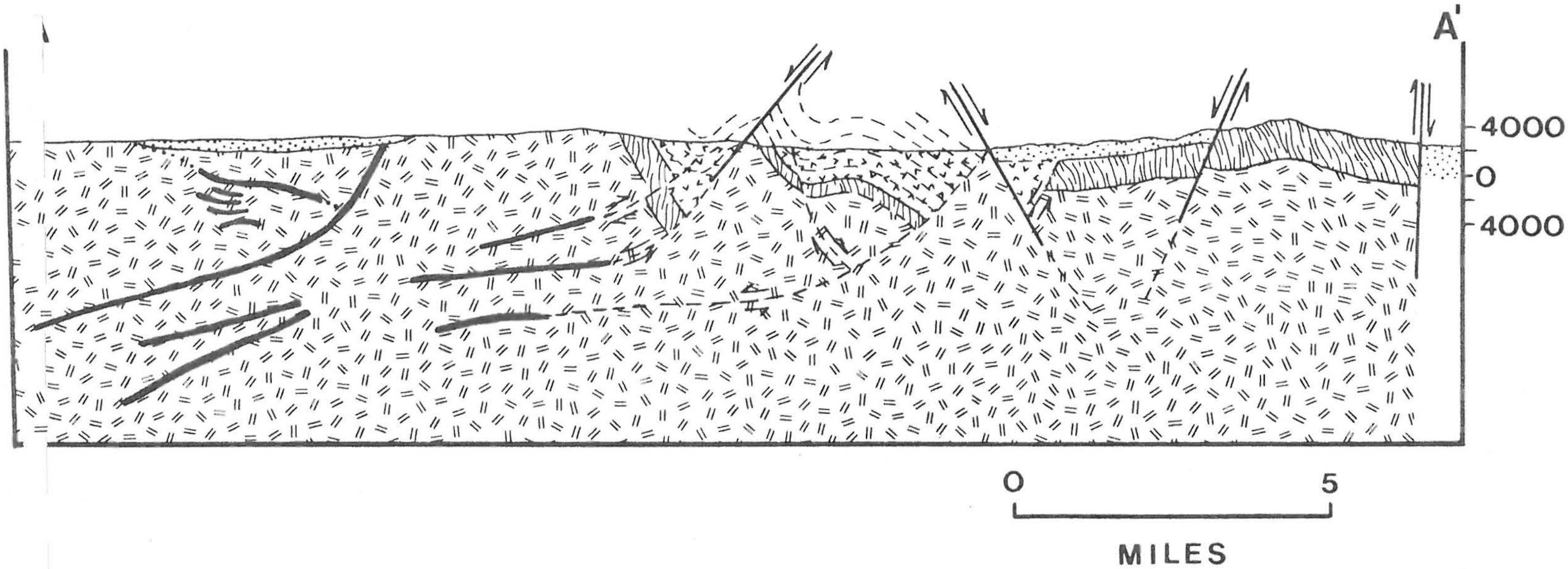


Figure 2. Structure section across the northern Tortilla and Dripping Spring Mountains. Heavy lines in subsrface are seismic reflections taken from Anschutz seismic cross section AZ 18.

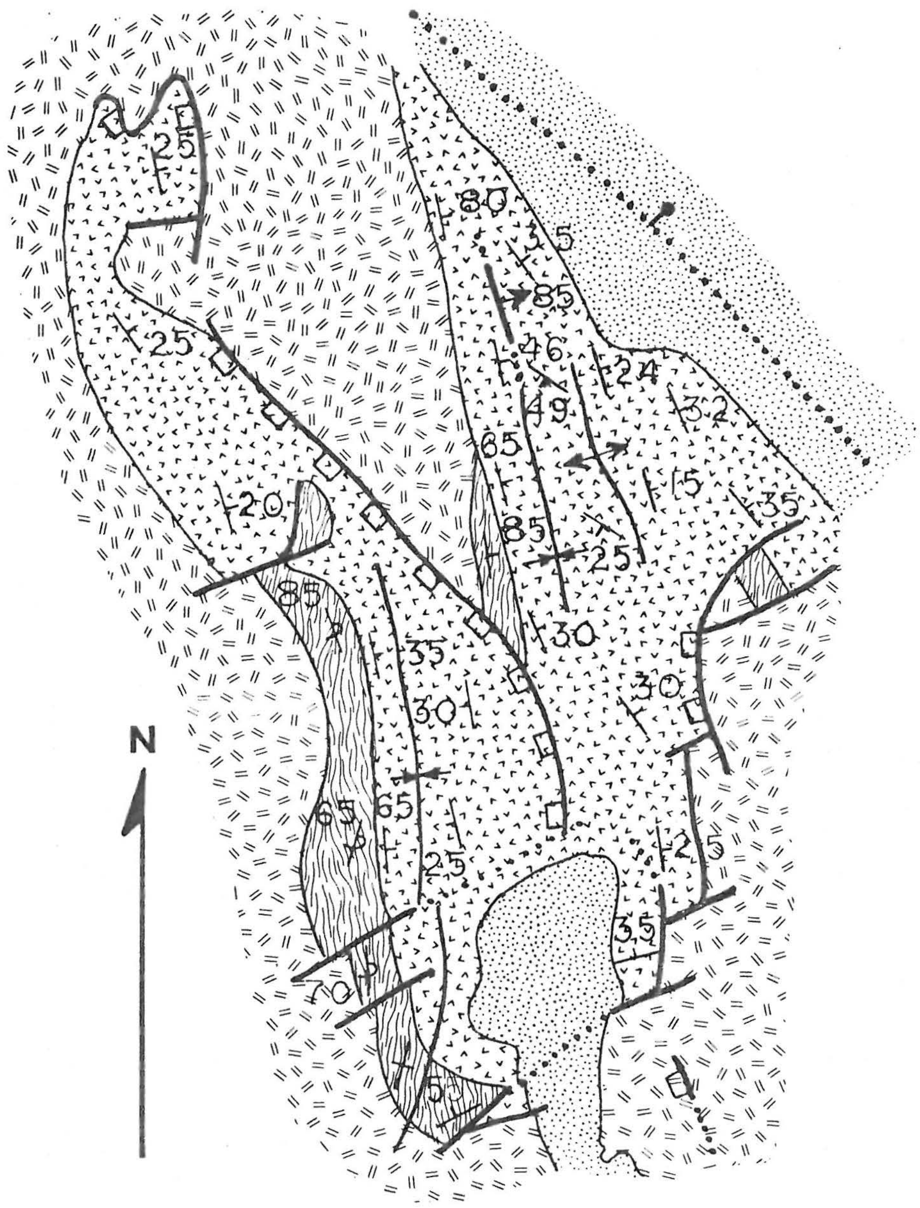


Figure 3. Simplified geologic map of the Hackberry Wash and Ripsey Wash areas in the northern Tortilla Mountains.

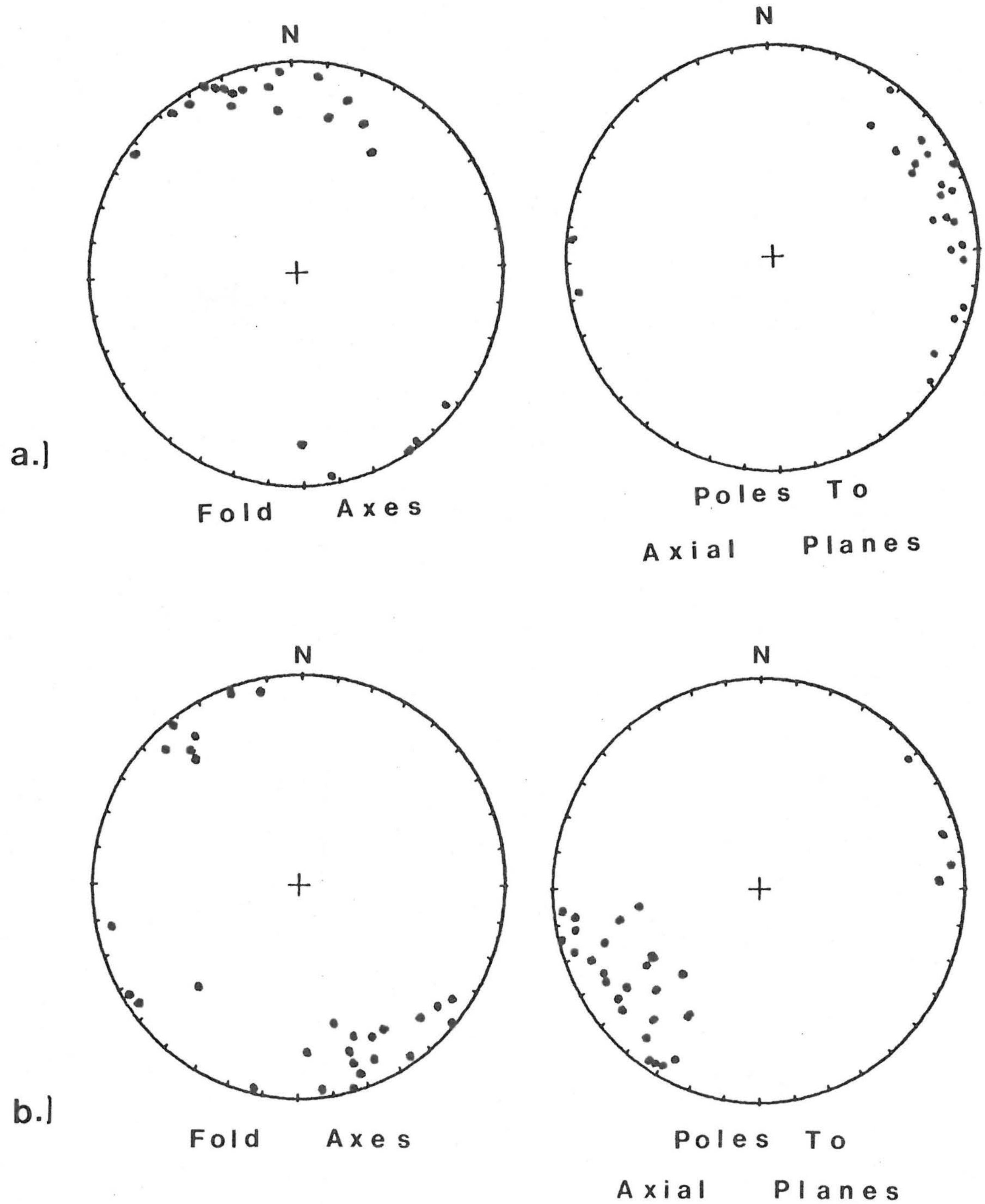


Figure 4. Lower hemisphere, equal area projections of kink fold axes and poles to axial planes. a.) Hackberry Wash. b.) West of Hackberry Spring.

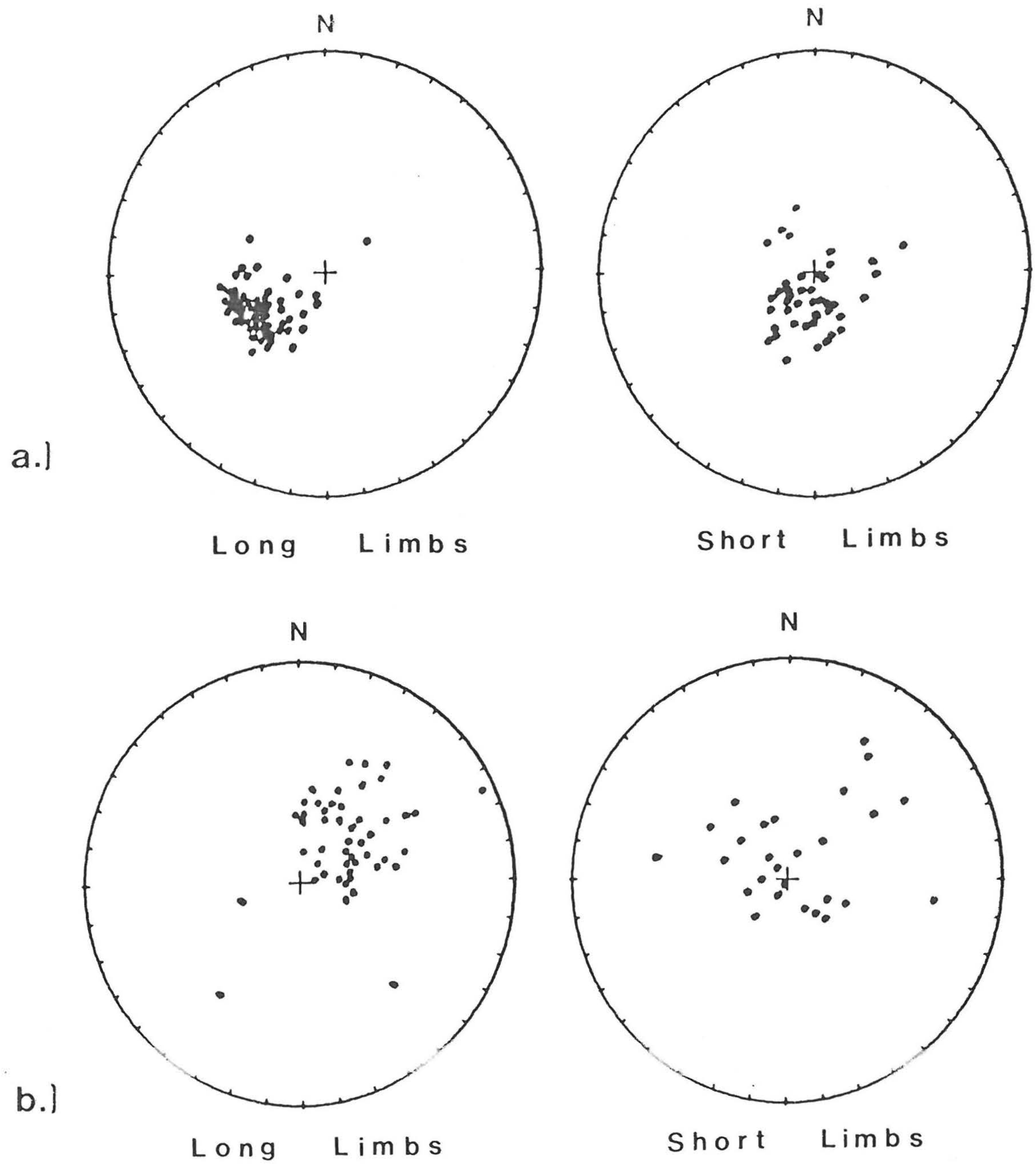


Figure 5. Lower hemisphere, equal area projections of poles to unrotated (long) limbs and rotated (short) limbs of kink folds. a.) Hackberry Wash. B.) West of Hackberry Spring.

