New work in the San Manuel and Mammoth districts (Pinal County, Arizona) -- an introduction *via* Tucson Wash

by Eric R. Force and William R. Dickinson

Guidebook
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This trip examines the structural context of two mining districts that overlap spatially. In the first, the Mammoth district, Au-Ag-Pb-Zn-Mo-V-(Cu) vein mineralization is of mid-Tertiary age. We will be seeing its relation to a mid-Tertiary detachment fault and side ramp, coeval rhyolite, and younger faults. The second is the San Manuel district, consisting of a Laramide porphyry copper deposit segmented by faults, where we will examine the history of tilting and ponder the original geometry of mineralization prior to tilting and faulting. The trip will focus on excellent natural exposures in Tucson Wash for both districts. Four-wheel drive is required some times of year. All stops are in Mammoth 7 1/2' quadrangle (fig. 1).

The Mammoth and San Manuel districts occupy the northern boundary area between the Catalina(-Rincon-Tortolita) Mountain metamorphic core complex and the San Pedro trough (fig. 2). Physiographically, the link with the San Pedro trough will be more obvious. The faults we will see in conjunction with ore-body geology are part and parcel of the scheme of mid-Tertiary crustal extension described by Dickinson (1991).

Three generations of extensional faulting occurred in this area, making it exceptionally extended and exceptionally complex. Each generation of faulting resulted in deposition of a conglomeratic formation (table 1), because of the great structural relief produced by faulting. These formations function as recorders of tectonic events. Careful geologic book-keeping does enable understanding of the complex sequence and geometry; both authors, however, find themselves repeatedly returning to the area for and with new insights.

The area of the field trip is the subject of many publications, the most famous of which are Lowell (1968), which described the discovery of the Kalamazoo orebody of the San Manuel district by reconstructing the original orebody and its alteration zones across the San Manuel fault, and Lowell and Guilbert (1970), which used the San Manuel district as a model for porphyry-type alteration zonation. Monographic works are Schwartz (1953) and Creasey (1965) on the San Manuel district and Peterson (1938) on the Mammoth district. Other pertinent works include Steele and Rubly (1947), Creasey (1950), Heindl (1963), Thomas (1966), Force and Cox (1993), and a thesis by Weibel (1981). The regional context is described by Dickinson (1991). A paper by Force, Dickinson, and Hagstrum on the tilting history of the San Manuel porphyry system is being reviewed; this guidebook provides a preview. Dickinson (in press) and Force and Cox contain the most up-to-date maps for the field-trip area, and illustrations from other publications are included in this guidebook.

Road log

The starting point of this log is the western cutoff to downtown Oracle on highway 77, i.e. the first cutoff coming from Tucson.

miles

0.0 Road junction. The Oracle Granite forms the blocky outcrops here and several miles ahead. It is about 1.45 Ga in age and forms the basement for much of the area in sight from this point, including parts of the Santa Catalina Mountains to the south and the Black Mountains and Black Hills to the north. You may see dikes of aplite and younger Precambrian diabase within the Oracle in some of the road-cuts.

3.1 Second Oracle road.

4.0 Turn left (north) off highway 77 through a cattle guard onto the old highway. The first exposures are still Oracle Granite but farther on they are the overlying Kannally Member of the San Manuel Formation (Miocene), consisting of Oracle-cobble conglomerate dipping east or northeast about 30°.

7.1 Low road cuts of two sedimentary breccia lenses within San Manuel Formation. One is derived entirely from diabase, the other from quartzite. Sources are not presently exposed.

7.2 Intersection. We will be turning left here later, but for now go straight. At this point we cross the Red Rock fault, an important structure apparently coeval with the San Manuel fault, into the so-called Purcell window, which consists of Precambrian and Laramide igneous rocks on the upper plate of the San Manuel fault.

7.4 STOP 1. The road cut (by gate) exposes gray Laramide porphyry (henceforth called San Manuel porphyry) intrusive into Oracle Granite. This stop merely serves as an introduction to these rock types as exposed in the Purcell window.

Here we are above the Kalamazoo segment of the San Manuel porphyry copper deposit, which began production in 1991. The upper boundary of ore is about 2700 feet below us. East from here we can see in the foreground a conglomerate-cobble quarry and other operations for decorative rock, and in the background some workings of the San Manuel open-pit and the head-frames of lifts that serve both the San Manuel and Kalamazoo operations.

7.7 Return to mile 7.2 and turn right (north).

8.1 Prospect adit along a rhyolite dike in Oracle Granite. The hilltop above and two other hilltops nearby are formed by shallow rhyodacitic intrusives of Tertiary age.

8.5 Cross the Turtle fault, not well exposed here, into Cloudburst Formation conglomerate of mostly late Oligocene age. The Turtle fault dips steeply northward and is apparently coeval with Cloudburst accumulation, because lower parts of the Cloudburst are cut by the fault but upper parts lap across it. The Turtle divides the rocks of the region into two blocks with different tilting histories, and therein lies a tale about the San Manuel porphyry system (at stop 4). We will see the fault plane itself at stop 6B.

9.1 Turn right (east) down Tucson Wash at Black Canyon Ranch. From this point for many miles, travel is in this sandy wash. Four-wheel drive is commonly needed and mileages are approximate, because exact mileage depends on the route taken! Tucson Wash is so named because its bed was the first wagon route between the Mammoth mining district and the pueblo of Tucson.

9.4 STOP 2. Conglomerate of Cloudburst Formation forms steep bluffs above the narrow wash. This stop is an introduction to the Cloudburst Formation where it is little-altered (though you may see veins containing manganese oxides and barite, especially at the east end). The Cloudburst Formation is approximately 12,000 to 15,000 feet thick. There must have been an enormous crustal hole to fill. We are in typical upper member at this stop; the lower member consists of interlayered intermediate volcanics and volcaniclastic conglomerate. The Cloudburst is the oldest of three tilted conglomeratic mid-Tertiary units in the area; the San Manuel and Quiburis Formations are the younger ones (table 1). The Cloudburst Formation accumulated in response to the first stage of crustal extension in the area, along the Cloudburst detachment fault, which we will see at stop 6D. North of the Turtle fault as at this stop, the

Cloudburst dips rather steeply, but south of the Turtle fault as at stop 4 it is more gentle.

Clasts in the Cloudburst here include Precambrian rocks (Oracle, diabase), Laramide San Manuel porphyry intrusive, and Tertiary volcanics. Deposition of streamflood and minor debris-flow deposits was in shallow channels on a broad alluvial fan and braidplain.
Clast imbrication shows dominantly east-northeastward transport in this member. At the west end of the outcrop, slickensides are along splays of the Black Canyon fault, apparently coeval with the San Manuel fault.

10.3 STOP 3. The Shultz Spring area consists of Cloudburst Formation (upper member) that has been altered and weakly mineralized (Force and Cox, 1993). Alteration is of iron minerals in conglomerate matrix and clast rims. It forms concentric zones elongate NNW that from weakest outer to strongest inner zones (fig. 3) are 1) chloritic green matrix, 2) specular hematite+chlorite green-gray to black matrix, and 3) pyrite. Some adularia is present in zones 2) and 3). Leslie Cox finds (in Force and Cox, 1993) that weak Ba,Ag,Pb,Mo,Au mineralization is centered on the concentric alteration zones; Zn is centered along the western margin.

At the stop itself, limonite after pyrite replaces conglomerate matrix and cobble rims. Above this outcrop to the left (west) are specularite+adularia in matrix and to the right (east) is the base of a tuff unit. Across the wash (south) is chloritic green-matrix conglomerate.

The Mammoth vein set, which we will see at stop 6A, predates the San Manuel fault, contains some of the same elemental constituents as the Shultz Spring area, and has the same trend. Here at stop 3, we are on the other (upper) plate of the San Manuel fault. Force originally thought that Shultz Spring might be an upper-plate segment of the Mammoth system, offset in the same way that the Kalamazoo orebody was offset from the San Manuel orebody, but careful geometric analysis (including recalculation of the vector for San Manuel fault), showed that this is unlikely to be the case. More likely, the Shultz Spring area is an offset segment of the Ford mine area on the lower plate, which we will drive past.