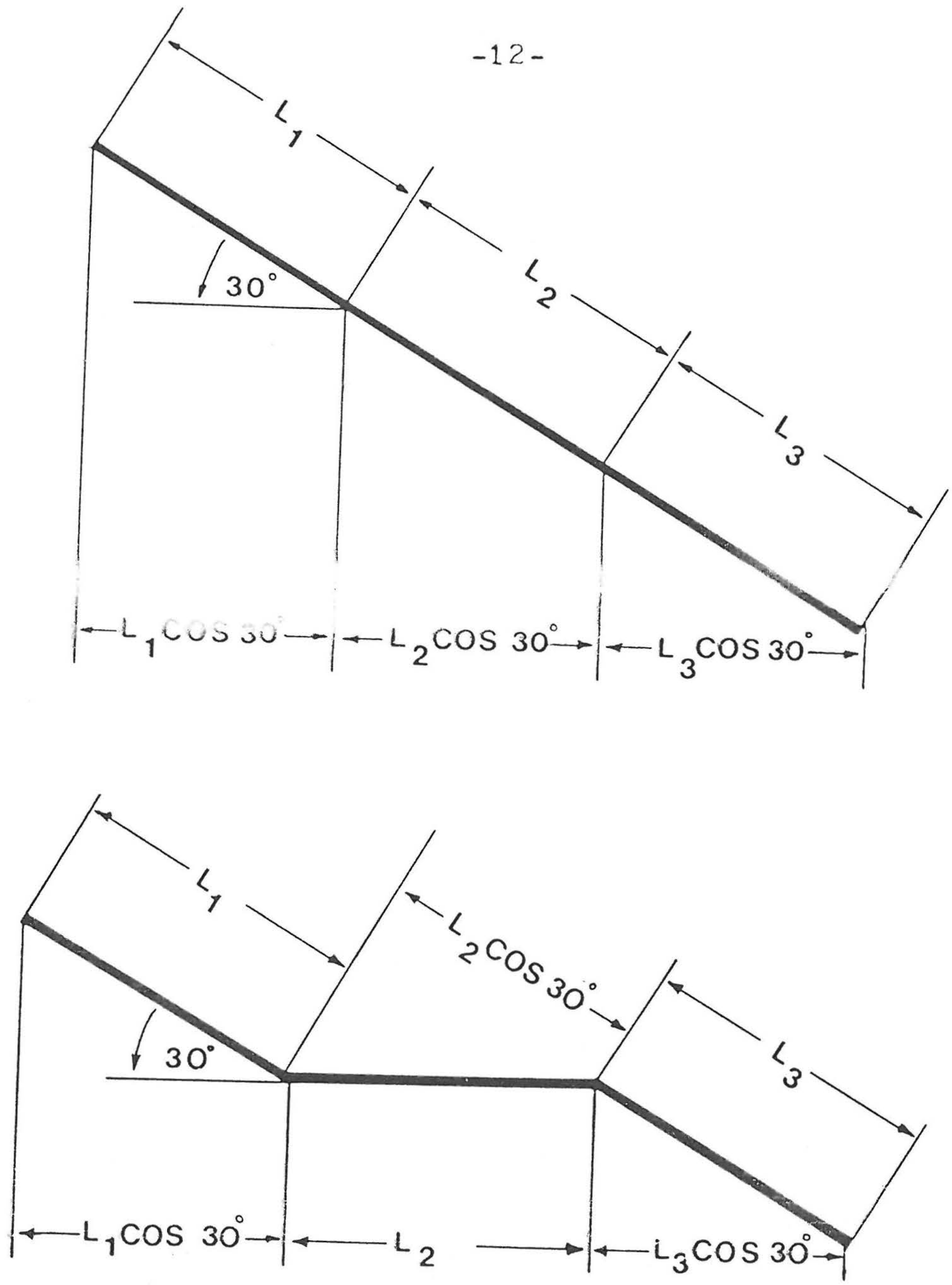


Figure 6. Schematic diagram of a kink fold. The horizontal length or projection of the rotated limb (L_2) is longer than that of the unrotated limb ($L_2 \cos 30^\circ$).

STOP DESCRIPTIONS

Stop 1 View of Hackberry Wash

View looking west at steeply dipping San Manuel formation. Prominent, light-colored beds dipping toward us are steeply dipping beds of monolithologic megabreccias at the base of the San Manuel. Beyond the megabreccias lie steeply dipping beds of the Apache Group, and Ruin Granite. All are in depositional contact.

Stop 2 Folded San Manuel Formation

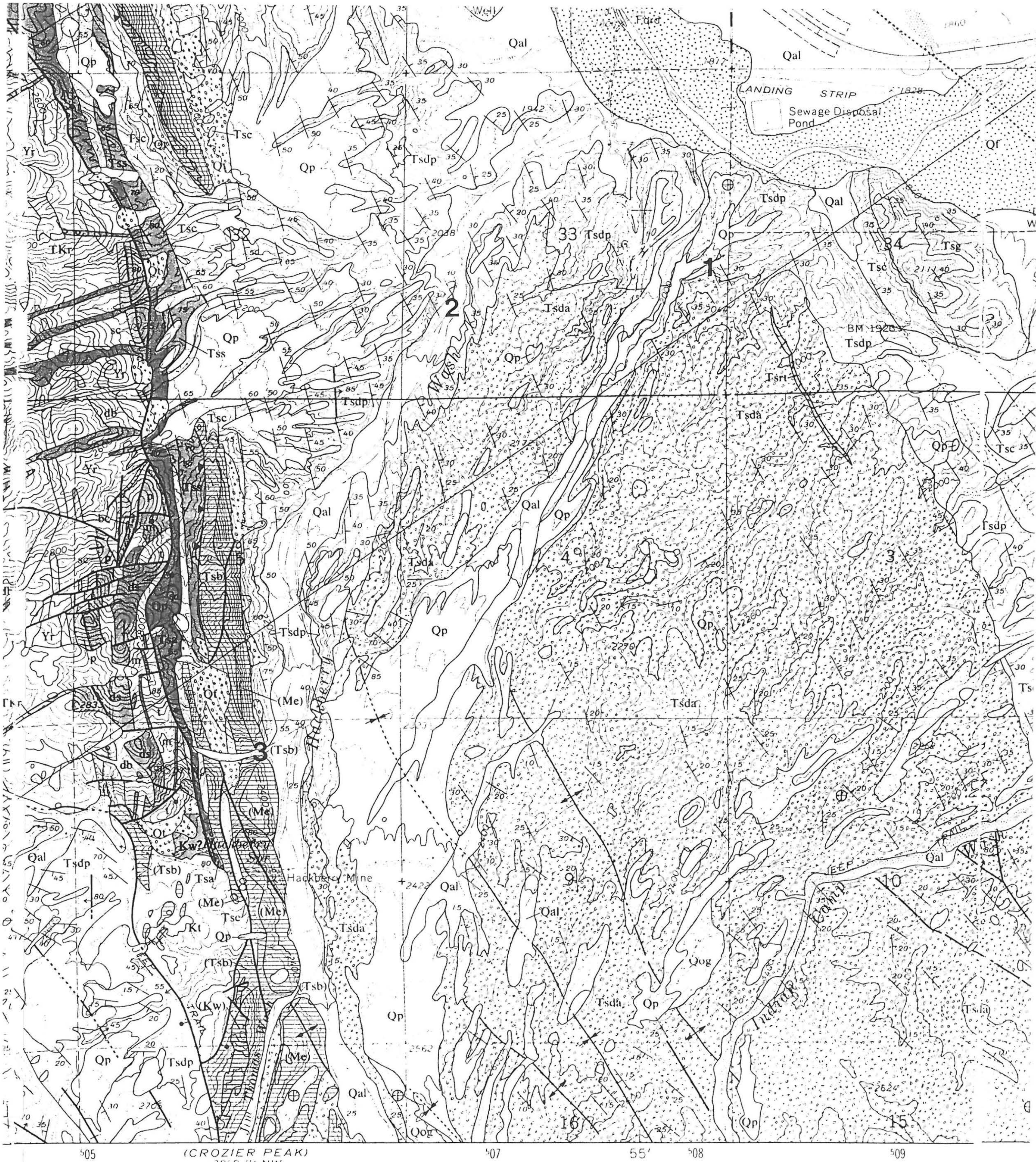
These outcrops illustrate the typical thin-bedded, coarse-grained nature of the formation. Note also the dessication cracks, and the lack of paleocurrent indicators.

The folds exposed here are typical of the folds in the northeast-dipping beds. They are straight-limbed with angular hinges. The middle limbs are rotated counterclockwise towards the horizontal. Note that the kink bands are not visibly related to any faults.

Stop 3 Megabreccias and Base of San Manuel Formation

This east-west wash exposes a cross section through several megabreccias, as well as the base of the formation. The uppermost (easternmost) breccia is composed of clasts of Escabrosa Limestone. The lower breccias consist of monolithologic lenses of quartzite, massive limestone, thin-bedded limestone, and basalt or diabase clasts. Note the variable clast sizes, amounts of rotation, and degrees of rounding. Despite the pervasive fracturing and rotation, there is virtually no mixing of clasts. Slickensided fault surfaces occur at the base of some of the breccias on the south side of the wash. Undeformed sandstones and conglomerate occur below the breccias, near the head of the wash.

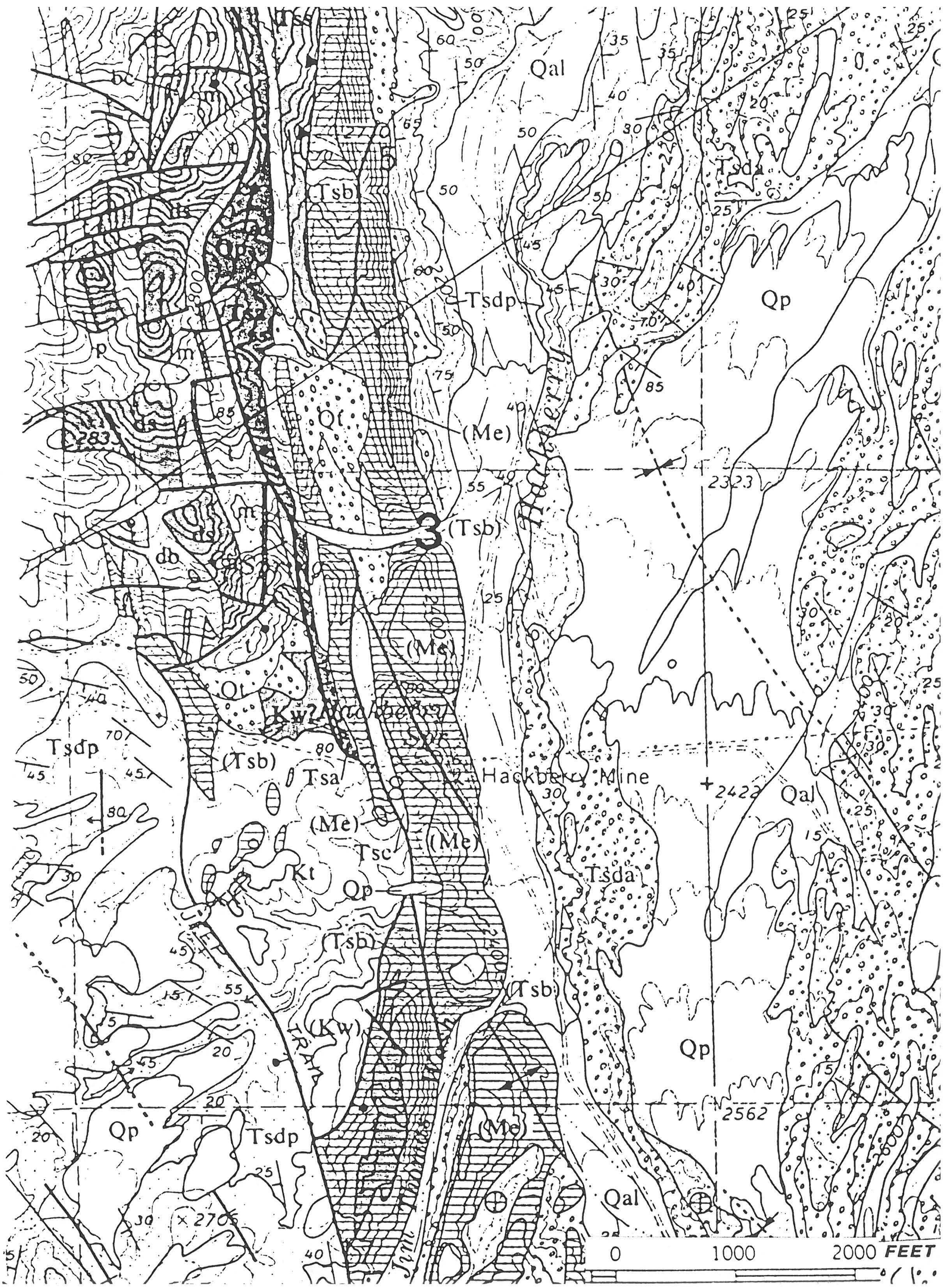
Troy and Bolsa Quartzite occur below the San Manuel formation, forming the headwall at the west end of the wash. The basal contact of the San Manuel is not actually exposed. However, there is no evidence to suggest it is a fault. Exposures a short distance to the south suggest rather that it is an unconformity.



SCALE 1:24 000

CONTOUR INTERVAL 40 FEET
DOTTED LINES REPRESENT 20-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL

QUADRANGLE LOCATION


Qal
Tsda
Tsb
Tsdp
Qp
(Me)
Qt
(Tsb)
Hackberry Mine
Tsa
Tsc
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Qal
2323
2422
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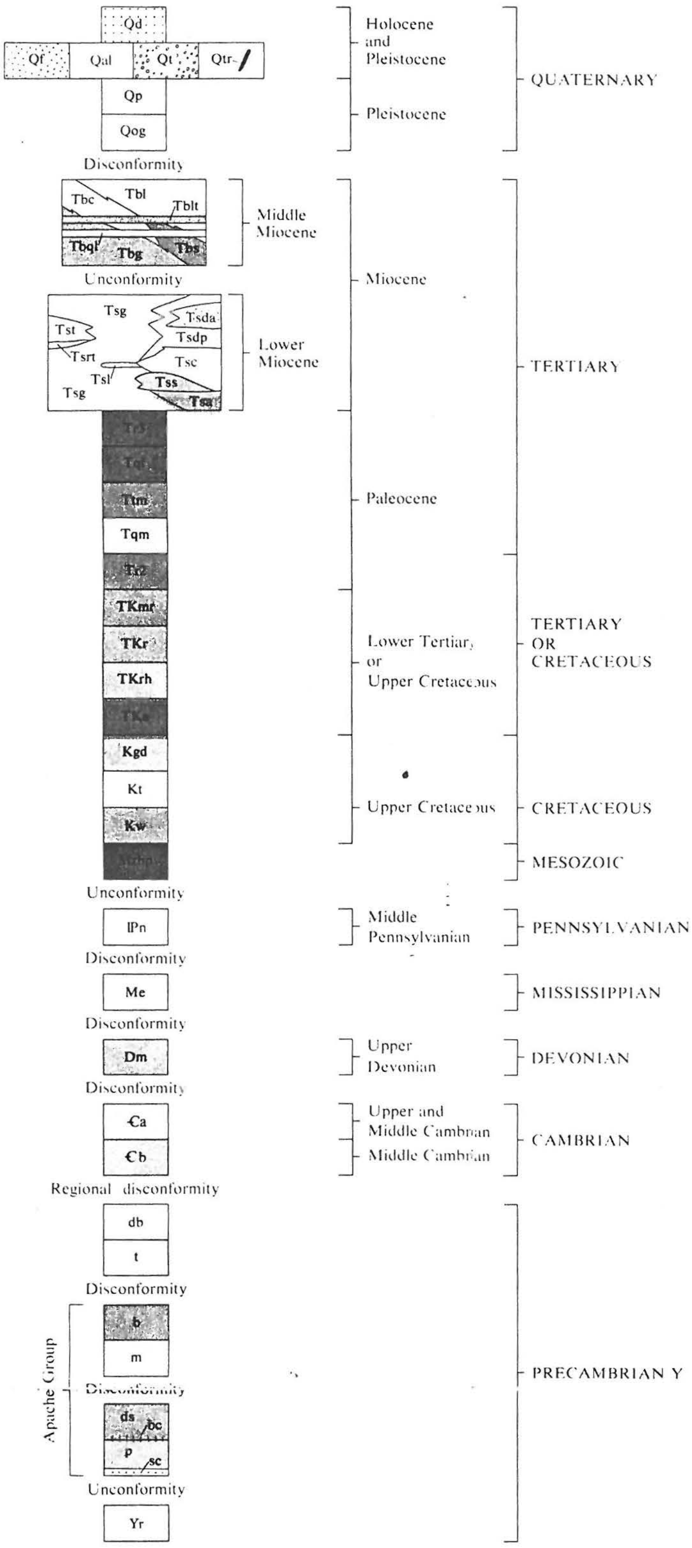
0 1000 2000 FEET