10.5 Tuff unit of Weibel (1981) on the left (east). The 22.5 Ma K-Ar K-feldspar date reflects some resetting by adularia added during Shultz Spring alteration.

10.6 Turn right (southwest) up subsidiary wash, which we refer to informally as Lowell Wash. We have somewhere crossed the buried Turtle fault and are in Cloudburst Formation conglomerate that dips gently eastward above basement rocks of the Purcell window.

11.0 STOP 4. Cloudburst Formation conglomerate rests unconformably on Oracle Granite (containing a diabase intrusive body). The attitude of this unconformity is quite irregular here, reflecting relief on the erosional surface and accumulation of Cloudburst Formation against buttresses. Note however that the dip of the unconformity is rather gentle, like the bedding in overlying Cloudburst Formation.

Just upstream is exposed an intrusive contact of San Manuel porphyry in Oracle Granite like that at stop 1, which is actually quite nearby as the crow flies. We may or may not have access to this contact due to growth of the subsidence zone caused by block-cave mining of the Kalamazoo orebody. The Black Canyon fault repeats some of these contacts up the wash.

In this wash and one to the west where exceptionally fresh San Manuel porphyry crops out, J. T. Hagstrum of U.S.G.S. conducted a paleomagnetic study of the Laramide intrusive (prior to the initiation of Kalamazoo mining). He found that the San Manuel porphyry has been rotated $33 \pm 12^{\circ}$ about an axis trending N. 46° W. since its crystallization. This result is of considerable interest since Lowell (1968) suggested a tilt of about 70° to the ENE. We then re-examined the geological evidence of tilting history. We found that originally sub-horizontal mid-Tertiary horizons and strata that directly overlie the San Manuel porphyry intrusive and its host rocks have mean dips of about 30° to the northeast (table 2), similar to this stop. Precambrian and Paleozoic layers and strata that were originally sub-horizontal (including the diabase body; Howard, 1991) in the region have a mean dip of 45^{o} to the northeast (table 2). Thus the tilt of a Laramide intrusive should be between 30 and 45^{o}; greater tilts would require a severe and reversing pre-Laramide tilting history.

Why did Lowell (1968) advocate greater tilt? His restoration (his fig. 2) tilts the San Manuel porphyry system through the entire magnitude of the steep dip angle of Cloudburst Formation north of the Turtle fault as at stops 2 and 6; at the time it was not realized that this fault separates two blocks with different tilting histories. We shall see at stop 6 that the area north of the Turtle fault is an allochthon related to the Cloudburst detachment fault.

How then can Lowell's cross-section (1968, his figs. 2 and 5) show a severely tilted porphyry? In addressing this problem we find that both the porphyry copper orebodies and the igneous bodies are basically tabular in shape, and that Lowell in orienting his cross-section parallel to the slip vector for the San Manuel fault oriented it nearly parallel to the strike of these bodies. Naturally the intersection of a vertical cross-section and a dipping body nearly parallel to it will be nearly horizontal, but this has nothing to do with tilting history.

We find that a 30^{o} rotation about the best mid-Tertiary rotation axis yields the cross-sectional relation that Lowell (1968) considered evidence of a 70^{o} tilt. Table 3 shows the present attitude of the tabular igneous and ore bodies, and the axis about which we rotated them to get the original attitude. Note the similarity of the original attitude to that of other productive Laramide dikes of the region, as given by Heidrick and Titley (1982).

So how was Kalamazoo discovered if Lowell (1968) did not fully understand the geometry and tilting history? None of these problems made any difference, because Lowell's fault reconstruction was accurate, and his apparent-dip cross-section parallel to fault slip still led to ore. It is possible, however, that an accurate picture of ore geometry and tectonic history may lead to further discoveries in this district.

This revision of Lowell's (1968) tilting history may also have exploration implications in other porphyry districts. The original orientation of the San Manuel porphyry intrusive was a steeply dipping tabular body rather than an equant upright body. The arrangement of ore and alteration zones in the model of Lowell and Guilbert (1970), based on San Manuel-Kalamazoo as a type area, occurs there as mitten- or envelope-shaped zones around certain parts of this dipping tabular body, rather than a bullet-shaped system. Thus the zonation of their model system is topologically correct, but the top and shape of the model may not be good exploration guides.

11.4 Return to mile 10.6 in Tucson Wash.

12.5 to 12.6 STOP 5 in two parts.

At 5A we will dismount to see the Tucson Wash Member of the San Manuel Formation. This is the upper member of the formation but up the hill before us (north) it rests directly on Cloudburst Formation; here we are in a narrow block perhaps between two splays of the San Manuel fault; the authors are of two minds on this point. One splay is at 5B around the corner to the north, and the other would be somewhere under alluvium of the wash (south).

The most interesting aspect of this stop is the provenance of clasts in this member of the San Manuel Formation. The Tucson Wash Member contains clasts of volcaniclastic conglomerate of the lower member of the Cloudburst Formation, some with epidote alteration, and clasts of rhyolite, Mammoth-type vein quartz, and Oracle Granite. Southwest of the San Manuel open pit it contains clasts of porphyry ore. Thus derivation was from the northeast, in the area of stop 6. Stratigraphically downward these clasts become larger, until at 5B they include large slide blocks resting against the San Manuel fault plane. Apparently, during movement on the San Manuel fault, coarse debris was being shed into a resulting basin from the upthrown block to the northeast.

At 5B, we can see on the left (west) the San Manuel fault separating the base of the Tucson Wash Member of San Manuel Formation on the upper plate from Oracle Granite on the lower plate.

The San Manuel fault here is a narrow zone in which black calcite has grown. The dip is southwestward (into the hill) about 30°. Oracle Granite shows propylitic assemblages because we are in the outer parts of the alteration aureole of the San Manuel deposit; note the dumps forming the southern margin of the wash.

13.3 Ford mine (see stop 3). We are in Oracle Granite in this interval, weakly altered, and locally cut by aplite dikes.

13.7 to 14.0 STOP 6 in four parts.

At 6A, the Mammoth vein crosses the wash. Brecciated rhyolite and quartz veinlets are exposed at wash level on the left (west) side. The veinlets show a characteristic morphology for the Mammoth veins, in which specular hematite forms thin bands parallel to both vein margins at about 10 and 90 percent of vein thickness. Adularia is common in these bands and toward vein margins.

Above the wash, blocks and/or outcrops of more substantial vein material are present; blocks have sometimes fallen onto the wash surface. These may contain vanadinite, wulfenite, and other minerals for which the Mammoth vein set is renowned.

Minerals have been produced from the Mammoth vein set intermittently since 1879. About two million tons of ore had been removed as of 1959. The earliest production was mostly of gold; later on molydenum, vanadium, lead, and zinc each became major products (table 4).

Above the wash to the right (east) are the workings of the Collins cut on the Mammoth vein set, worked most recently for silica. At about the elevation of the surface workings, the Cloudburst-Oracle unconformity is exposed, though complicated by rhyolite intrusion. Thus the Collins cut is the lower-plate correlative of stop 4. This fact was used in recalculating the slip vector for the San Manuel fault. Our magnitude is close to that calculated on other grounds by Lowell (1968).

The Mammoth vein set consists of two main segments offset by the Mammoth fault. When reconstructed across this fault, it shows an intricate vertical zonation (fig. 4). In higher portions (i.e., the top of the Mammoth-Tiger segment) only gold and silver were recovered. In intermediate portions, wulfenite and vanadinite predominated, and it is this portion of the Collins segment that we are in at stop 6A. In the lowermost portions (i.e., the bottom of the Collins segment), lead and zinc sulfides predominated.

The Mammoth vein set is approximately coextensive with intrusive rhyolite that generally contains muscovite after K-feldspar. Some quartz of the vein set probably came from cooling rhyolite by the reaction K-feldspar+water=quartz+muscovite.

The vein set was itself emplaced along a fault that (now) dips steeply southwest and is upthrown on the east, based on offset of the Oracle-Cloudburst unconformity. Reconstruction of the dip of this structure prior to mid-Tertiary tilting shows that it originated as a reverse fault. It apparently post-dates the Turtle and Cloudburst faults. The relationship of some of these faults is shown in figure 5.

At 6B (13.75 mi) on the right (east) side, we encounter the Turtle fault. It dips steeply northward and separates shattered Oracle Granite to the south from Cloudburst Formation to the north. Here we are in the lower member of the Cloudburst, and some conglomerates at 6B have the aspect of lahars. Note the epidote alteration in the fault plane and in the Cloudburst Formation, and the Mammoth-type veinlets in the fault plane.

We have seen on the upper plate of the San Manuel fault that the Turtle fault separates different tilt domains, and the same is true here on the lower plate. South of the Turtle fault, the Cloudburst-Oracle unconformity is gently dipping, whereas north of it, bedding in the Cloudburst dips steeply northeast, as we shall see at 6C. At 6D we will see that the Cloudburst detachment fault separates an upper and lower plate into the same two tilt domains, even though its attitude is very different from that of the Turtle fault. Thus the Turtle fault is apparently a side-ramp of the Cloudburst detachment, or in other words, it is the southern boundary of the Cloudburst or Tar Wash allochthon. This in turn suggests that movement on the Turtle fault was largely strike-slip.

At 6C (13.8 mi) we will turn left (west) on foot up Cloudburst Wash, a main tributary of Tucson Wash. Here we see Cloudburst Formation, still lower member but here containing more normal conglomerates, locally with cobbles of Oracle Granite. Cobbles of Tertiary volcanics are most abundant in most beds, and a few have the appearance of bombs or lapilli. A short distance upstream is the top of a volcanic flow of intermediate composition. Note that both lithologies are moderately altered to epidote-chlorite assemblages. Barite is locally present.

High on the slope to the left (southwest) the Mammoth vein set is about parallel to the wash. Some blocks of vein material have washed down. Here the wallrocks of the vein are Cloudburst Formation, and the vein is low-grade. However, adjacent to the vein, the Cloudburst Formation is heavily impregnated with epidote and chlorite.

If there is time, one can walk upwash past the base of the flow to a picturesque waterfall (normally dry) in conglomerate. Here one can visualize what a cloudburst in Cloudburst Wash must produce. In these extremely indurated rocks one can also understand why the Cloudburst Formation was once thought to be Laramide. A scramble around the waterfall brings the surefooted enthusiast to the Mammoth vein crossing the wash (and a dangerous adit with open shaft).

The chlorite-epidote alteration looks like a type of hornfelsing, and in a way it is. Our traverse is through rock only about 100 or 200 feet above the subhorizontal Cloudburst detachment fault, which we will see at 6D. Movement on the fault placed young sediments and volcanics against rock that prior to faulting had been deeply buried and hot. Detachment faulting is a type of tectonic denudation, and juxtaposes hot lower-plate rock against cold upper-plate rock. Hence the appearance of new minerals in the upper plate is a type of contact metamorphism. Additional epidote-chlorite impregnation is related to the vein set, but the two alteration phenomena share the same structural top.

At 6D, the Cloudburst detachment fault is exposed on both sides of the wash, in four separate areas that constitute a single window. The fault is nearly horizontal, both regionally and in this exposure, but shows vertical relief of about 100 feet. Below the fault is shattered Oracle Granite. Above it is Cloudburst Formation (lower member), dipping steeply into the fault plane. The footwall is a chloritic breccia, but no physiographic ledge of resistant microbreccia is present. In this area the detachment is nearly horizontal; it formed with a gentle westward dip, but younger extension coeval with the San Manuel fault rotated it again.

Rhyolite clearly intrudes the fault plane in some outcrops and is offset in others, suggesting synchronous intrusion and faulting. The swarm of rhyolite bodies is not offset at map scale. Rhyolite intrusion probably occurred during a late stage of fault movement.

Now that we have seen all the components, it is worth considering the tectonic context of the Mammoth vein set. The exposures of Cloudburst Formation from 6B to 6D are all just above a single fault system that must rapidly change orientation from steep north dip on the Turtle-fault portion at 6B, to horizontal on the Cloudburst-fault portion at 6D. The upper-plate rocks were baked in response to juxtaposition against tectonically denuded hot lower-plate rock. At the same time, rhyolite was intruded into this region of extreme thermal gradients, and apparently cooled in this environment such that silica was released into a concurrently-moving fault plane parallel to the rhyolite swarm, forming the Mammoth vein set. Vein-related alteration is approximately coextensive with detachment-related thermal alteration. The richest portion of the district (according to Peterson, 1938) coincides with the lower-plate segment adjacent to the intersection of the Turtle and Cloudburst faults. Thus the district is clearly influenced by detachment faulting. The connection between detachment and mineralization is not quite so direct as in some districts where mineralization is along the detachment fault plane and formed concurrent with its movement, and where intrusives are absent (Spencer and Welty, 1986), but some features of the Mammoth vein set are quite comparable to detachment-driven mineralization in other districts. Among these are oxide-dominated assemblages, the importance of barite, specular hematite, adularia, and manganese oxides in these assemblages, and the elemental assemblage Au-Ag-Ba-Pb-Zn-Cu without As, Sb, Hg, or Tl (Long, in press). The Mammoth district is sufficiently well known that it could teach us about a gradation between epithermal and detachment-driven systems; R. J. Kamilli of U.S.G.S. is investigating this relation via fluid inclusions.

14.5 Rhyolitic ash-flow tuffs cross the wash. These rhyolitic extrusives are more areally extensive than the rhyolitic intrusives, but even in the heart of the Mammoth district, extrusive rhyolites, mostly tuffaceous, are common.

14.8 Last exposures of Cloudburst Formation. Here we are in the upper member but virtually all clasts are volcanic. The source direction is unclear.

15.7 Rhyolite in wash to left (north), originally intrusive into Cloudburst Formation. This monolith was then buried by basin fill of the Quiburis Formation that forms surrounding bluffs, and has now been re-exhumed. Similar rhyolite farther north is dated at 23 Ma; all are probably closely related to Mammoth-district rhyolites.

16.2 Good exposure of Quiburis Formation, the youngest of the extensional conglomerate units of the area (table 1). The Quiburis is post-mid-Miocene and formed in response to basin-range faulting along the Mammoth and Cholla faults. It fills the present San Pedro trough. The dip is gentle to the east, but must exceed the depositional dip, because a lacustrine facies across the San Pedro River still shows some eastward dip.

From here it is easiest to proceed to the railroad trestle, bear left (north) just past it, and detour around borrow pit. The outcrops here include a sandy facies of Quiburis Formation transitional between fanglomerate to the west and lacustrine clay and evaporites to the east. Continue east to join highway 77 just north of the town of Mammoth.

End of trip.

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Table 1.-- Relative timing of faulting and accumulation of sedimentary units, from younger to older, in the trip area.

Sedimentary unit	Faulting
Quiburis Formation (post mid-Miocene)	Basin-range faulting on Mammoth and Cholla faults
San Manuel Formation (lower Miocene)	Low-angle (at present) normal faulting on San Manuel fault, and coeval steep faulting on Red Rock and Black Canyon faults
Cloudburst Formation (upper Oligocene to lower Miocene)	Detachment on sub-horizontal (at present) Cloudburst detachment fault and steep Turtle fault

Table 2.-- Present mean attitudes of formerly horizontal features of varying ages, from younger to older, in the structural blocks containing segments of the San Manuel porphyry system

Feature	Present mean attitude (strike,dip)
San Manuel Formation bedding	N35W, 30 NE
Cloudburst Formation (upper member) bedding	N20W, 30 NE
Cloudburst-Oracle unconformity	N41W, 30 NE
Paleozoic sedimentary bedding of Black Hills (SSE of Mammoth)	N52W, 48 NE
Precambrian diabase sills	N20-40W, 40-50 NE
Apache Group sedimentary bedding (NNW of Mammoth)	N30W, 45 NE

Table 3.-- Present and original approximate attitudes of the San Manuel porphyry ore envelope and igneous intrusion.

Present plane	N58E, 47 SE
Rotation axis for restoration	trend N42W, horizontal plunge, rotate NE side up about 31°
Original plane	N79E, 58 SE

Table 4. Grades and totals by commodity of production from the Mammoth vein set, from Keith and others (1983) for the period 1886 to 1981

(--, no data)

Commodity	Quantity[1]	Apparent grade[2]
Ore	5,310,000 st	
Au	349,000 oz	0.07 oz/ton
Ag	1,660,000 oz	0.31 oz/ton
Mo	3,943,046 lb	--
V	2,540,842 lb	--
Pb	132,680,000 lb	12.5 percent
Zn	87,312,000 lb	8.2 percent
Cu	10,445,000 lb	0.98 percent
Mn	41,600 lb	--
U	-0-	--

[1] st, short tons; oz, ounces; lb, pounds.