CORRELATION OF MAP UNITS



DEFINITION OF MAP UNITS

SURFICIAL DEPOSITS

Qd	Mill tailings
Qf	Alluvium of the Gila River flood plan
Qal	Alluvium
Qt	Talus
Qtr	Travertine
Qp	PEDIMENT GRAVELS
Qog	OLDER GRAVELS

BIG DOME FORMATION (middle Miocene)

Tbl	Limestone conglomerate
Tbc	Conglomerate
Tblt	Lapilli tuff
Tbs	Sandstone and conglomerate
Tbql	Quartz-latite ash-flow tuff
Tbg	Granitic conglomerate

SAN MANUEL FORMATION (lower Miocene)

Tsg	Granitic conglomerate
Tsda	Dark conglomerate
Tsdp	Dark playa deposits
Tst Tsrt	Tuffaceous sandstone and conglomerate Tsrt, rhyolitic to dacitic tuff
Tsc	Playa claystone
Tsl	Limestone conglomerate
	MEGABRECCIA — units that can be assigned to a particular formation are shown in the color of that formation and its symbol given in parentheses
(Kw)	Williamson Canyon Volcanics
(IPn)	Naco Limestone
(Me)	Escabrosa Limestone
(Dm)	Martin Formation
(t)	Troy Quartzite
(db)	Diabase
(Yr)	Ruin Granite
(Tsb)	Megabreccia, undivided. Includes Williamson Canyon Volcanics
Tss	Playa sandstone
Tsa	Quartzite conglomerate

Tr1	RHYODACITE PORPHYRY
Tql	QUARTZ LATITE PORPHYRY
Ttm	TEAPOT MOUNTAIN PORPHYRY (Paleocene)
Tqm	QUARTZ MONZONITE
Tr2	RHYODACITE PORPHYRY
TKmr	MELANOCRATIC RHYODACITE PORPHYRY
TKr	RHYODACITE PORPHYRY
TKrh	RHYODACITE PORPHYRY
TKa	ANDESITE
Kgd	GRANODIORITE
Kt	TORTILLA QUARTZ DIORITE (Upper Cretaceous)
Kw	WILLIAMSON CANYON VOLCANICS (Upper Cretaceous)
[illegible]	BASALT PORPHYRY
IPn	NACO LIMESTONE (Middle Pennsylvanian)
Me	ESCABROSA LIMESTONE (Mississippian)
Dm	MARTIN LIMESTONE (Upper Devonian)
Ꞓa	ABRIGO FORMATION (Upper? and Middle Cambrian)
Ꞓb	BOLSA QUARTZITE (Middle Cambrian)
db	DIABASE
t	TROY QUARTZITE (Precambrian)

APACHE GROUP

b	Basalt
m	Mescal Limestone (Precambrian)
ds bc	Dripping Spring Quartzite (Precambrian) bc, Barnes Conglomerate Member
p sc	Pioneer Formation (Precambrian) sc, Scanlan Conglomerate Member
Yr	Ruin Granite (Precambrian Y)

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GENERALIZED GEOLOGY AND STRUCTURE OF THE WINKELMAN 15-MINUTE QUADRANGLE AND VICINITY, PINAL AND GILA COUNTIES, ARIZONA

By M. H. KRIEGER, Menlo Park, Calif.

Abstract.—A northwest-trending belt of steeply east-dipping Precambrian and Paleozoic sedimentary rocks extends across the Winkelman 15-minute quadrangle and separates areas of contrasting structures. To the southwest for 60 mi is an expanse of Precambrian basement, largely granite; to the northeast the Precambrian and Paleozoic sedimentary rocks are gently tilted and intricately faulted. The structure within the Winkelman 15-minute quadrangle is interpreted as a monocline separated into en echelon segments by strike-slip and normal faults. Other monoclines lie to the north and northwest. Most of the tilting that formed the monoclines occurred after deposition of the early(?) Miocene San Manuel Formation. Structural features that repeat the Precambrian and Paleozoic sedimentary rocks within the area and that resemble high-angle faults are believed to have formed as low-angle thrusts, tilted to their present nearly vertical position during development of the monoclines. Structural features that are younger than the monoclines include low-angle gravity slide surfaces which are older than the high-angle normal faults, that formed the basin-and-range topography on which the Pliocene sediments were deposited.

This paper describes and interprets the geologic structure within and adjacent to the Winkelman 15-minute quadrangle (fig. 1). The four 7½-minute quadrangles that make up the 15-minute quadrangle are being published in the quadrangle-map series at a scale of 1:24,000 (Krieger, 1974a-d). The interested reader is referred to these maps for more details on the structure and for fuller descriptions of the stratigraphy of the area. The most obvious structural features are en echelon belts of steeply dipping Precambrian and Paleozoic sedimentary rocks that contrast with structural features to the northeast and southwest. Southwest of the 15-minute quadrangle, Precambrian basement rocks are extensively exposed; northeast of it, Precambrian and Paleozoic sedimentary rocks are gently tilted and intricately faulted. The northwest-trending en echelon belts within the 15-minute quadrangle are interpreted as a single monocline later separated into segments by strike-slip and high-angle normal faults.

Acknowledgments.—I thank my colleagues in the U.S. Geological Survey, particularly Max D. Crittenden, Jr., and Norman G. Banks, for stimulating discussion, for many suggestions concerning the structural interpretations, and for critical review of the manuscript.

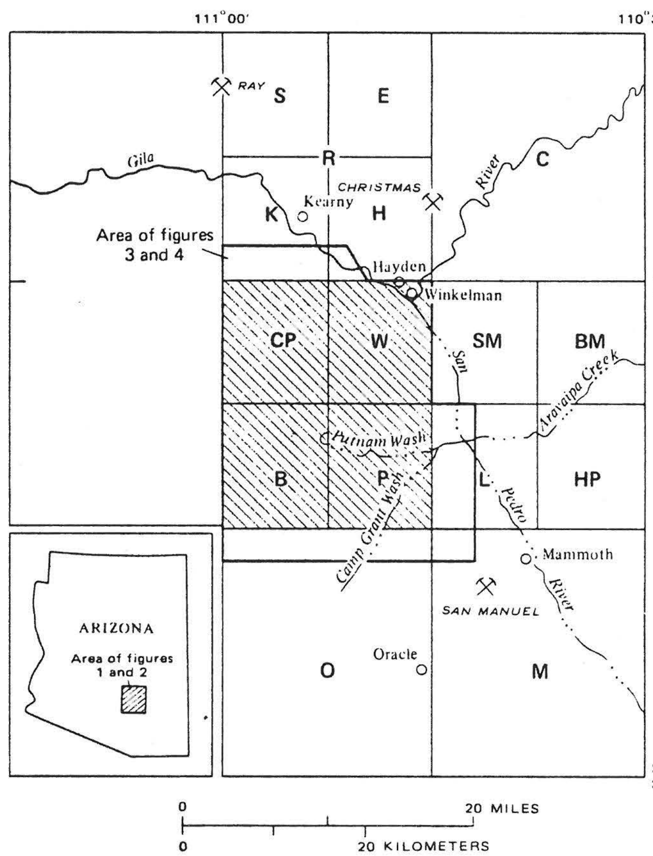


Figure 1.—Index map showing location of the Winkelman 15-minute quadrangle (hatched and shaded) and other quadrangles in southeastern Arizona, and showing location of features referred to in text. Quadrangle names and published data identified as follows: B, Black Mountain (Krieger, 1974c); BM, Brandenburg Mountain (Krieger, 1968a); C, Christmas (Willden, 1964); CP, Crozier Peak (Krieger, 1974b); E, El Capitan; H. Hayden (Ransome, 1919; N. G. Banks and M. H. Krieger, unpub. data, 1973); HP, Holy Joe Peak (Krieger, 1968b); K, Kearny, (Cornwall and Krieger, 1974); L. Lookout Mountain (Krieger, 1968c); M, Mammoth (Creasey, 1965, 1967); O, Oracle (from aerial photographs by U.S. Soil Conservation Service and from Creasey and others, 1961); P, Putnam Wash (Krieger, 1974d); R, Ray (Ransome, 1919); S, Sonora (Cornwall and others, 1971); SM, Saddle Mountain (Krieger, 1968d); W, Winkelman 7½-minute (Krieger, 1974a).

STRATIGRAPHY

Rocks in the area discussed (figs. 2,3) range in age from Precambrian to Holocene. The oldest Precambrian rocks are the Pinal Schist and intrusive rocks, mostly the Ruin Granite (Oracle Granite of Peterson, 1938). Batholithic masses of Ruin Granite, dated at about 1,430 m.y., by Silver, (1968) and Damon, Livingston, and Erickson (1962), were intruded after a period of intense deformation that produced nearly vertical east-trending foliation and bedding in the schist. The schist and granite are overlain with profound angular unconformity by unmetamorphosed Precambrian sedimentary rocks of the Apache Group and the disconformably overlying Troy Quartzite. Diabase, about 1,200 m.y. old (Silver, 1960; Damon and others, 1962), forms dikes and sills in the Apache Group and Troy Quartzite and sill-like masses in the schist and granite parallel to the pre-Apache erosion surface. The sills inflated the Precambrian sedimentary section but apparently did not perceptibly tilt the strata. Because of their abundance and narrow outcrop width due to steep dips, diabase sills in sedimentary rocks are not shown in figure 3. Sills in granite and schist are shown with exaggerated width to illustrate their relation to the pre-Apache erosion surface.

After a long period of erosion, Cambrian formations were deposited disconformably on the Precambrian sedimentary rocks and diabase. Devonian, Mississippian, and Pennsylvanian rocks overlie the Cambrian strata.

Volcanic rocks of Late Cretaceous age that disconformably overlie older rocks in the area are (1) the Williamson Canyon Volcanics (fig. 3) of andesitic composition, most abundant northeast of the Winkelman quadrangle, (2) the Cloudburst Formation, composed of volcanic rocks of probable latitic composition, fanglomerate, and sedimentary breccias in the southern part of the area and now standing nearly vertically and underlain by a gently dipping gravity slide surface, and (3) a rhyodacitic to quartz latitic pyroclastic unit, found only

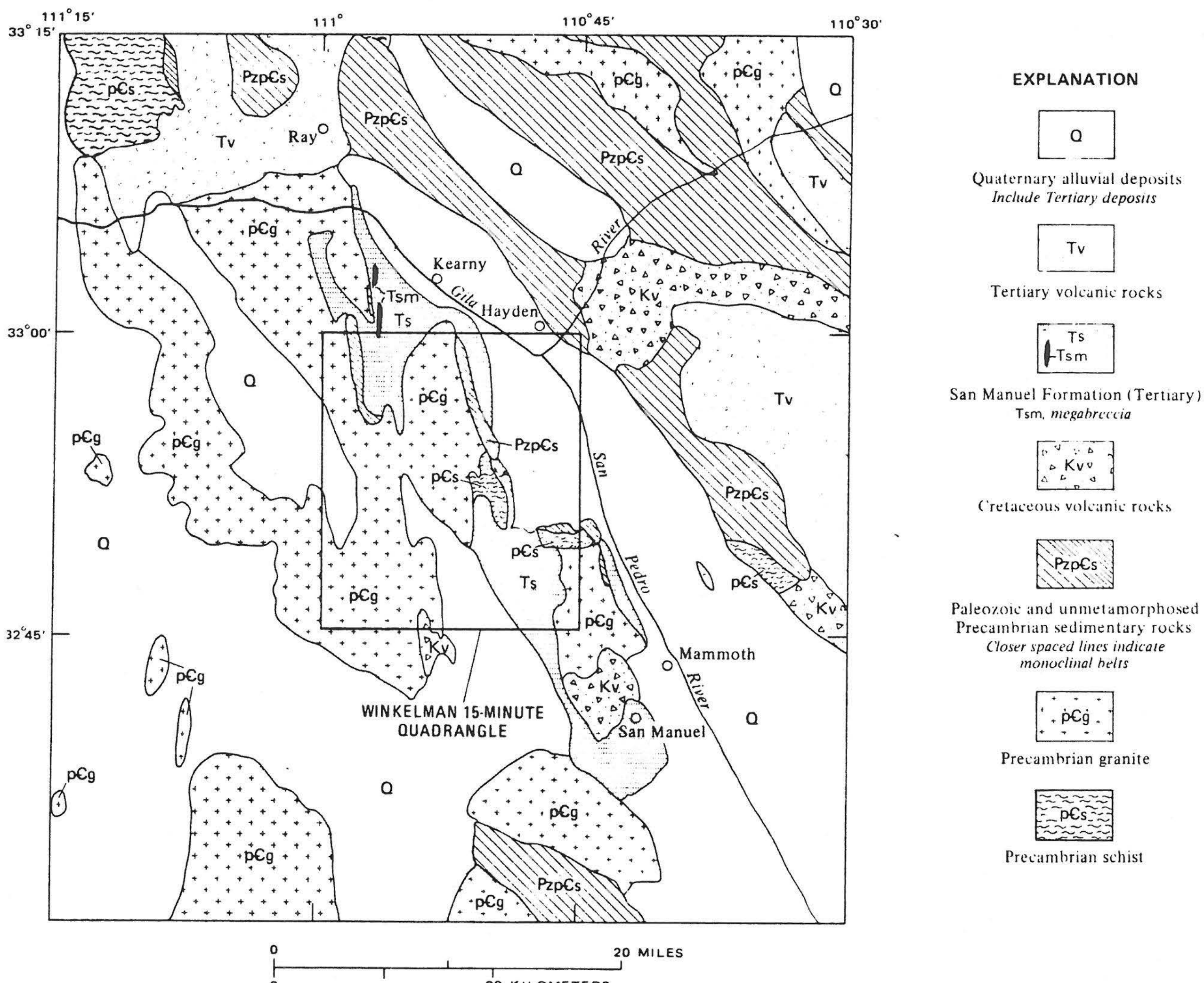


Figure 2.—Regional geologic setting of the Winkelman 15-minute quadrangle. Modified from Wilson, Moore, and Cooper (1969).

in the northwest part of the Crozier Peak quadrangle. The Williamson Canyon Volcanics was considered to be Late Cretaceous by Willden (1964) and Late Cretaceous or early Tertiary by Creasey (1965, 1967). It is now considered to be Late Cretaceous because in the Crozier Peak quadrangle it is intruded by Late Cretaceous diorite (Krieger, 1974b). The Cloudburst Formation is also designated as Late Cretaceous because Creasey (1965, 1967) considered it to be probably the same age as the Williamson Canyon Volcanics in the Christmas quadrangle. The rhyodacitic to quartz latitic volcanic rocks are considered to be Late Cretaceous in age because some of them resemble the Glory Hole Volcanics (east of the area of fig. 3), which is intruded by 69-m.y.-old granodiorite (Simons, 1964; Creasey, 1967).