[2] Assumes recovery of all commodities.

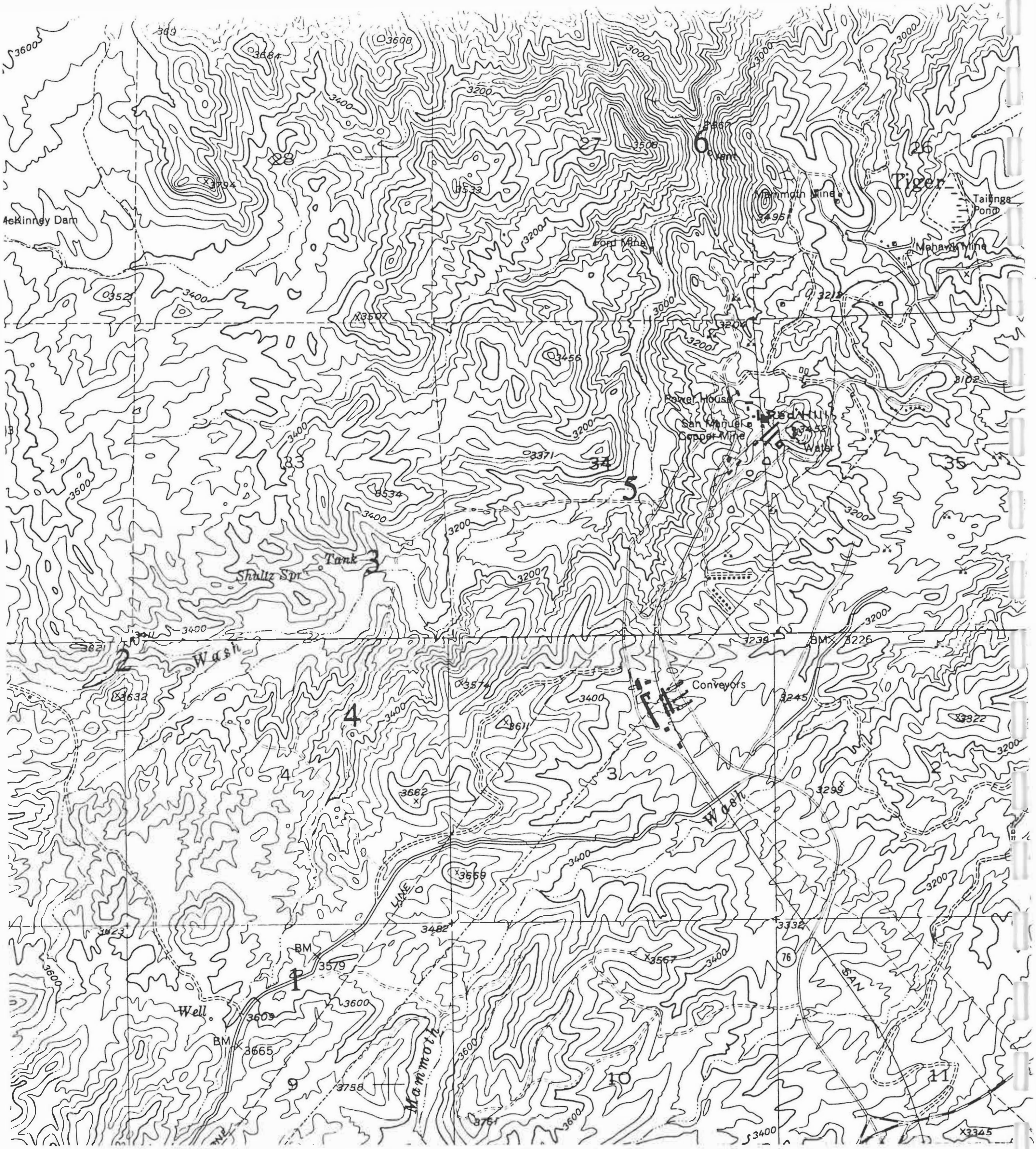


Figure 1 -- Part of Mammoth 7 1/2' quadrangle showing the location of field-trip stops.

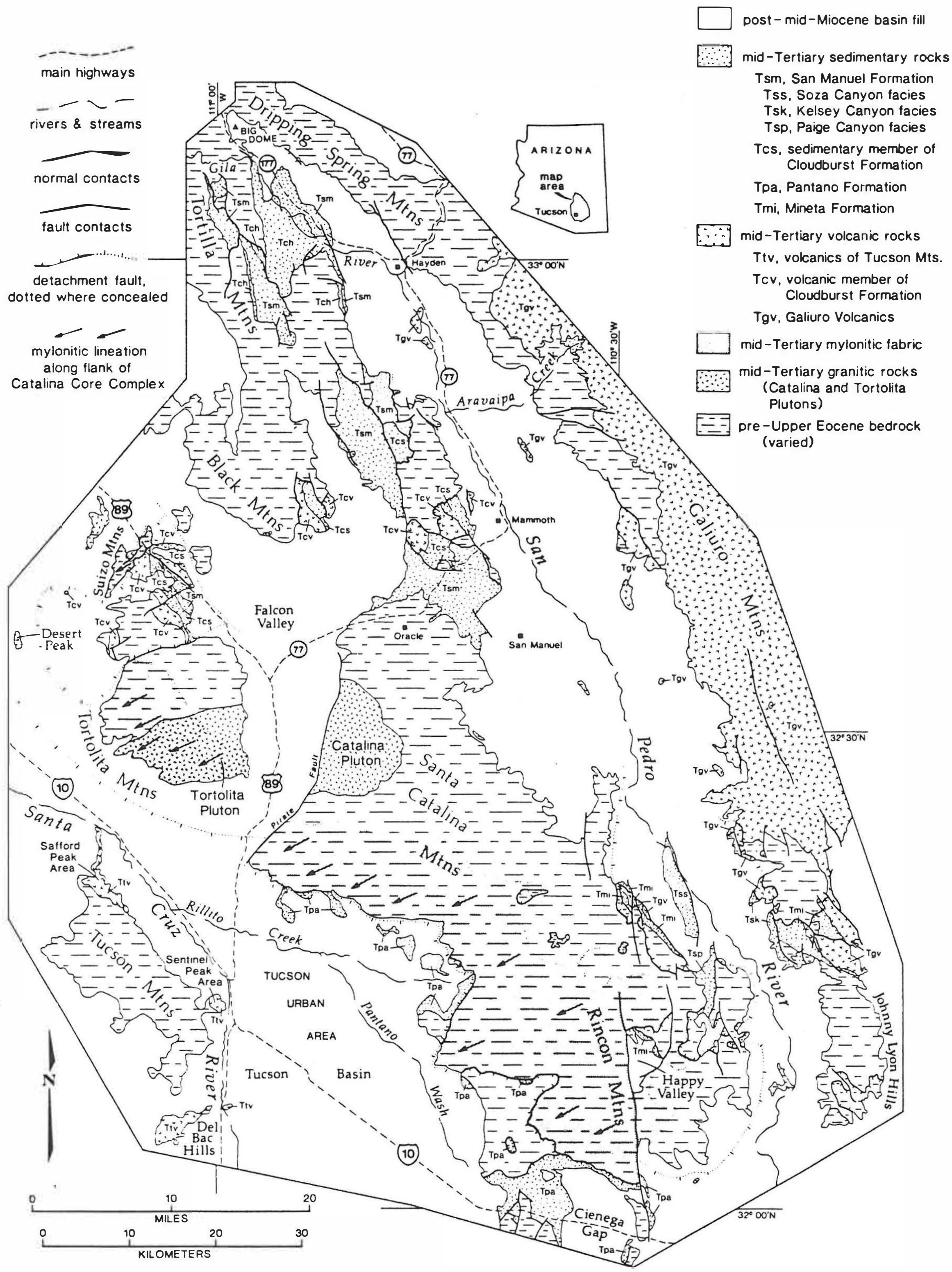
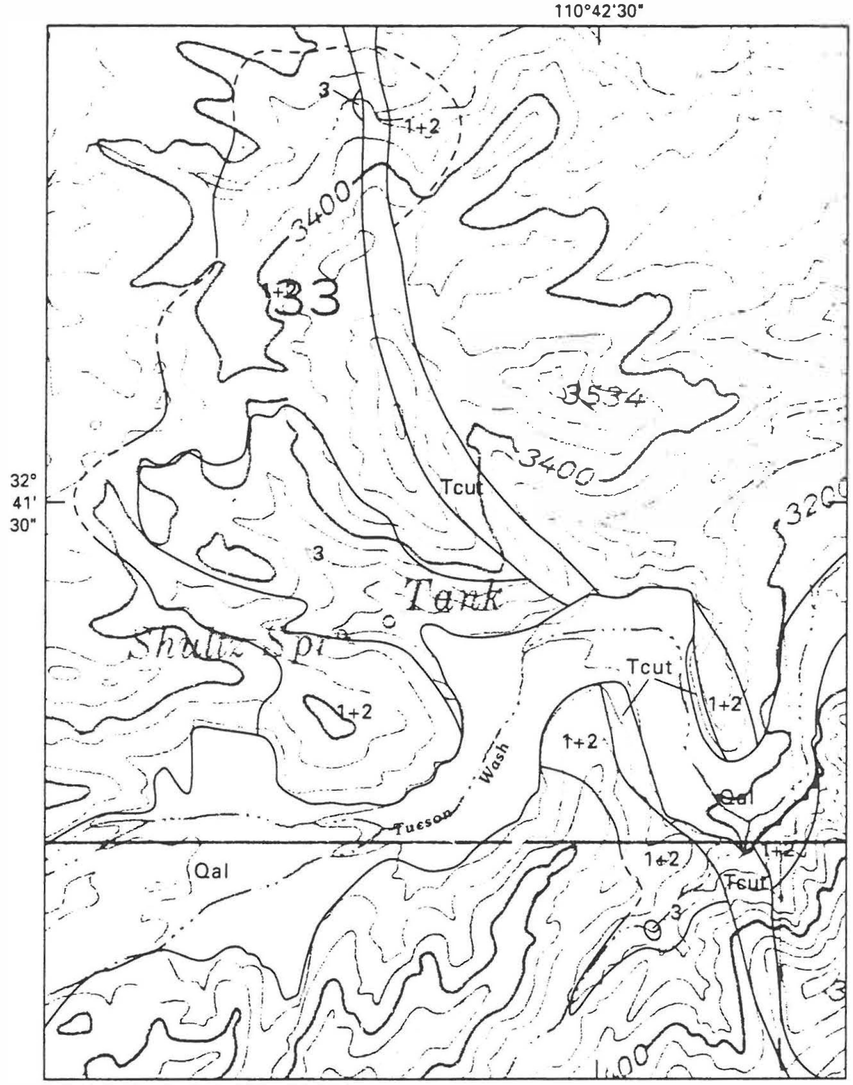


Figure 2 -- Some geologic features in the region of the field trip. Highway 77 as shown is the old road containing stop 1; Tucson Wash is just north of it (from Dickinson, 1991).



Base from U.S. Geological Survey 1:24,000
Mammoth, 1948 (photorevised 1972)

SCALE 1:12 000

0 500 1000 1500 2000 2500 FEET

0 250 500 750 METERS

CONTOUR INTERVAL 40 FEET

EXPLANATION

——— **Contact**—Between geologic units and/or alteration zones; dashed where approximately located

1+2 **Alteration types 1 (green matrix) and 2 (specular hematite), undivided**

3 **Alteration type 3 (pyrite)**

Figure 3 -- Alteration zones at Shultz Spring (stop 3), from Force and Cox (1993). Tcut is a tuff in the upper Cloudburst Formation; no other lithologies except Quaternary alluvium (Qal) are shown.

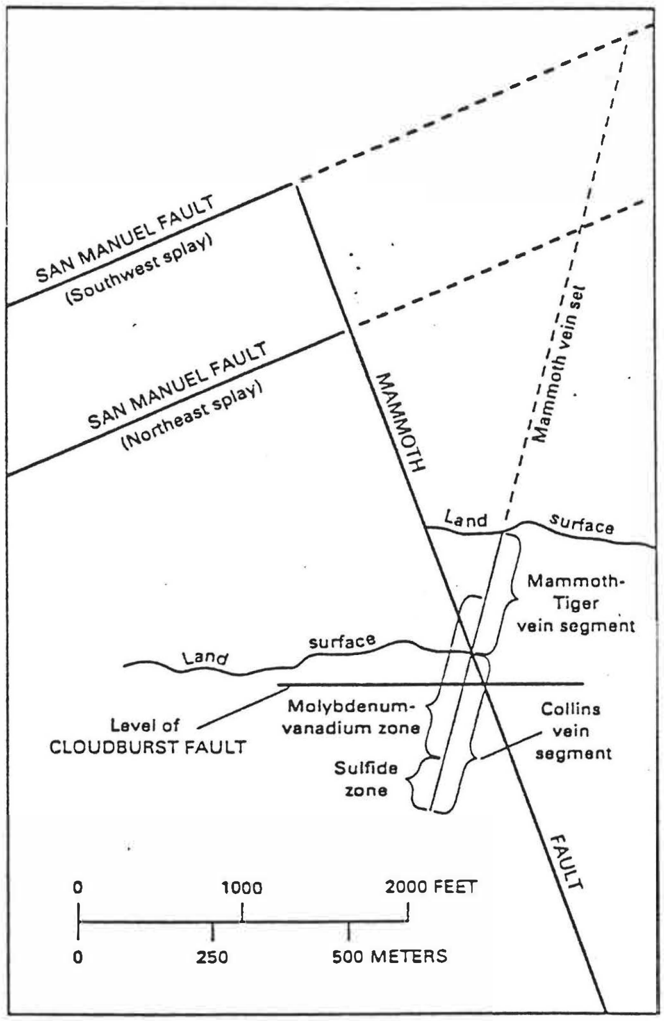


Figure 4 -- Reconstruction of the Mammoth vein set showing elemental zonation (from Force and Cox, 1993).