Late Cretaceous diorite and granodiorite and Late Cretaceous and (or) early Tertiary (Laramide) porphyry masses and dikes of several lithologic types, but largely rhyodacite porphyry, intrude the older rocks. Only the diorite is shown in figure 3. Many of the porphyry dikes and masses are east trending, but older porphyry masses, some possibly of Early Cretaceous age, are conformable and probably were intruded as sills in the Precambrian sedimentary rocks before tilting.

According to the new nomenclature for Cenozoic stratigraphy in eastern Pinal County (Krieger and others, 1974), Tertiary sedimentary deposits in the area (fig. 3), formerly called the Gila Conglomerate or Group, are now divided into the San Manuel Formation (oldest), the Big Dome Formation, and the Quiburis Formation (youngest). Pleistocene and Holocene alluvial deposits, also formerly included in the Gila Conglomerate or Group, overlie these formations.

The San Manuel Formation consists of alluvial and playa deposits and interbedded andesite and megabreccias (not shown separately in fig. 3). The playa deposits and megabreccias are well developed in the Kearny quadrangle (Cornwall and Krieger, 1974). The San Manuel is Miocene (probably early Miocene) in age. Discordant dates on biotite and sanidine from a rhyodacite tuff bed in the upper part of the formation in the Crozier Peak quadrangle are 18 and 24 m.y., respectively. The San Manuel Formation is overlain unconformably by the alluvial Big Dome Formation in the Kearny and Crozier Peak quadrangles. In the Kearny quadrangle, north of the map area, a nonwelded ash-flow tuff in the Big Dome Formation yielded late Miocene K-Ar ages of 14 m.y. on biotite and 17 m.y. on hornblende (Banks and others, 1972). The Quiburis Formation consists of both alluvial and lakebed facies and was deposited in the basin now occupied by the San Pedro River. It contains Hemphillian vertebrate fossils, indicating a middle Pliocene age (John Lance, oral commun., 1963, in Krieger, 1974a). Tertiary volcanic rocks shown in figure 2 include the Galiuro Volcanics (Krieger, 1968, a-d) east of the San Pedro River and the volcanic rocks in the Ray-Superior area. The Galiuro Volcanics has been dated at 22-26 m.y. and probably is about the same age as the San Manuel Formation. The Apache Leap Tuff (part of the volcanic rocks shown in the northwest part of fig. 2) has been dated at 20 m.y. It is older than the Big Dome Formation and probably younger than the San Manuel Formation. Beneath the Apache Leap Tuff is the Whitetail Conglomerate, which contains near its top in the Ray area (Cornwall and others, 1971) a rhyolite tuff bed dated at 32 m.y. (Oligocene).

STRUCTURE

The most obvious structural features in the area are belts of steeply dipping Precambrian and Paleozoic sedimentary rocks that form a series of en echelon ridges separating extensive exposures of Precambrian granite and minor schist on the west from tilted Tertiary sedimentary rocks and gently tilted and intricately faulted Precambrian and Paleozoic sedimentary rocks on the east (figs. 3,4). The steeply dipping belts formed as monoclines, not as the eastern limbs of anticlines. The belts within the Winkelman 15-minute quadrangle are interpreted as parts of a single monocline, later separated by strike-slip and high-angle normal faults. Monoclinal folding commenced before, but continued during and after, deposition of the early(?) Miocene San Manuel Formation.

Within the steeply dipping belts, the section is locally repeated by faults with steep dips which are considered to have formed as low-angle thrusts and to have been tilted to their present nearly vertical position during monoclinal folding. These thrusts and related tears are the oldest structures recognized. They are intruded by Laramide porphyries that are older than the San Manuel Formation. All the other structures are mainly younger than the San Manuel. Possibly some movement on strike-slip faults that segmented the monocline commenced before San Manuel time, but much of it was later. Low-angle gravity slide surfaces underlie the Cloudburst Formation and part of the San Manuel Formation. North-trending high-angle normal faults cut older structural features; some are younger than the Big Dome Formation.

Structural Features Older Than The San Manuel Formation

Thrusts

Faults interpreted to be tilted thrusts (fig. 4) include (1) Ripsey Wash fault, an imbricate structure in the Crozier Peak and southwestern Kearny quadrangles, (2) Romero Wash fault in the Winkelman 7½-minute quadrangle, (3) a thrust extending southward from the Crozier Peak into the Black Mountain quadrangle, and (4) possibly a thrust in the northwestern part of the Lookout Mountain quadrangle. All now have steeply dipping attitudes that closely follow beds of the monoclinal fold. The Ripsey Wash and Romero Wash faults are intruded by Cretaceous porphyries (not shown in fig. 3). Because the folding occurred largely after deposition of the San Manuel Formation, as shown by steep dips in that formation, and because the San Manuel contains clasts of the porphyries, the structural features cannot have formed as high-angle normal or strikeslip faults after formation of the monocline. The Ripsey Wash and Romero Wash faults may

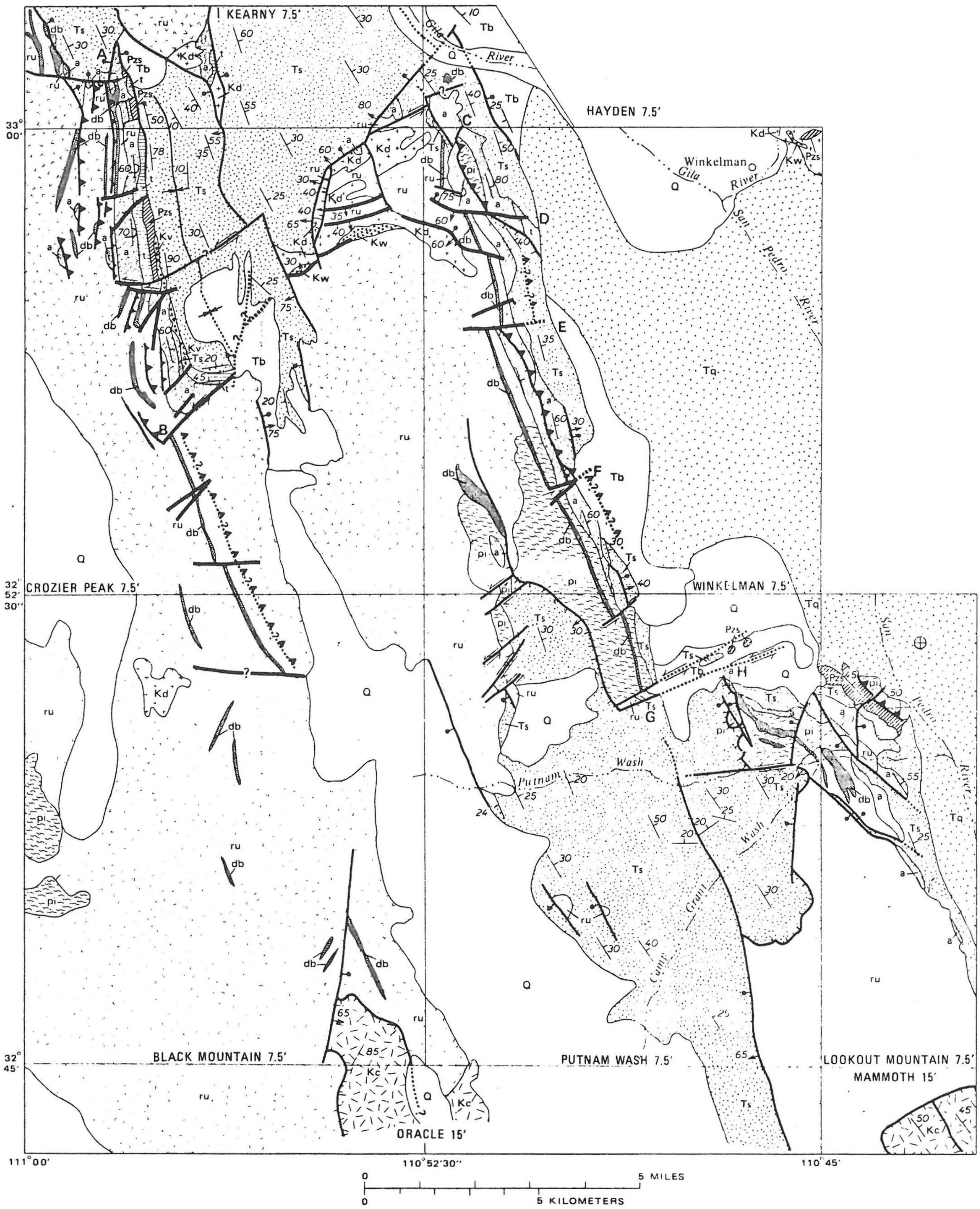
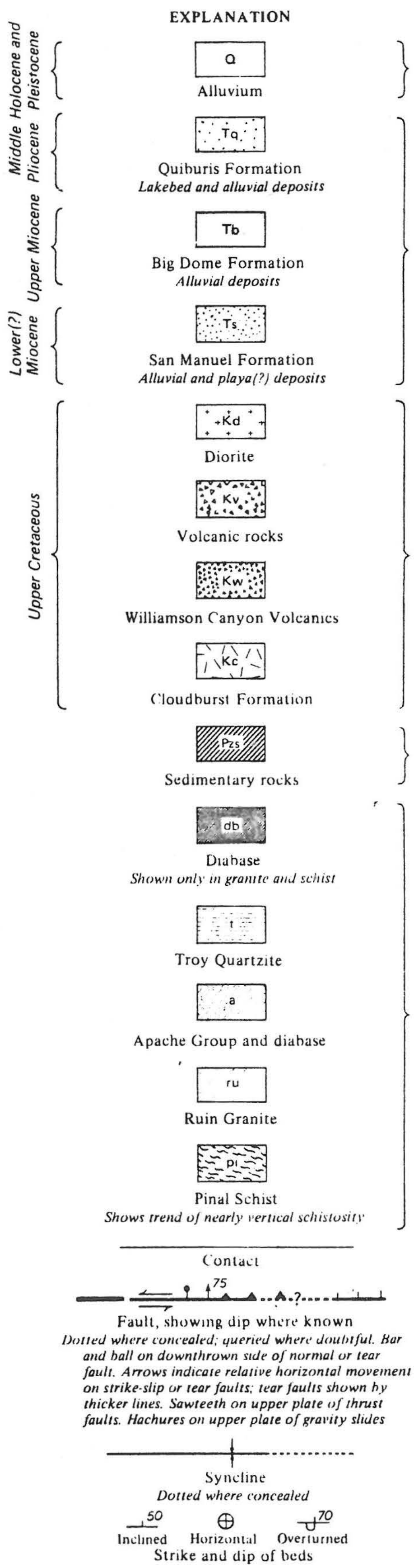


Figure 3.—Generalized geologic map of the Winkelman 15-minute quadrangle and adjacent areas.



have been part of a single thrust zone, cut and displaced by strike-slip and high-angle normal faults that segmented the monocline.

Ripsey Wash fault.—A north-trending belt of nearly vertical faults that extends from the southwestern part of the Kearny quadrangle (point A, fig. 4) to the central part of the Crozier Peak quadrangle (point B, fig. 4). This zone consists of several fault strands that separate thin east-facing slices of the basal part of the Apache Group, resting with sedimentary contact on the underlying basement (Ruin Granite), from similar slices to the west. Just north of point B at least three such slices, too small and too poorly exposed to show even on the detailed map (Krieger, 1974b), are spaced at distances of 50–100 ft. It is difficult to interpret this series of faults as anything other than a zone of imbricate thrusts that was later tilted. If the monocline extended upward indefinitely, high-angle normal faults could have downdropped the tilted slivers, but the presence of Cretaceous porphyries in some of the faults proves that faulting preceded tilting. If the monocline flattened upward, as it must have and as is suggested for the separate monocline in the Kearny quadrangle discussed below, the slivers should be nearly horizontal or tilted in discordant directions. Figure 5 represents diagrammatic sections across the fault zone, showing relations before and after tilting.

Romero Wash fault.—This fault (fig. 4) is exposed in two segments, a northern segment from south of point C (Hayden quadrangle) to west of point D (Winkelman quadrangle) and a southern segment from west of point E to west of point F. In the northern segment east of the fault the Apache Group rests on the Pinal Schist, and the beds dip steeply east; west of the fault the Apache rests on granite, and the beds are overturned but still occur in normal sequence, except where broken by small faults, most of which are not shown in figures 3 or 4. Some of these faults may be imbricate structures related to the major thrust, not younger high-angle faults as shown on the detailed map (Krieger, 1974a). In the southern segment the beds both east and west of the fault dip steeply east. West of the fault the Apache rests on granite to the north and schist to the south. East of the fault it rests on granite, except at the southern end, where the section is repeated without intervening granite. At the southern end of this segment (point F), two strands of the fault repeat the Apache Group. The southern segment of the fault (points E to F) is occupied by a tabular body of Cretaceous porphyry, whose nearly vertical dip and concordant relations show that the fault formed before or during Cretaceous time. Figure 6 represents a diagrammatic section across the fault, showing relations before and after tilting.

Other thrusts.—The occurrence of diabase as sill-like masses in granite and schist parallel to, and generally not more than 500 ft below, the pre-Apache erosion surface is well illustrated in the Winkelman and parts of the Crozier Peak and Putnam Wash 7½-minute quadrangles (fig. 3). This relationship was recognized by Shride (1967, p. 56), who stated that at depths

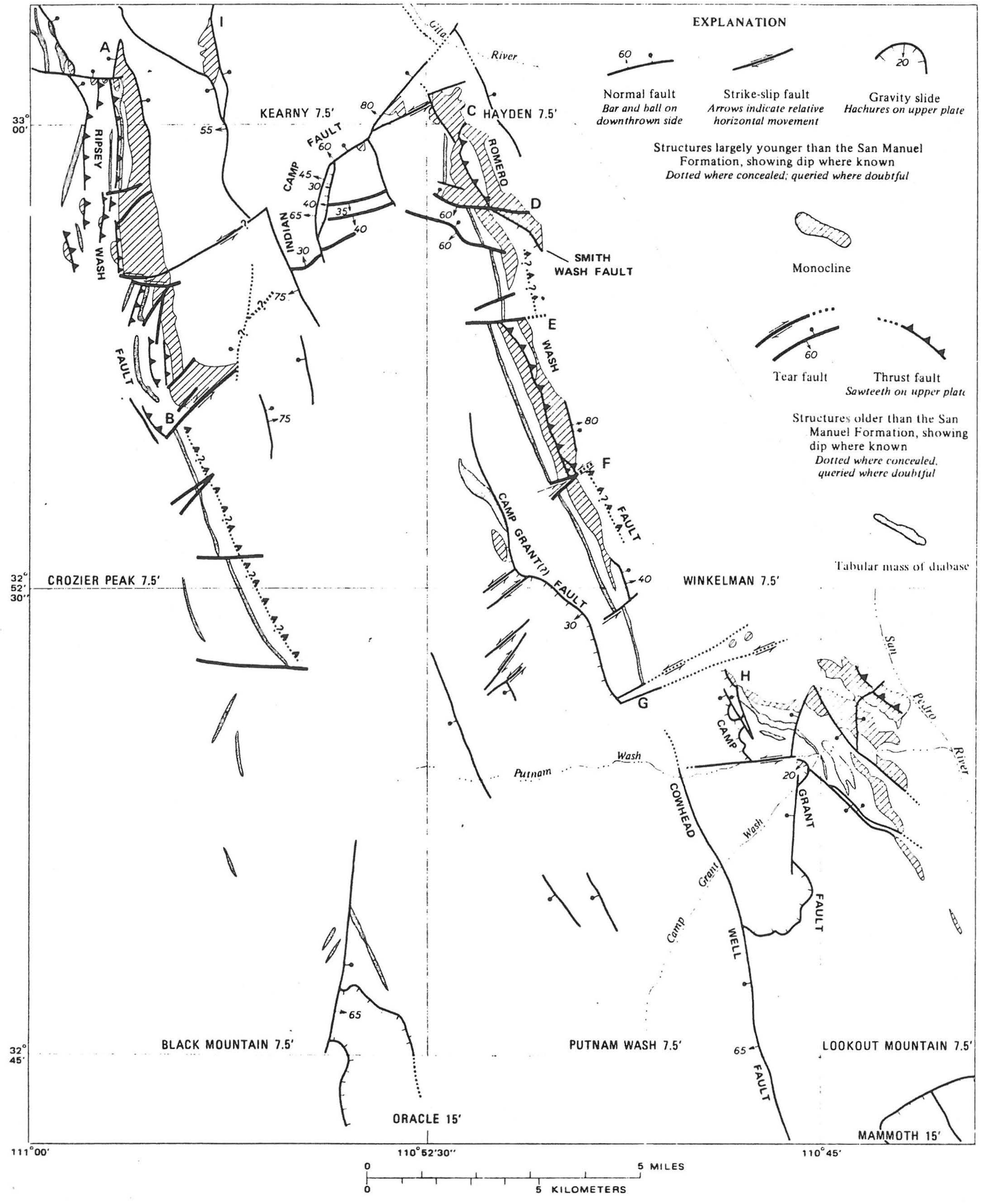


Figure 4.—Generalized structure map of the Winkelman 15-minute quadrangle and adjacent areas.

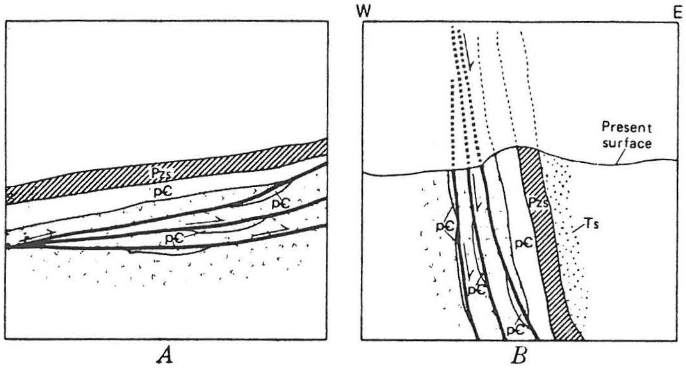


Figure 5.—Diagrammatic sections across Ripsey Wash fault showing suggested relations (*A*) before, and (*B*) after tilting. Ts, sedimentary strata; Pzs, Paleozoic strata; p€, Precambrian sedimentary strata.

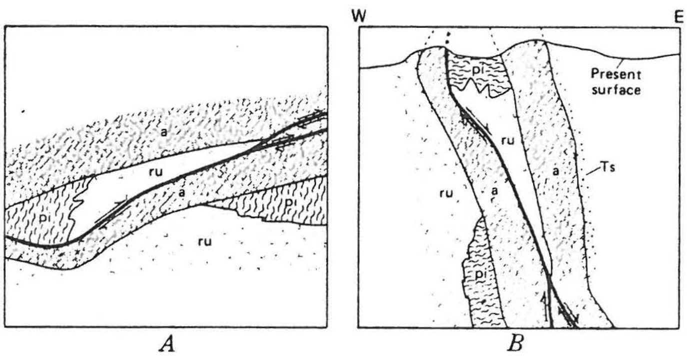


Figure 6.—Diagrammatic sections across Romero Wash fault showing suggested relations (*A*) before, and (*B*) after tilting. Ts, sedimentary strata; a, Apache Group; ru, Ruin Granite; pi, Pinal Schist.

of more than 500 ft below the base of the Apache Group extensive intrusions of diabase are practically nonexistent. It seems likely that the tabular mass of diabase that extends south of point B into the Black Mountain quadrangle may be such a sill originally intruded into the Ruin Granite within 500 ft of the pre-Apache surface. I explain its presence here, apparently miles "below" the nearest Apache Group, as the result of a thrust (fig. 4) perhaps related to a deeper strand of the Ripsey Wash fault; unrecognized normal faults in the granite may complicate the structure. Other tabular masses of diabase, mostly in the Black Mountain quadrangle, may owe their position to unrecognized tilted thrusts, or they may represent feeders to the diabase sills and sill-like masses.

In the northwestern part of the Lookout Mountain quadrangle, the section of steeply dipping Precambrian and Paleozoic rocks is repeated by a series of faults. Some of these faults cut the San Manuel Formation and therefore cannot be thrusts similar to the Ripsey Wash and Romero Wash faults. The beds face east and become progressiely younger, except in the northeasternmost exposures where the beds are overturned and face west or south. This was shown on the map of the Lookout Mountain quadrangle (Krieger, 1968c, sec. *AA'*) as a steeply east-dipping thrust that moved from east to west, or as a high-angle reverse fault. The structure was throught to represent the east limb of a tight syncline in which the west limb had been sheared out. Its relation to the thrusts to the northwest is unknown.

Tears

Numerous northeast-, east-, and southeast-trending, steeply dipping cross faults cut Precambrian and Paleozoic rocks. Some of them exhibit features characteristic of tear faults related to thrusting; they terminate at a thrust or transfer movement from one thrust surface to another. If they are tears that have been rotated almost 90° during development of the monocline, the typical tear-type displacement, which originally would have been strike slip, may now appear as high-angle dip-slip movement. Examples of this are two east-southeast-trending high-angle faults with apparent reverse movement in the northwest part of the Winkelman quadrangle, west and southwest of point D. They dip about 60° to the south, and both show relative uplift on the south. These same relations may also be obtained by strike-slip or oblique-slip, rather than reverse movement. The northern fault appears to offset the Romero Wash fault but not enough to account for the offset of the Apache Group. Where the fault offsets the San Manuel Formation, the south side has been relatively downdropped; that is, the movement is in the opposite sense.

Structural Features Younger Than the San Manuel Formation

Structural features that are mostly younger than the San Manuel Formation include (1) folds that tilted the thrusts and the Precambrian and Paleozoic sedimentary rocks to form north-trending, steeply dipping, east-facing monoclines, (2) east- to northeast-trending strike-slip faults that separate the major monocline into en echelon segments, (3) gently dipping gravity slides that placed tilted Cretaceous and Tertiary rocks on the Ruin Granite, and (4) north-trending high-angle normal faults. Folding may have commenced before, but much of it occurred during and after deposition of the San Manuel. Movement on some of the strike-slip faults may also have commenced before, but most of it ocurred after San Manuel time, and some of it is younger than the gravity sliding that postdates the San Manuel. High-angle normal faults are mostly related to deformation that produced the basin and ranges; one of these basins was filled with the Pliocene Quiburis Formation on which the San Pedro River now flows.

Monoclines

Three north-northwest-trending, en echelon belts of steeply dipping to overturned Precambrian and Paleozoic sedimentary rocks (figs. 3, 4) extend from the Lookout Mountain to the southwest part of the Kearny quadrangle. A remnant of another belt is exposed in the south-central part of the Kearny quadrangle (figs. 2, 3, and Cornwall and Krieger, 1974). A fourth belt of tilted Precambrian sedimentary rocks is found 15–20 mi northwest of the Kearny quadrangle (fig. 2, and Schmidt, 1966).

The belts that lie mainly within the Winkelman 15-minute quadrangle (from points A to B, points C to G, and southeast of point H, fig. 4) are interpreted to have originally been part of a single monocline later segmented by strike-slip and high-angle normal faults. The steeply dipping Apache Group rocks are not exposed continuously in the middle segment (points C to G). Their presence beneath the San Manuel Formation, however, is suggested by the tabular mass of diabase in granite and schist, which elsewhere lies within 500 ft of the pre-Apache surface; it is also confirmed by small patches of Apache Group (not shown in fig. 3), north of point G.

The monocline near point I is a separate but probably contemporaneous feature. This monocline extends from southwest of point I northward across the Kearny quadrangle (Cornwall and Krieger, 1974) for over 6 mi. Remnants of Precambrian sedimentary rocks resting on granite lie west of the steeply dipping San Manuel Formation near point I. North of point I nearly vertical tabular masses of diabase lie a short distance west of the fault that separates Ruin Granite from the San Manuel Formation and indicate the northward extension of the monocline. The suggestion is untenable that the monocline was originally part of the monocline in the Winkelman 15-minute quadrangle and was moved from point A to south of point I along a southeast-trending strike-slip fault. Two belts of east-trending porphyry dike swarms show no evidence of offset. One belt extends from the northwest part of the Kearny quadrangle (Cornwall and Krieger, 1974), westward across the northeast part of the adjacent Grayback Mountain quadrangle (H. R. Cornwall and M. H. Krieger, unpub. data, 1973); the other extends from the southwestern part of the Kearny quadrangle into the southeast part of the Grayback Mountain quadrangle. The apparent strike-slip fault is a high-angle normal fault that bounds the southwest side of a younger horst block.

These tilted belts are interpreted as the eroded remnants of east-facing monoclinal folds that separate vast areas of granite on the west from Tertiary sediments on the east. The almost complete absence of west-facing beds, as well as the absence of Precambrian or Paleozoic sedimentary rocks for more than 60 mi to the southwest, appear to rule out the possibility that the monocline is the east limb of an anticline. Isolated examples of west-facing beds—southwest part of the Winkelman quadrangle (Krieger, 1974a), northwest part of the Lookout Mountain quadrangle, (Krieger, 1968c), and northwest part of the Crozier Peak quadrangle (Krieger, 1974b, sec 23, T. 5 S., R. 13 E.)—are interpreted as the result of drag or later deformation.

The alternate view that the tilted belts are the result of drag along high-angle faults appears improbable because the Apache Group is in normal sedimentary contact with granite and schist and because diabase in the basement, within 500 ft of the base of the Apache, precludes the existence of large high-angle faults west of the belts. In the west-central part of the Kearny quadrangle (Cornwall and Krieger, 1974), a nearly horizontal mass of diabase trends westward from a north-trending diabase mass that marks the trend of the monocline in this area. It is interpreted as a sill intruded not more than 500 ft below the pre-Apache surface and representing the area where the monocline flattened westward. The overlying Precambrian and Paleozoic sedimentary rocks were eroded after formation of the monocline.

The folding occurred before and continued after deposition of the San Manuel Formation because, adjacent to the monoclinal ridges, the San Manuel Formation also dips steeply, though generally 20°–30° less than the older rocks. Although some of the tilting of the San Manuel Formation could have been caused by drag along the faults that separate the San Manuel from older rocks, the extensive areas of tilted San Manuel east of the faults could not have been formed by drag. Deposits of claystone and mudstone with abundant mud cracks and curled mud chips indicate deposition of part of the San Manuel Formation in a flat playa environment. In the Kearny quadrangle (Cornwall and Krieger, 1974), megabreccias (landslide blocks) slid from the west or southwest out onto interfingering playa and alluvial deposits and were immediately buried by additional playa and alluvial deposits. The sediments and interbedded megabreccias now dip steeply to almost vertically east. Away from the monocline the San Manuel Formation dips less steeply because of the eastward flattening of the monocline. Attitudes of the San Manuel Formation away from the monocline may be partly due to later structural features. The fact that the oldest unit in the San Manuel in the Putnam Wash quadrangle is composed largely of clasts of Ruin Granite indicates that Precambrian basement was exposed, before San Manuel time, somewhere west and southwest of the Winkelman 15-minute quadrangle. Likewise, much of the San Manuel Formation in the northwestern half of the Kearny quadrangle is composed of granitic clasts, derived from the northwest and west. However, Paleozoic and Precambrian sedimentary rock clasts are abundant in the San Manuel Formation and form extensive megabreccias, especially in the Kearny quadrangle (Cornwall and Krieger, 1974), proving that these sedimentary rocks had not been entirely stripped from the granite and schist basement by San Manuel time.

Strike-slip faults

Two major left-lateral strike-slip faults appear to separate into segments what is interpreted to have been a single monoclinal ridge (fig. 4). The northern fault moved the monoclinal ridge from points B to C, and the southern one moved it from point G to east of point H.

Although conclusive proof is lacking that the northern and middle segments were originally continuous, the following evidence suggests this interpretation: (1) In the Crozier Peak quadrangle, east of point B (fig.3) the strike of vertical to steeply overturned strata changes abruptly from a north to an east-west trend with a gentler northward dip, suggesting drag, and (2) The small patches of Apache Group, not entirely in normal stratigraphic sequence, west of point C (southeast corner of Kearny quadrangle and northeast part of Crozier Peak quadrangle), may have been dragged into their present position by the fault. In this area the fractured condition of granite and diorite bedrock may have been caused by the strike-slip fault. The position of the strike-slip fault across or beneath the San Manuel Formation, northeast of point B, is uncertain because of concealement both by the Big Dome Formation and by colluvial slumping of the San Manuel Formation and because of offset by younger north-northwest-trending high-angle faults. How much of the movement on the strike-slip fault is older than the San Manuel Formation and how much is younger is uncertain. The fold in the older rocks is reflected in the younger deposits, which also swing east.

The following evidence supports a southern strike-slip fault: (1) Small exposures of Paleozoic rocks north of point H lie considerably west of the main outcrops in the northwest part of the Lookout Mountain quadrangle (fig. 3), (2) Apache Group, assumed to be buried beneath the San Manuel Formation, north of point G, is west of the Apache Group near point H, and (3) what is interpreted to be the continuation of the post-San Manuel Camp Grant fault (fig. 4), northwest of point G, is offset westward from the northern exposure of Camp Grant fault near point H. Movement on this strike-slip fault appears to be younger than the Camp Grant fault, which cuts the San Manuel Formation.

Gravity slides

Gravity slides—décollements or detachments—are concave-upward surfaces that separate sedimentary or volcanic rocks from older rocks. The younger rocks generally dip in the opposite direction from the fault surface. The best example of a gravity slide in the Winkelman 15-minute quadrangle is Camp Grant fault in the Putnam Wash quadrangle. Other probable gravity slides are beneath the Cloudburst Formation (fig. 3) in the Black Mountain and Mammoth quadrangles and involve San Manuel Formation in the southern part of the Winkelman 15-minute quadrangle. The Cloudburst Formation in the southeast part of the Black Mountain quadrangle is nearly vertical and is surrounded on at least the west, north, and east sides by the Ruin Granite. The contact between the Cloudburst and granite is concealed by alluvium, except on the west where it is an east-dipping normal fault. The gravity slide is assumed to be a nearly horizontal concave-upward surface (Krieger, 1974c, sec. *AA'*). In the Mammoth quadrangle, Creasey (1965, 1967) interpreted the structure as a gently east-dipping thrust; the overlying Cloudburst Formation dips mostly 35°–65° eastward. The Indian Camp fault in the northeastern part of the Crozier Peak quadrangle and the Smith Wash fault in the northwest part of the Winkelman 7½-minute quadrangle are questionably interpreted as gravity slides.