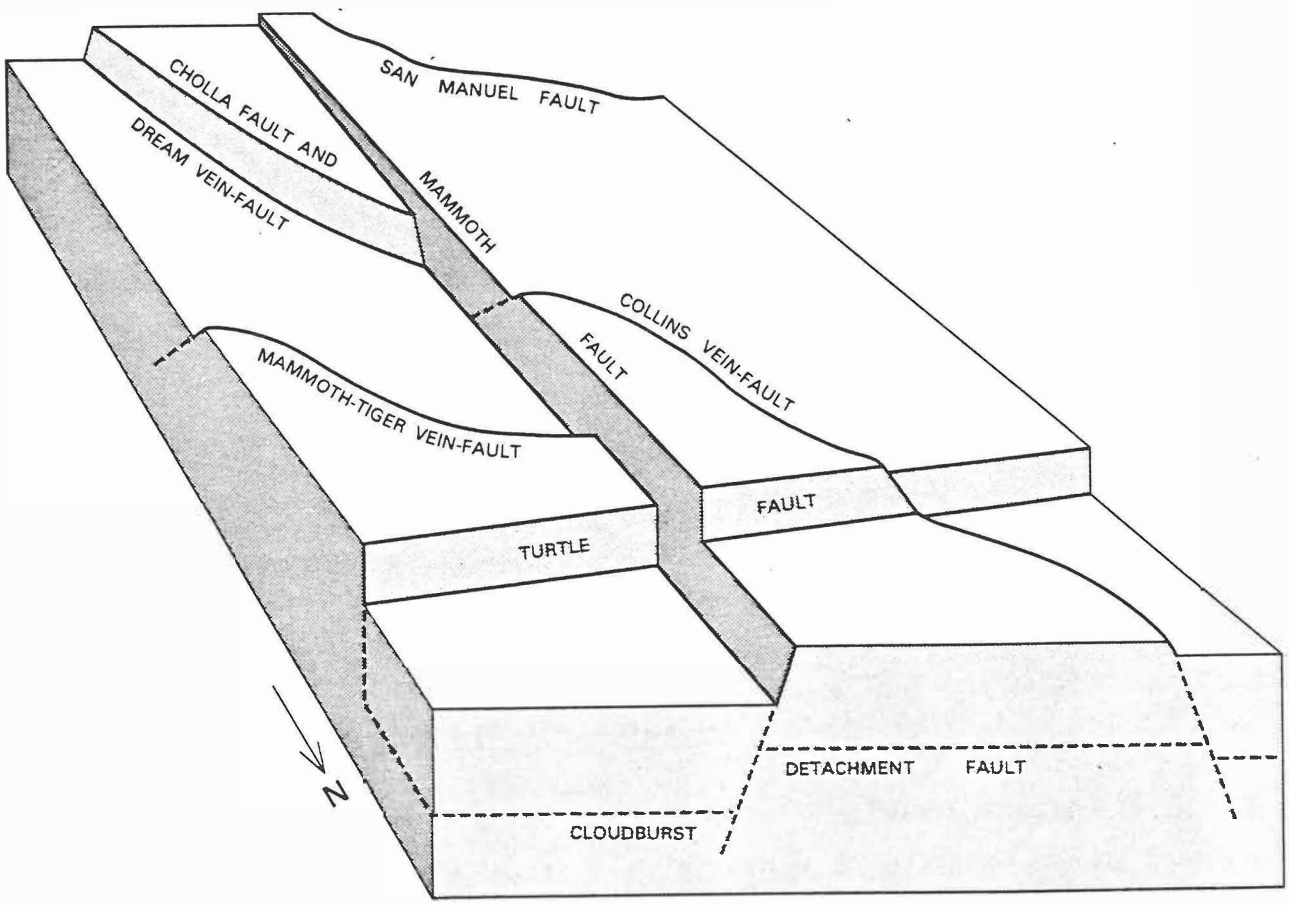


Figure 5 -- Block diagram showing the relation of some of the faults in the field-trip area (from Force and Cox, 1993).

from Creasey 1965 USGS PP 471

GEOLOGY OF THE SAN MANUEL AREA, PINAL COUNTY, ARIZONA

By S. C. Creasey

ABSTRACT

The San Manuel area is in southeastern Arizona about 30 miles northeast of Tucson. It is covered by the Mammoth 7½-minute quadrangle and includes the San Manuel porphyry copper deposit and the St. Anthony vein deposit, which yielded silver, gold, vanadinite, molybdenite, lead, and zinc. The San Manuel mine began production in 1955, and the St. Anthony mine closed in 1952 after a production of about 2 million tons of ore.

The Black Hills, the chief physiographic feature in the San Manuel area, are a small low-lying fault-block range in the Mountain Region of the Basin and Range province. They are bounded on the east and west by gravels, partly faulted against bedrock. To the northwest they pass into a gently rolling region of low relief, but to the south-southeast they grade into the Santa Catalina Mountains, one of the large rugged ranges in southeastern Arizona.

Precambrian rocks comprise granodiorite, quartz monzonite—Oracle Granite of Peterson (1938)—aplite, alaskite, and some diabase. Crosscutting relations and textural and lithologic similarities indicate that the oldest rock is the granodiorite, followed by the quartz monzonite, aplite, and alaskite; some diabase and aplite have mutual crosscutting relations. In adjacent areas rocks like the granodiorite intrude older Precambrian Pinal Schist.

Granodiorite porphyry, which occurs as small irregularly shaped masses and dikes in the Precambrian quartz monzonite, is the principal host rock for the disseminated copper ores of the San Manuel deposit. The granodiorite porphyry is older than the Cloudburst Formation and some diabase. One lead-alpha age determination made on zircon from the granodiorite porphyry suggests a Cretaceous age for the zircon and, by inference, for the porphyry.

The crosscutting relations of the diabase clearly establish that part of the diabase is Precambrian and that part is Cretaceous(?) or younger.

The Cloudburst Formation, of Late Cretaceous or early Tertiary age, consists of about 6.800 feet of intercalated fanglomerate and propylitized latite flows; neither the top of the section nor the bottom is exposed in the San Manuel area. The formation overlies the Precambrian granitic rocks on a low-angle thrust fault and is unconformably overlain by the Gila Conglomerate.

About two-thirds of the San Manuel area is underlain by Gila Conglomerate, the basin fill for the San Pedro Valley. The Gila ranges from coarse boulder conglomerate to fine marly silt; these deposits represent fanglomerates and playa or lake deposits, respectively. On the basis of differences in lithology and attitude, two members of the Gila Conglomerate, designated lower and upper, are recognized. The lower member, consisting chiefly of indurated conglomerate, dips 25° E. Four bedlike masses and one lens of sedimentary breccia lie conformably within the lower member. The breccia masses and lens comprise one, two, or three rock types. The fragments of the breccias are angular and jumbled, and they, unlike fragments in the surrounding conglomerate, show no indication of water transport or sorting. The breccia deposits are probably due to landslides or mudflows, or both. The upper member of the Gila Conglomerate is chiefly limy silt that dips 5° to 10° E. The two members are separated by an angular unconformity.

Remnants of pediment gravel cap some of the interfluves in the areas underlain by Gila Conglomerate. Apparently, the pediment once covered virtually all the Gila Conglomerate and some of the contiguous bedrock. Unconsolidated recent sand and gravel mantle the floor of the San Pedro River valley and the floors of all the washes except those of the smallest tributaries.

After intrusion and solidification, the Precambrian granodiorite and quartz monzonite were fractured and sheared, and diabase and aplite invaded the ruptures. The next recognizable structures are of Cretaceous age. Whether deformation occurred during the intervening time cannot be determined because the rocks in which the structures would be recorded are missing. The regional distribution of the younger Precambrian Apache Group and the Paleozoic system indicate that these rocks once covered the San Manuel area but that erosion has subsequently removed them; it is possible, however, that some of these rocks might lie beneath the Gila Conglomerate in the San Pedro Valley.

The granodiorite porphyry probably intruded the Precambrian granitic rocks during the Cretaceous, and the San Manuel ore deposit formed before the accumulation of the Cloudburst Formation. Before the Basin and Range deformation, the Cloudburst Formation was thrust over the Precambrian granitic rocks, and rhyolite and rhyodacite intruded it, but whether the rhyolite and rhyodacite were introduced before or after the thrusting was not determined. The thrust is probably a local structure. The Basin and Range deformation produced the San Manuel, Mammoth, and other unnamed high-angle normal and reverse faults. Faulting continued during the accumulation of the basin-fill deposits.

The San Manuel porphyry copper deposit contains combined sulfide and oxide ore that averages about 0.8 percent copper. The altered zone that contains the ore is about 8,000–9,000 feet wide and is more than 9,300 feet long; the long dimension strikes about N. 80° E. The deposit is mined by block-caving.

The ore occurs in quartz monzonite, granodiorite porphyry, and diabase and lies along the contact of granodiorite porphyry (above) and quartz monzonite (below); granodiorite porphyry is, however, the most abundant host rock. The ore may be related in time and source to the granodiorite porphyry. The primary sulfide minerals in the San Manuel deposit are chalcopyrite, pyrite, and molybdenite. Chalcocite is supergene; it occurs in the lower part of the oxidized zone associated with chrysocolla and residual sulfides. Supergene enrichment is slight to undetectable.

Economic Geology
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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

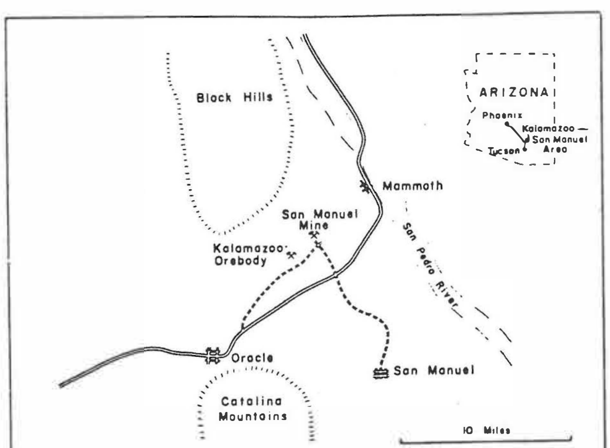


Fig. 1. Location map San Manuel District, Arizona.