A low-dipping gently curved fault surface (fig. 7) is well exposed on the north side of Camp Grant Wash about 2,000 ft southwest of its junction (at the quadrangle boundary) with Putnam Wash. This surface, interpreted as a gravity slide plane, dips 20° west and separates Ruin Granite on the east from the San Manuel Formation on the west. The surface on granite is remarkably smooth. Conglomeratic gouge a few inches thick separates the granite from the overlying conglomerate. Fracture cleavage in the gouge indicates that the upper block moved from east to west. The conglomerate dips about 35° northeast and is cut by by subparallel cycloidal (in section) faults and by steeper west-dipping faults. The steeper faults end downward at the gravity slide plane or at the cycloidal faults. These features are similar to what Anderson (1971, p. 43) has called "thin-skinned distension" in Tertiary rocks in Nevada in which Tertiary volcanic rocks are cut by "a system of closely spaced north- to northwest-striking shingling normal faults (many of which are low angle) that displace younger over older rocks in a west to southwest direction * . * . * . The structural units are floored at or near the present level of exposure by complex low-angle zones of detachment or decollement into which the numerous shingling normal faults merge." Absence of recognizable small stratigraphic units and difficulty in tracing faults in the San Manuel Formation make it impossible to determine whether or not the apparently great thickness of the formation in the Putnam Wash quadrangle is caused by repeated low-angle slicing and rotation.

Camp Grant fault is offset to the west by an eastward-trending strike-slip fault along Putnam Wash and probably by a major strike-slip fault near point G; it is cut by north-trending normal faults (discussed below). What is interpreted to be the offset part of the Camp Grant fault is exposed in the northwest part of the Putnam Wash quadrangle. It separates Pinal Schist on the east from northeast dipping San Manuel Formation on the west. The fault dips about 30° west. Camp Grant fault was questionably extended into the southwestern part of the Winkelman quadrangle. If the fault in that area is part of the Camp Grant fault, it is unusual in that it involves Precambrian rocks. Most of the gravity slides are believed to flatten downward and for the most part not to extend far into the basement. The attitude of the small mass of Apache Group suggests drag that might accompany faulting or gravity sliding. The Apache is cut by a north-trending fault (not shown in figs. 3, 4). West of the fault the Apache dips steeply eastward; east of the fault it also dips steeply eastward, but the dip flattens

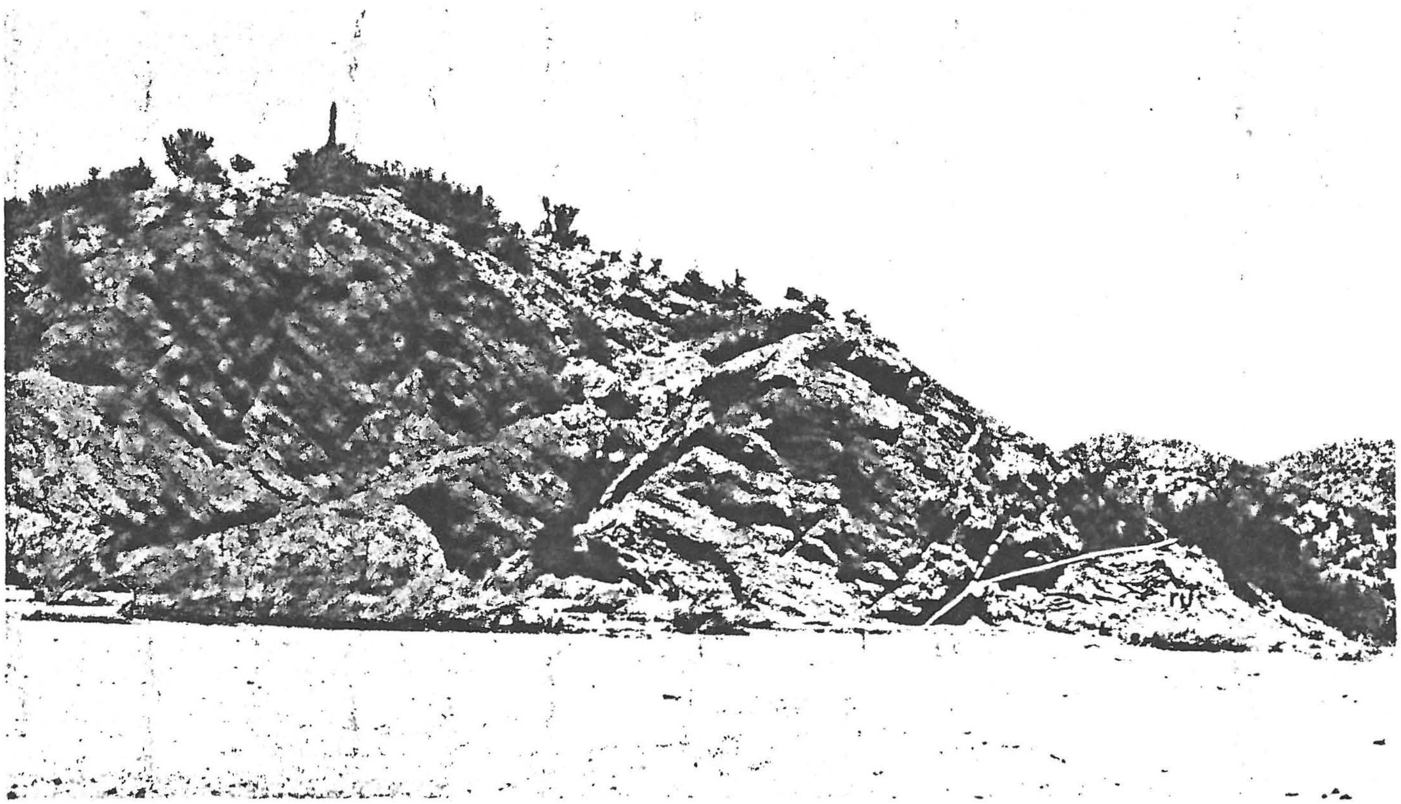


Figure 7.—Camp Grant fault, exposed on north side of Camp Grant Wash, about 2,000 ft southwest of junction of Camp Grant and Putnam Washes. Light-colored outcrop at right is Ruin Granite (ru). Fault surface here dips about 20° west. Overlying conglomerate of San Manuel Formation dips about 35° northeast and is cut by subparallel cycloidal faults and by steeper west-dipping faults that end downward at the cycloidal faults. The fault surface appears to steepen where it approaches the wash, but this is an optical illusion due to foreshortening because of the angle at which it is viewed and to removal of some of the younger rocks, where cut by one of the more steeply dipping small faults at the creek level.

rapidly (Krieger, 1974d, sec. *DD'*), and along the eastern margin of the outcrop, beds dip gently westward.

High-angle normal faults

High-angle, mostly north-northwest-trending normal faults cut the San Manuel Formation and older rocks. Renewed movement has also occurred since deposition of the Big Dome Formation, and some has occurred since deposition of the Quiburis Formation (east of the San Pedro River). Some of these faults are downthrown on the east, and some on the west. A few of these faults deserve special mention.

The Cowhead Well fault (fig. 4) extends for at least 12 mi, from north of Putnam Wash into the western part of the Mammoth quadrangle (south of the map area). It is younger than both the San Manuel Formation and the Camp Grant fault.

The fault that cuts off the Cloudburst Formation and the thrust that underlies the Cloudburst in the Southeastern part of the Black Mountain quadrangle may also be younger than the San Manuel Formation.

Faults occur between the San Manuel Formation and Precambrian and Paleozoic bedrock in many places, but the amount of displacement within the Winkelman 15-minute quadrangle in most places is believed to be small. The attitude of the San Manuel Formation, therefore, is likely due to folding (tilting), not to drag on the faults. In the Kearny quadrangle, however, considerable post-San Manuel displacement has occurred on the bounding faults. The bedrock mass west of point I is clearly a horst. Uplift on this block may have been responsible for development of the syncline in the San Manuel Formation that extends from the Crozier Peak quadrangle into the southwest part of the Kearny quadrangle. Playa deposits on the east side of the syncline are identical with those east of point I and at one time extended across at least the southern end of the block.

These high-angle normal faults are part of the Basin and Range fault system. Major faults, at least on the east side of the San Pedro River (fig. 2), produced the basin in which the Pliocene Quiburis Formation was deposited. This faulting took place largely after deposition of the San Manuel Formation, and some of it occurred after deposition of the Big Dome

Formation. The early Miocene Galiuro Volcanics east of the San Pedro River has been downdropped at least 5,000 ft from its position at the northern end of the Galiuro Mountains and was later buried by the Quiburis Formation (Krieger, 1968b,c). The change from low-angle gravity sliding and associated low-angle normal faults indicating major extension to high-angle normal faults indicating predominantly vertical displacement took place in the late Tertiary, as noted in Anderson (1971, p. 3534), in southwestern Nevada.

CONCLUSIONS

Structural features in the Winkelman 15-minute quadrangle are believed to have developed in the following sequence: Imbricate thrusts and related tears were formed in a flat environment and were later tilted, when an east-facing monoclinal fold developed a linear belt of steeply dipping to overturned Precambrian and Paleozoic sedimentary rocks. This folding, which began before but continued after deposition of the Miocene San Manuel Formation, developed other monoclinal folds to the north and northwest of the quadrangle. East-trending strike-slip faults separated the monocline in the Winkelman quadrangle into three en echelon segments. Some of this faulting apparently occurred after large areas of the San Manuel Formation became detached and moved over basement rocks on a low-angle gravity slide surface. All these structures are broken by north-trending high-angle normal faults.

The structural complexity of the area contrasts markedly with the structural features northeast of the Gila and San Pedro Rivers, as was noted by Ransome (1919, p. 82) and as can be seen in figure 2 and by examining published geologic maps of the area (see fig. 1 for references; also Wilson and others, 1969). Northeast of the rivers the beds are mainly gently tilted and intricately faulted; monoclinal flexures, where present, face both east and west. A major northwest-trending fault, approximately beneath the Gila and San Pedro Rivers, follows the boundary between the two blocks.

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FIELD TRIP

HANDOUTS

AGS SPRING FIELD TRIP, 1984

NOTICE NO. 2

1) At 7:00 P.M., Friday, April 13 in Room 206, Geosciences Building, U of A, the field trip leaders will give background talks on the areas we will visit Saturday and Sunday. Guidebooks will be available.

2) On Saturday, April 14, at 8:30 A.M., we will meet at the intersection of Oracle highway and 1st (formerly Tangerine). This is 4 miles north of Oracle and Ina and just past the turnoff to Oro Valley Golf Course.

   Both the Saturday and Sunday trips will require a high clearance vehicle, not necessarily 4-wheel drive. We will arrange transportation at the meeting place for anyone without a suitable vehicle.

3) Saturday morning's tour will include an easy 3 mile loop traverse which we expect will take about 3 hours. Saturday afternoon and Sunday will involve much shorter walks from the vehicles.

4) On Sunday, April 15, at 8:30 A.M. we will meet at Oracle Junction.

5) Bring your own lunches; cold carbonated beverages will be supplied.

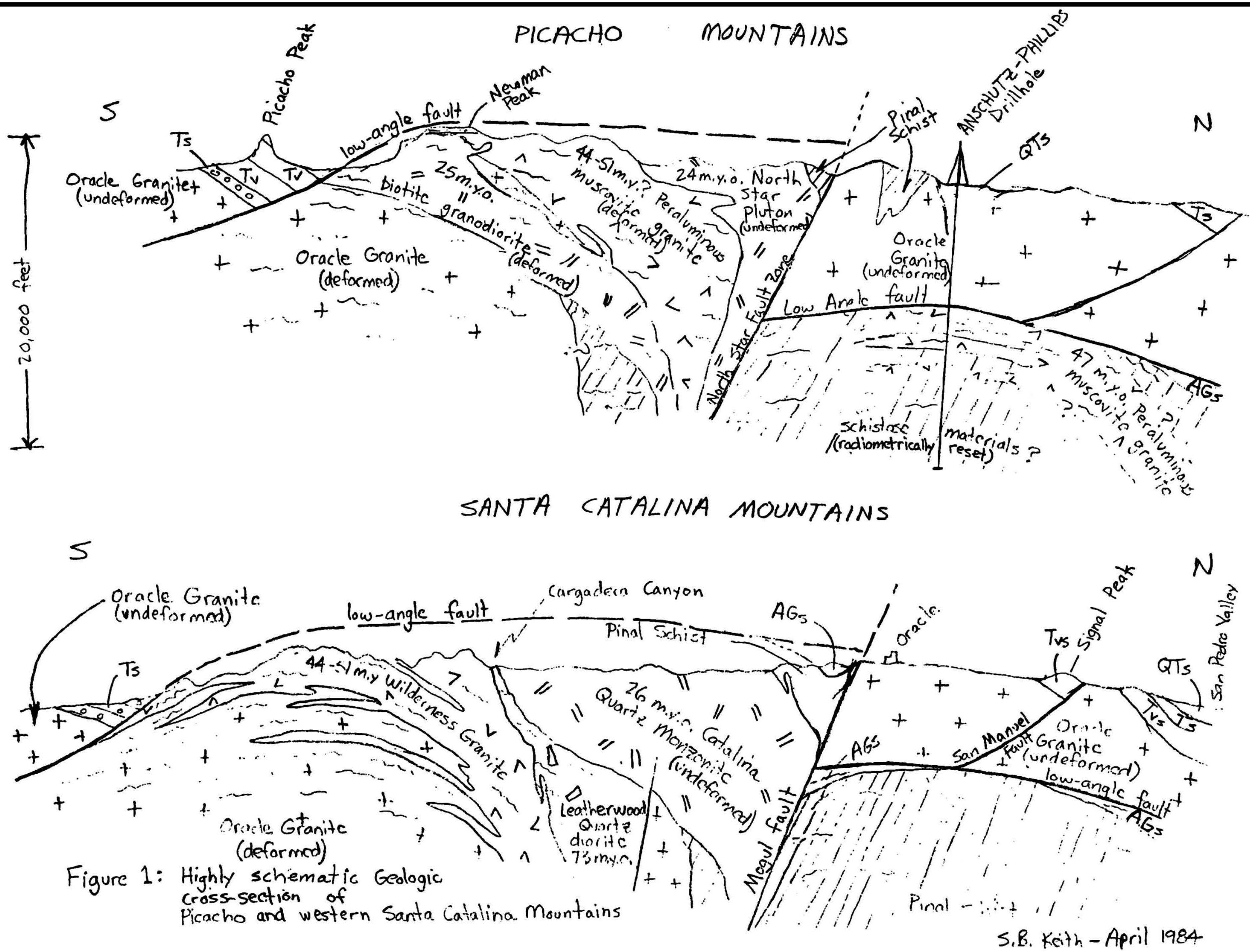


Figure 1: Highly schematic Geologic cross-section of Picacho and western Santa Catalina Mountains

TABLE 2. Geochronological data for basal Cloudburst volcanic member sample.

Sample number: CB-2A

Collected by: S.B. Keith and W.A. Rehrig, Spring 1977

material analyzed: whole rock

Sample description: Alkali basalt about 100 feet above base of Cloudburst volcanic section. Chemical analysis and petrographic description are in Table 1.

AGE: 27.8 ± 1.4 m.y. B.P.