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.

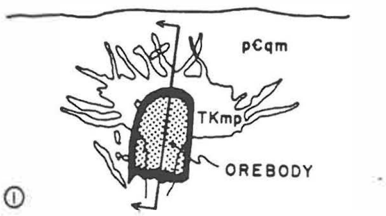
A system of high-angle, northwest-trending faults later produced relatively small, mostly normal fault displacements in both halves of the original orebody, and erosion stripped most of the Gila Conglomerate from the east end of the present San Manuel orebody. This erosion cycle developed extensive leaching 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).

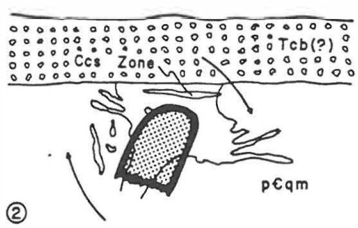
Figure 5 is a longitudinal geologic section of the Kalamazoo orebody and the overlying northeast-dipping Tertiary sediments. Figure 6 is a cross section illustrating the bisected hollow cylindrical shape of the orebody and shows a cross section of the mullion structure in the San Manuel fault zone.

Mineralization

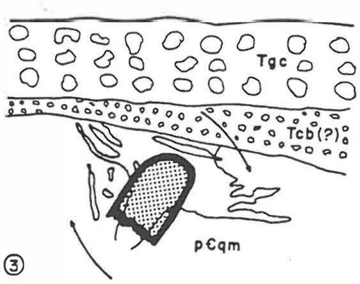
Ore mineralization is about equally distributed between coarse-grained Precambrian quartz mon-



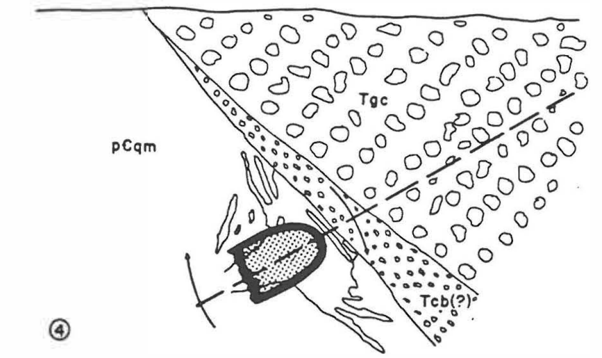
1. Precambrian quartz monzonite (pCgm) was intruded by a Laramide age monzonite porphyry (TKmp) dike swarm. A hollow cylindrical or pipe-shaped orebody with dimensions of approximately 8,000 × 3,500 feet was formed. It was probably nearly vertical and centered on the monzonite dike swarm. (Section line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



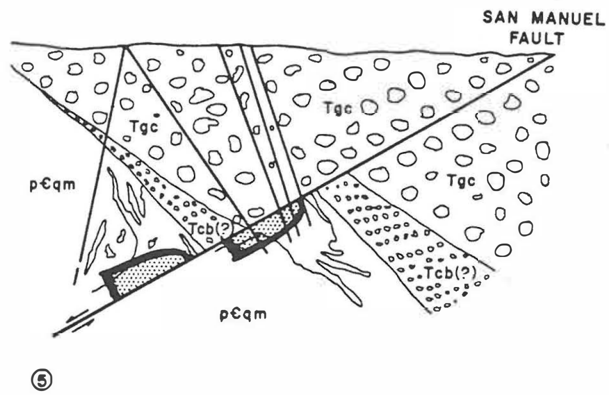
2. Tilting of the orebody was followed by erosion, then deposition of conglomerate and interbedded volcanics (Tcb?). A thin chalcocite blanket (Ccs) was formed at the water table.



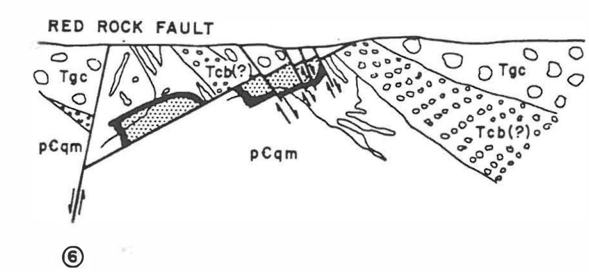
3. Continued tilting was followed by erosion of conglomerate and quartz monzonite and deposition of middle Tertiary Gila Conglomerate (Tgc).



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

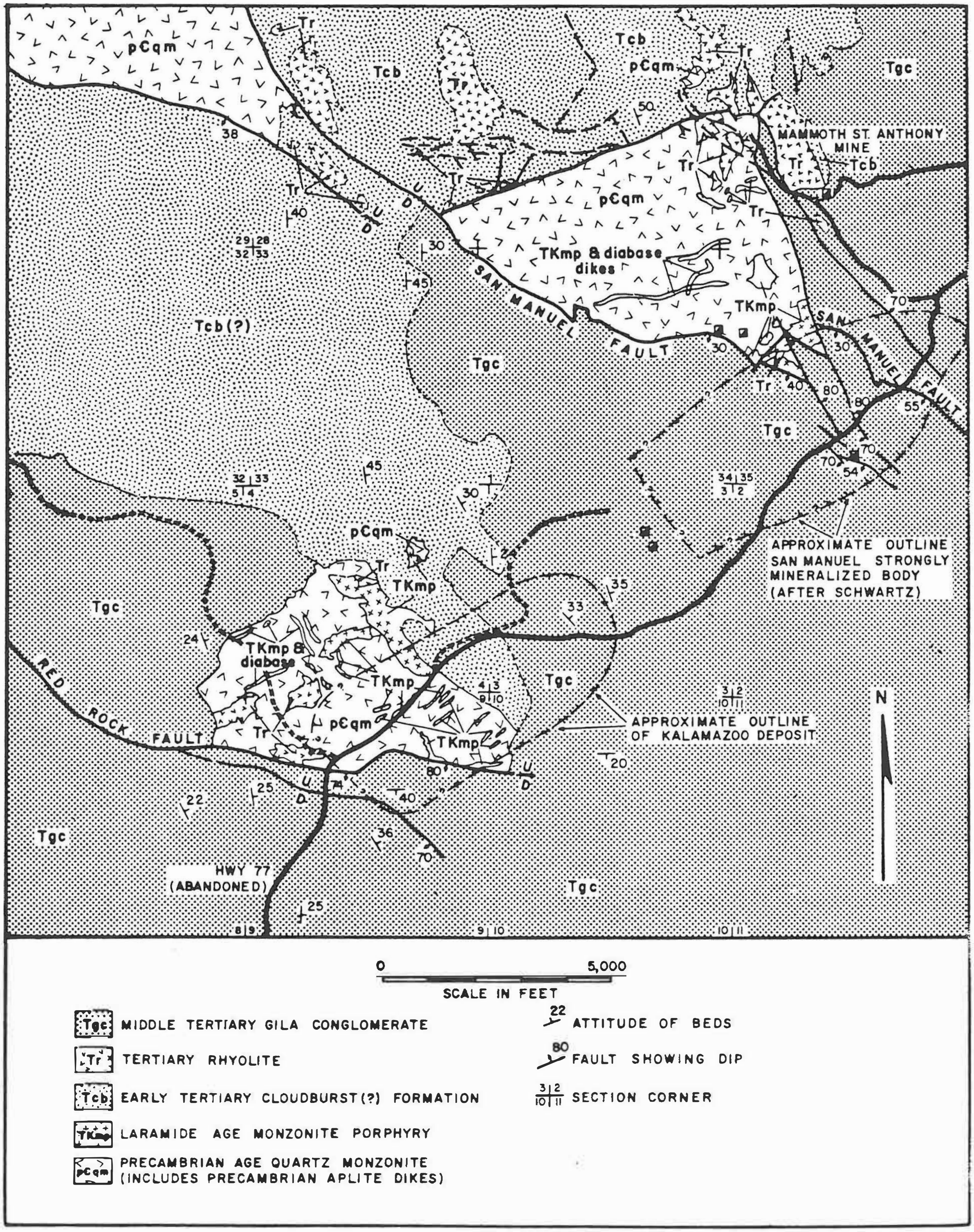


FIG. 3. Geologic map of the San Manuel area.