Analytical data:

Ar^{40*}/K^{40}: .001640

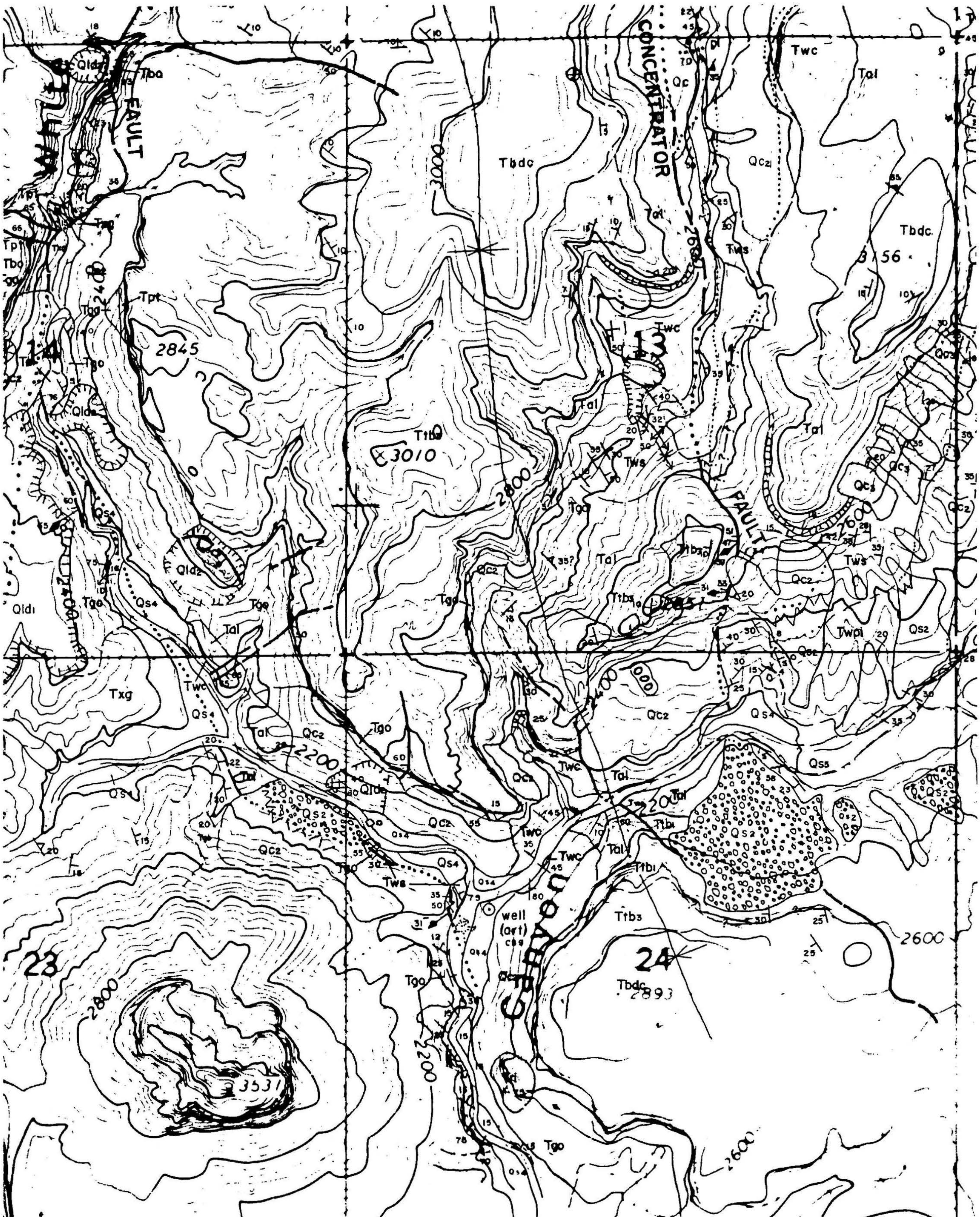
Ar^{40*} (ppm): .03109, .002857

Ar^{40*}/Total Ar^{40}: .198, .180

%K: 1.468, 1.513

K^{40} (ppm): 1.818

Dated by: Geochron Laboratories, Cambridge, Mass.



CONCENTRATOR
FAULT
FAULT
Canyon
13
14
23
24
2845
3010
3531
2893
3000
2800
2600
2200
Tbdc
Tbdc
Tbdc
Twc
Tal
Qc
Qc2
Qs4
Qs5
Tgo
Tws
Ttb3
Txg
Twpi
Qld1
Qld2
well (art)

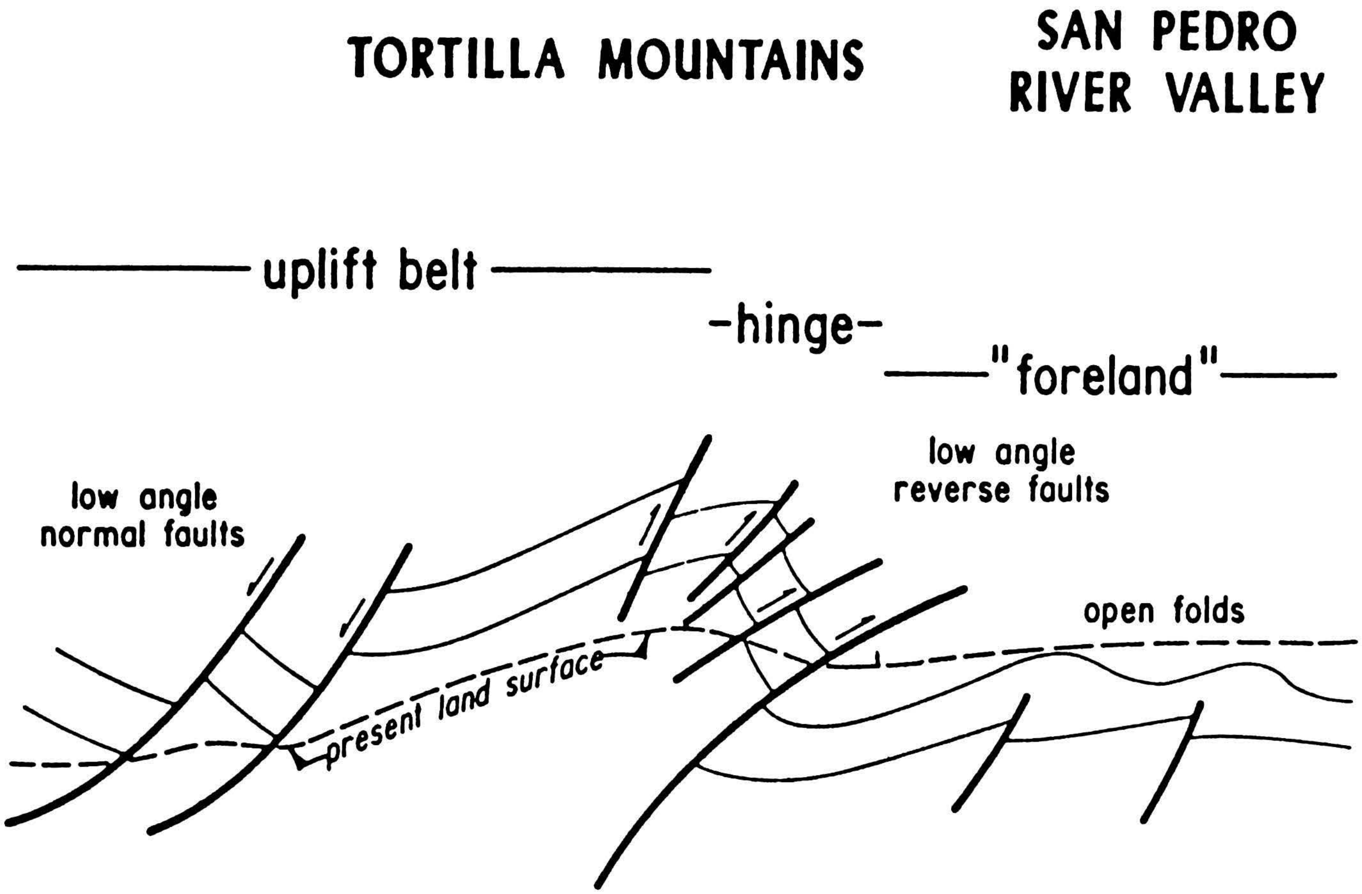


Figure 7. Reconstructed diagrammatic structure cross section across the Laramide basement-cored uplift in western Pinal County, Arizona. Precambrian basement is overlain by Paleozoic-Mesozoic sedimentary cover; section illustrates general geometry of Laramide uplifts in Arizona.

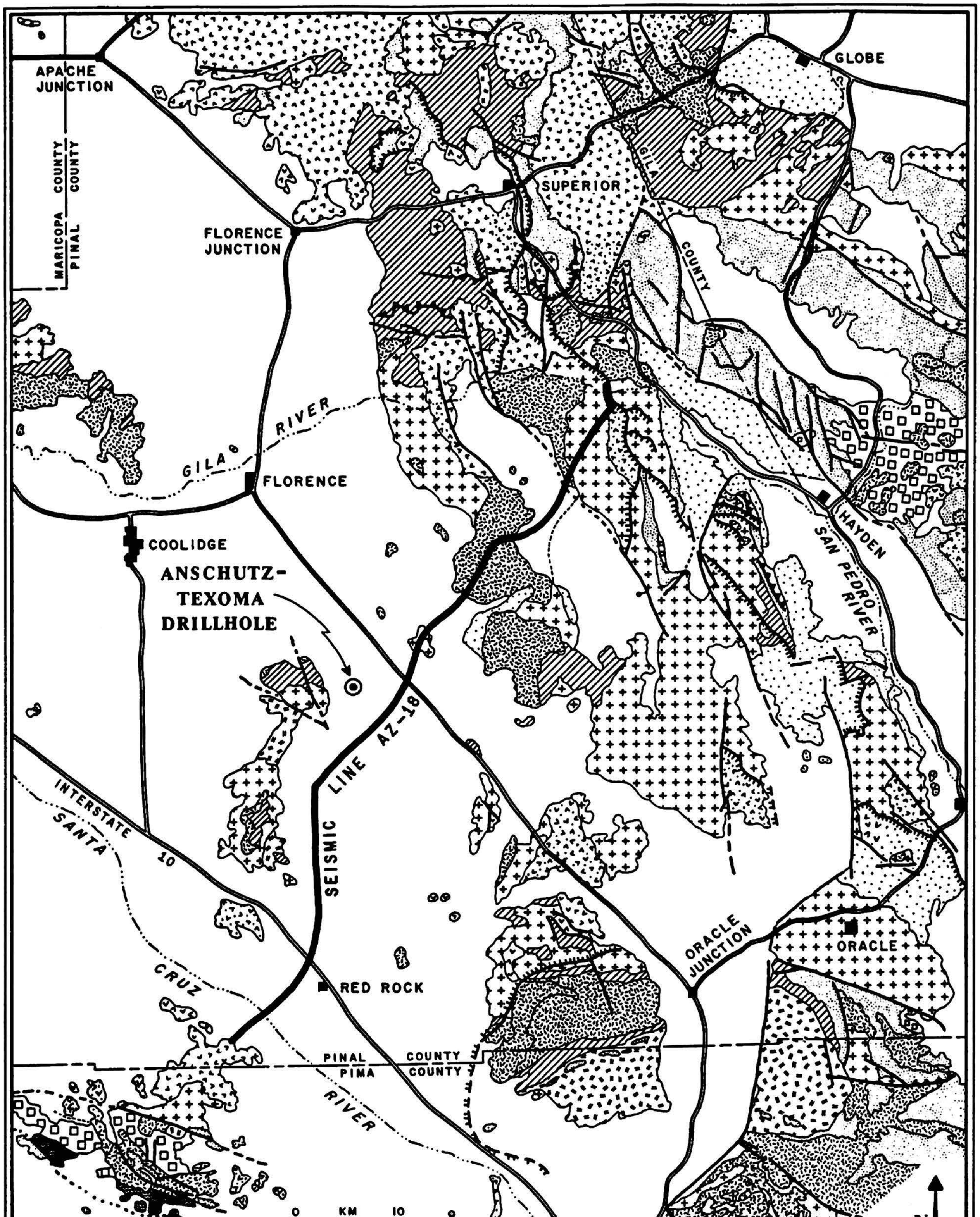
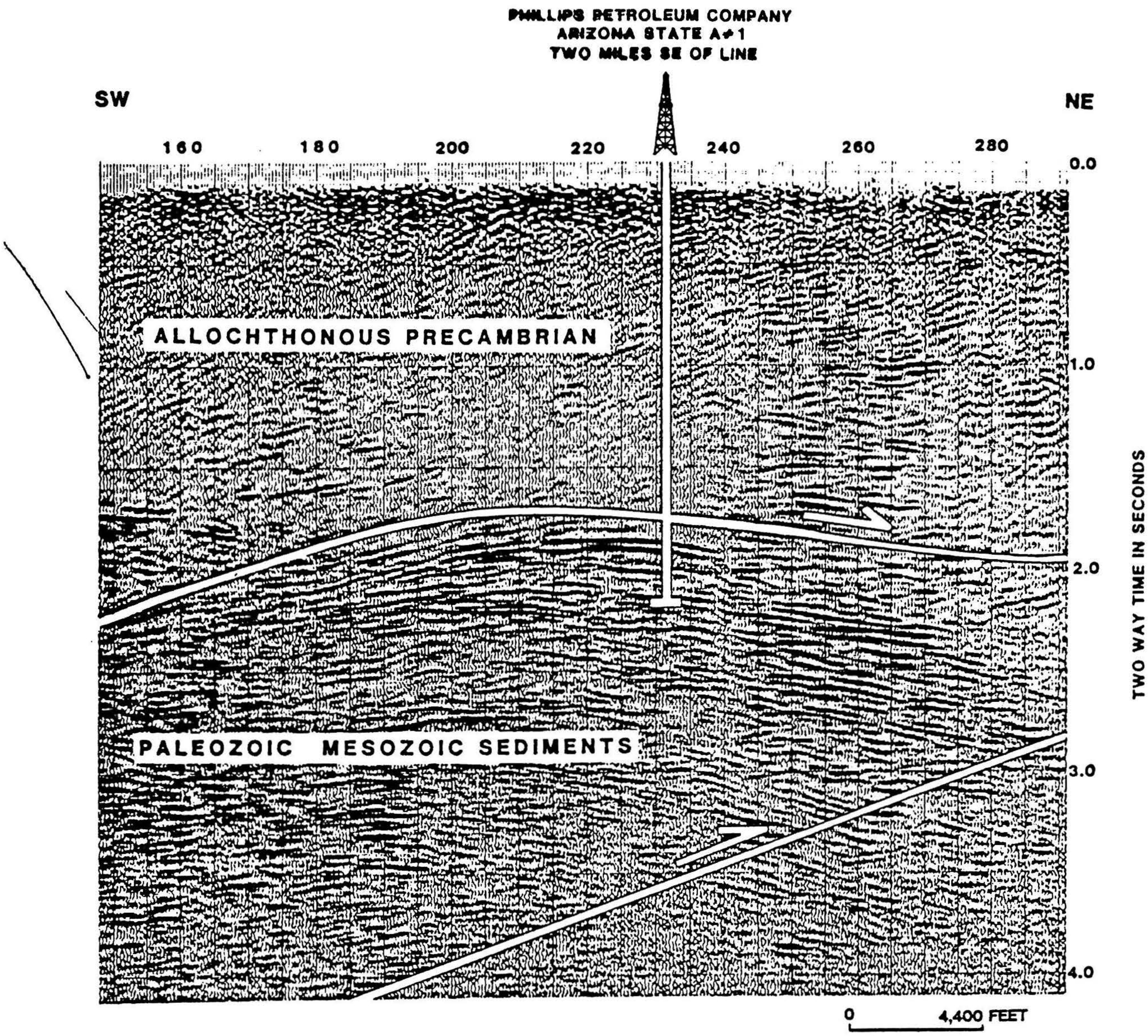


Figure 1: Geologic map of a portion of central Arizona showing location of seismic time cross-section AZ 18 and Anschutz-Texoma drillhole. Geology is modified from Wilson and others (1969).

continued on p. 6



from original full size figure
Ryfe and Robinson (1981)

from Ryfe and Robinson (1981)

ARIZONA STATE A-1

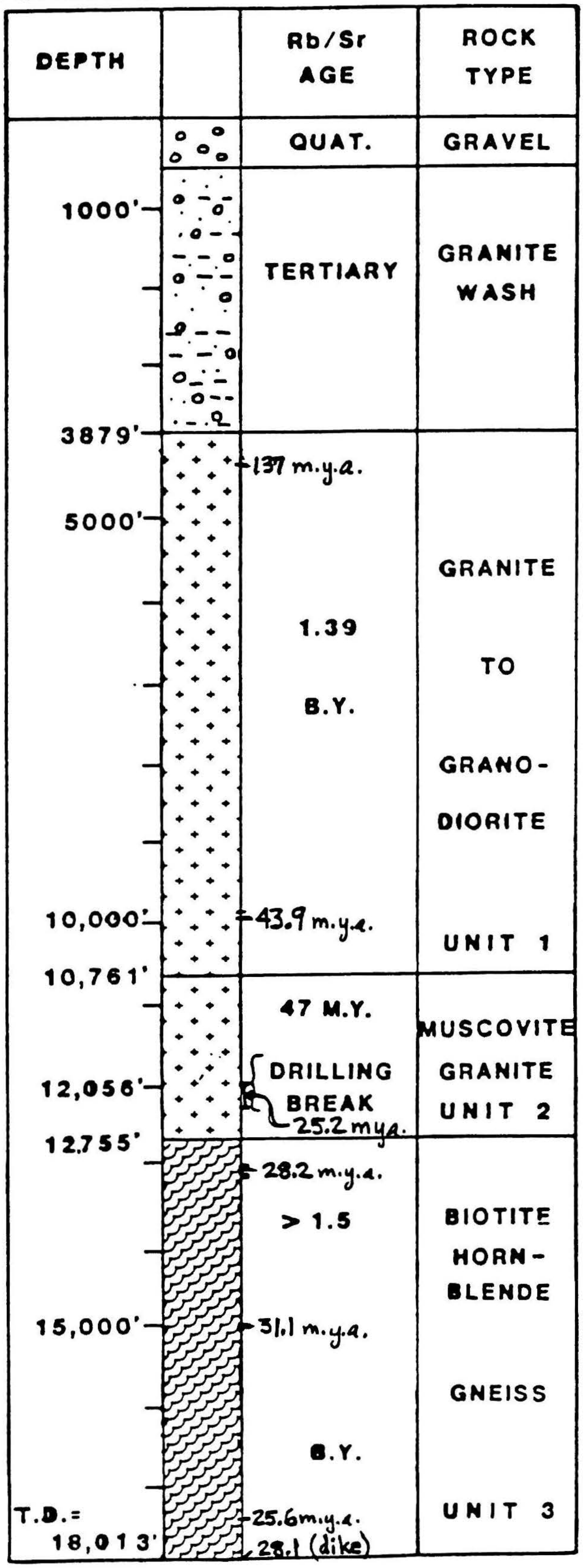
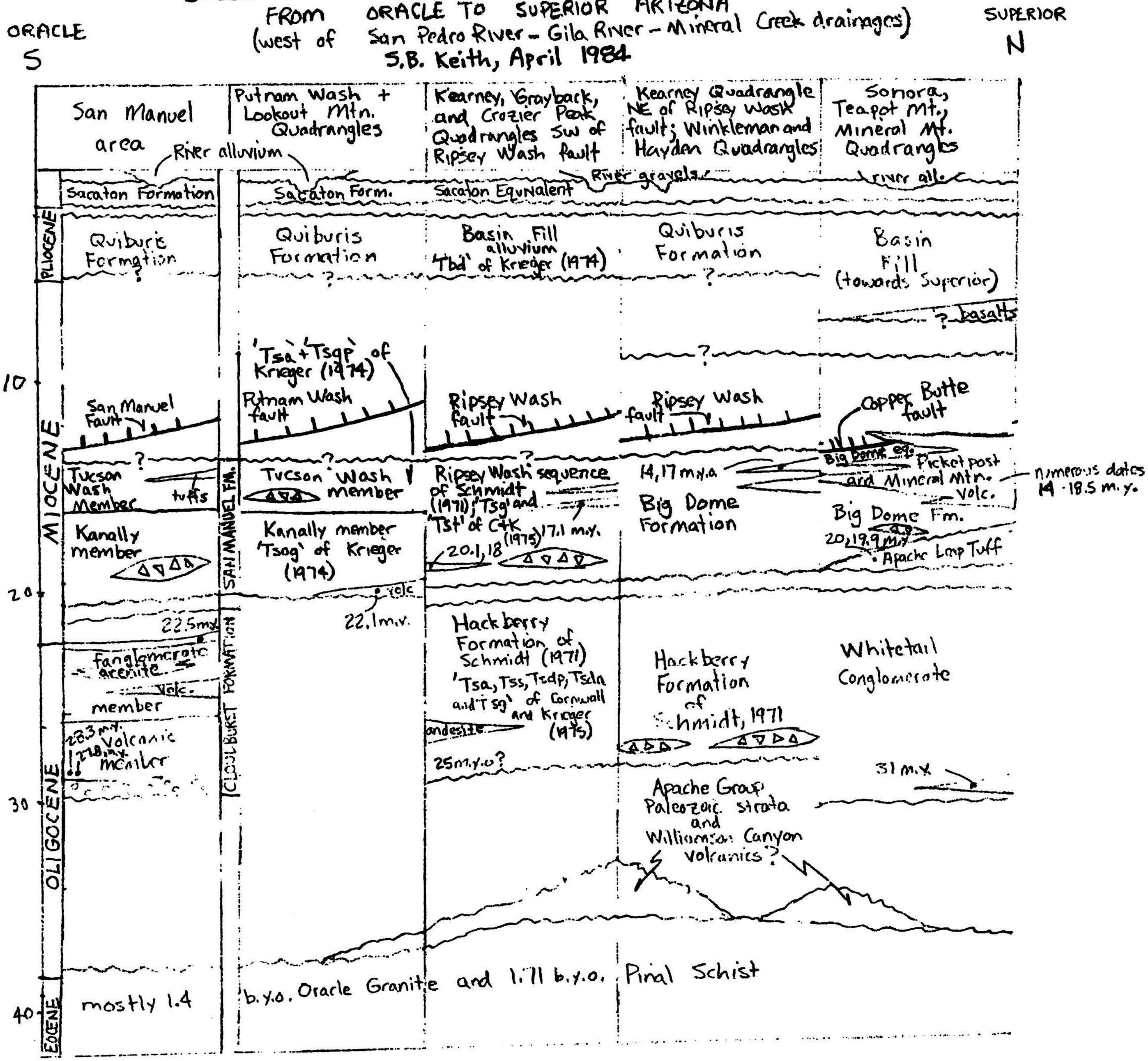
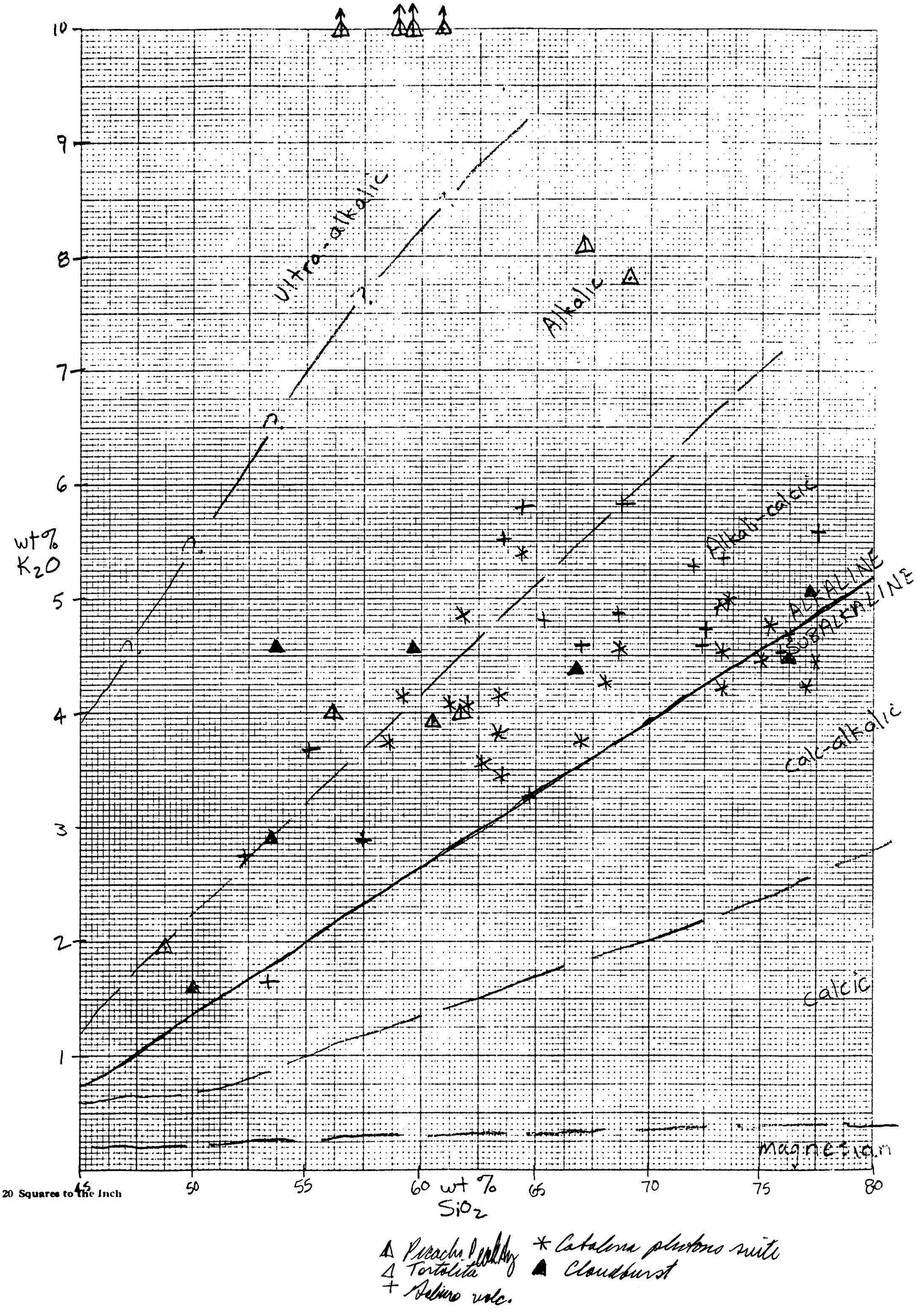


Figure 3

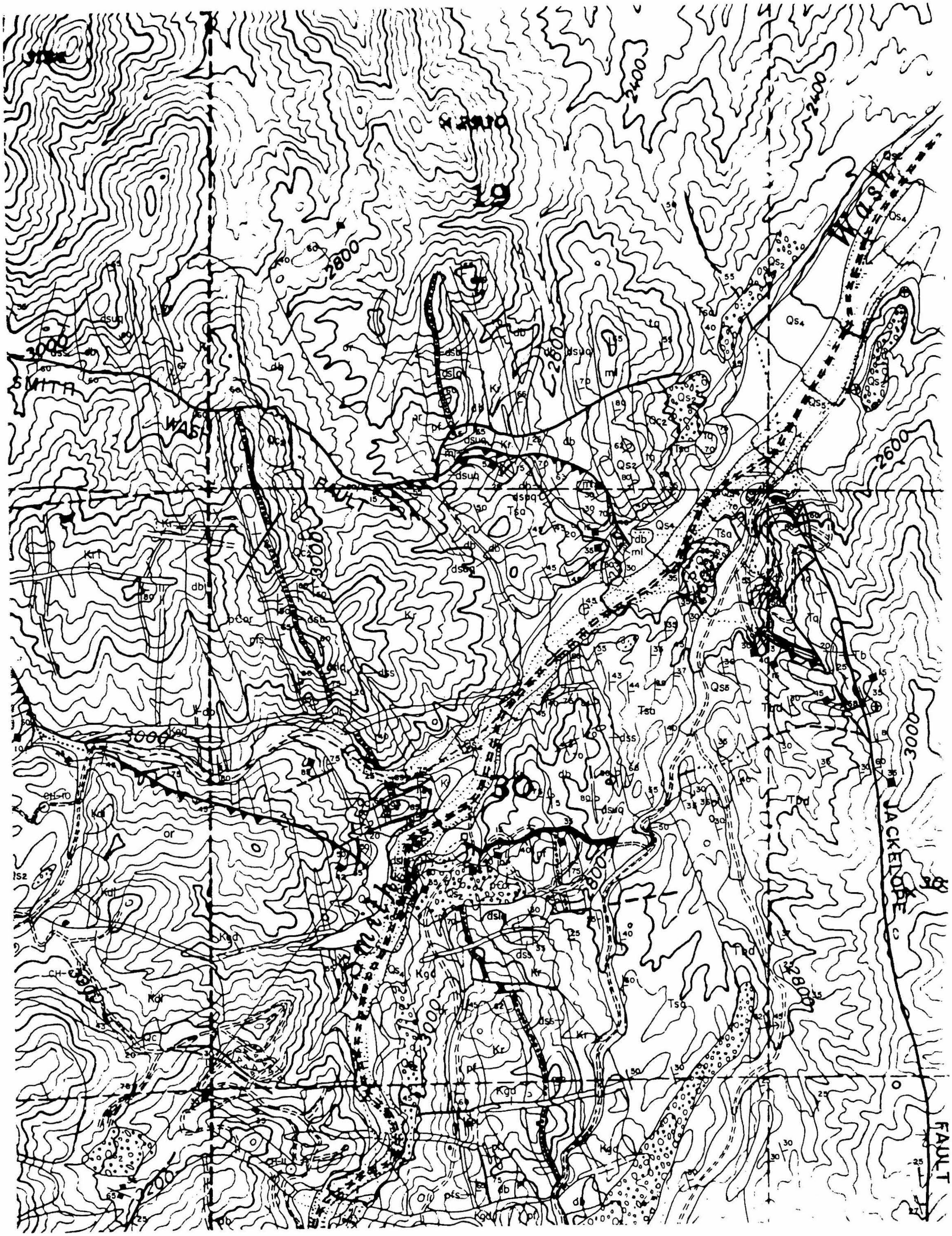
SUGGESTED CORRELATION OF TERTIARY STRATIGRAPHY FROM ORACLE TO SUPERIOR ARIZONA (west of San Pedro River - Gila River - Mineral Creek drainages)

S.B. Keith, April 1984





20 Squares to the Inch


SMITH
WASH
FAULT
Wash
JACKELOPE
FAULT
19
30
2400
2600
2800
3000