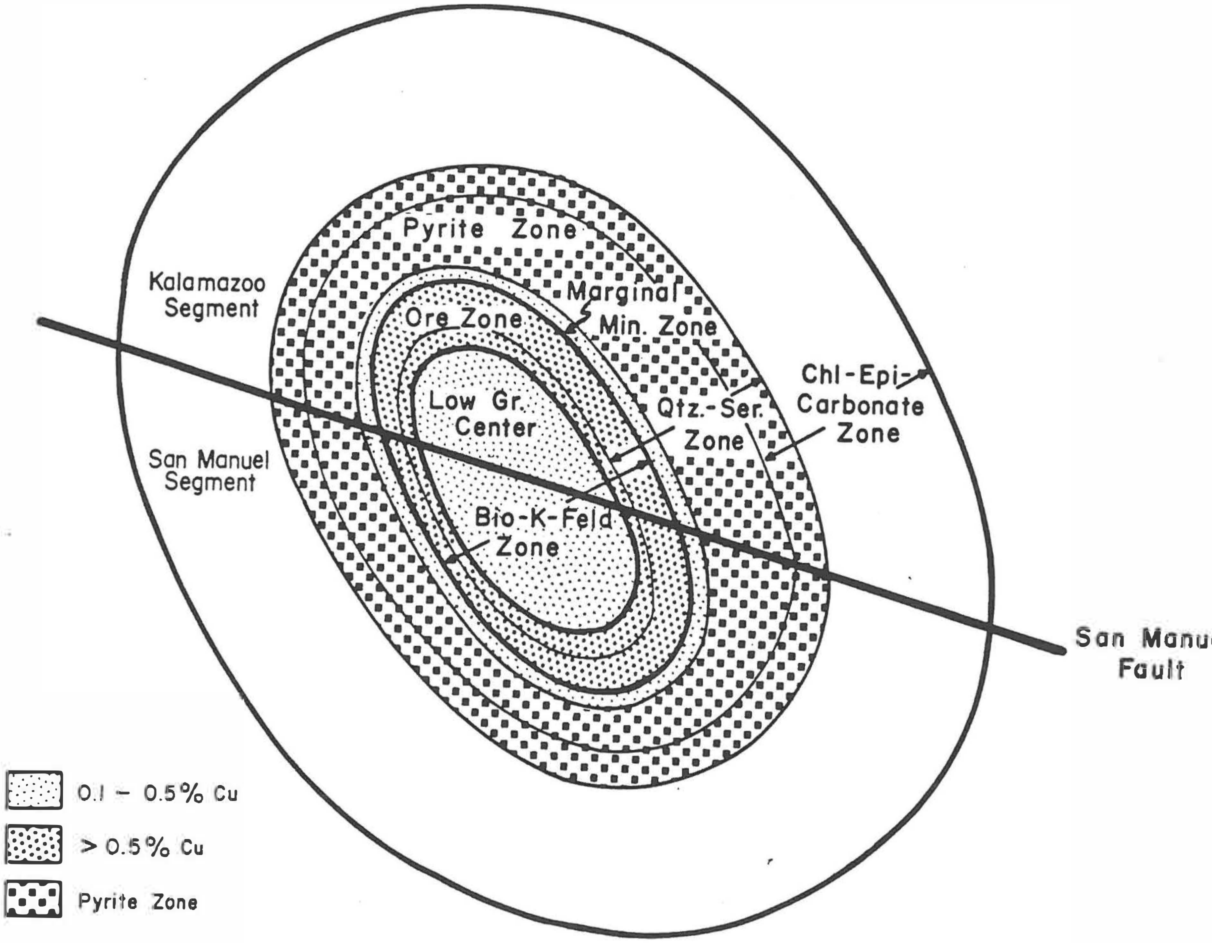


FIG. 4. Schematic horizontal plan showing alteration and mineralization zones.

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

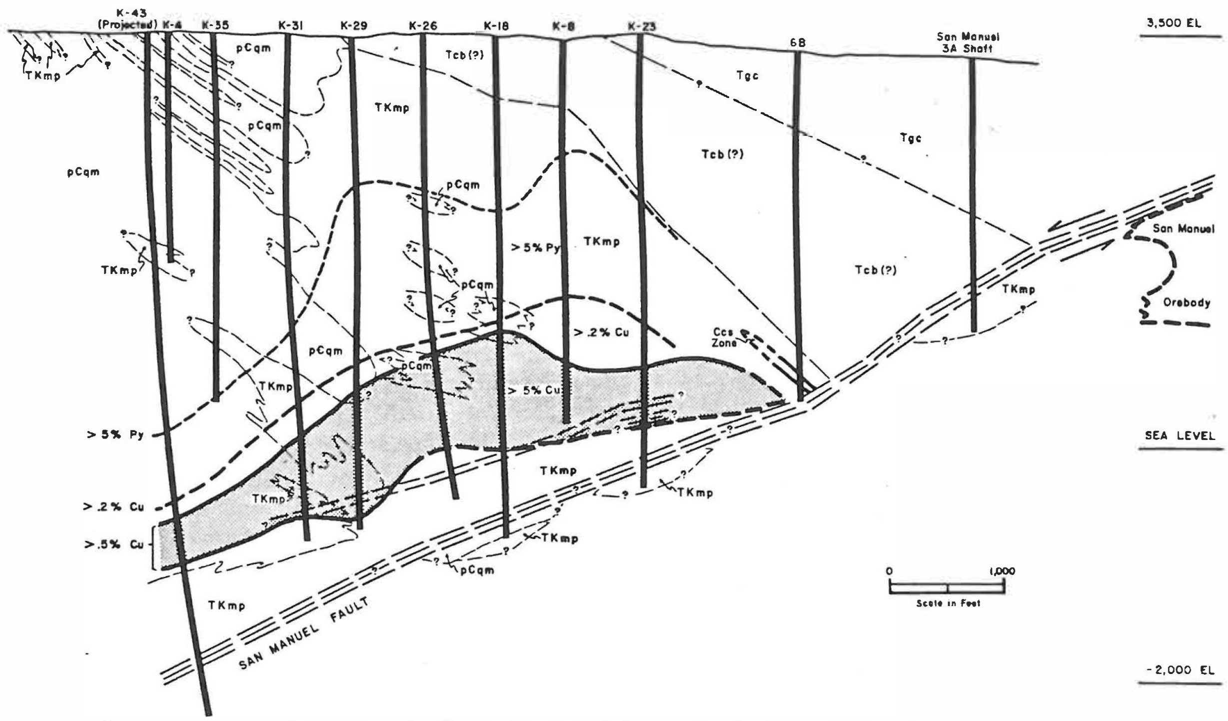


FIG. 5. Longitudinal section of Kalamazoo orebody looking northwest.

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.

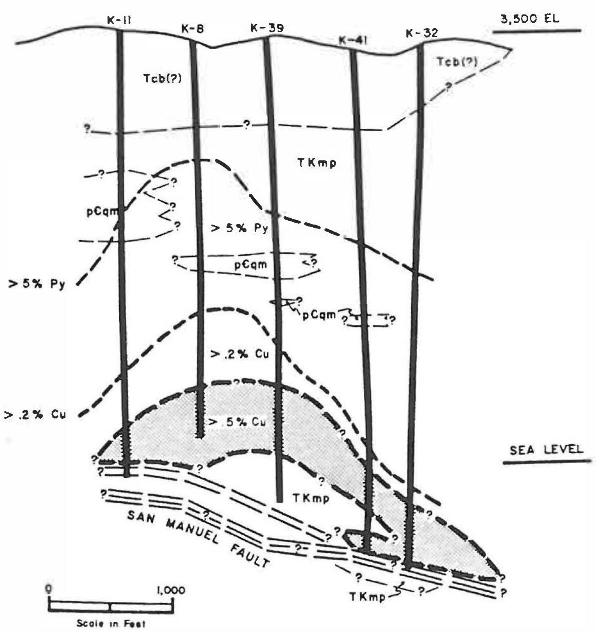


FIG. 6. Cross section of Kalamazoo orebody looking northeast.

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

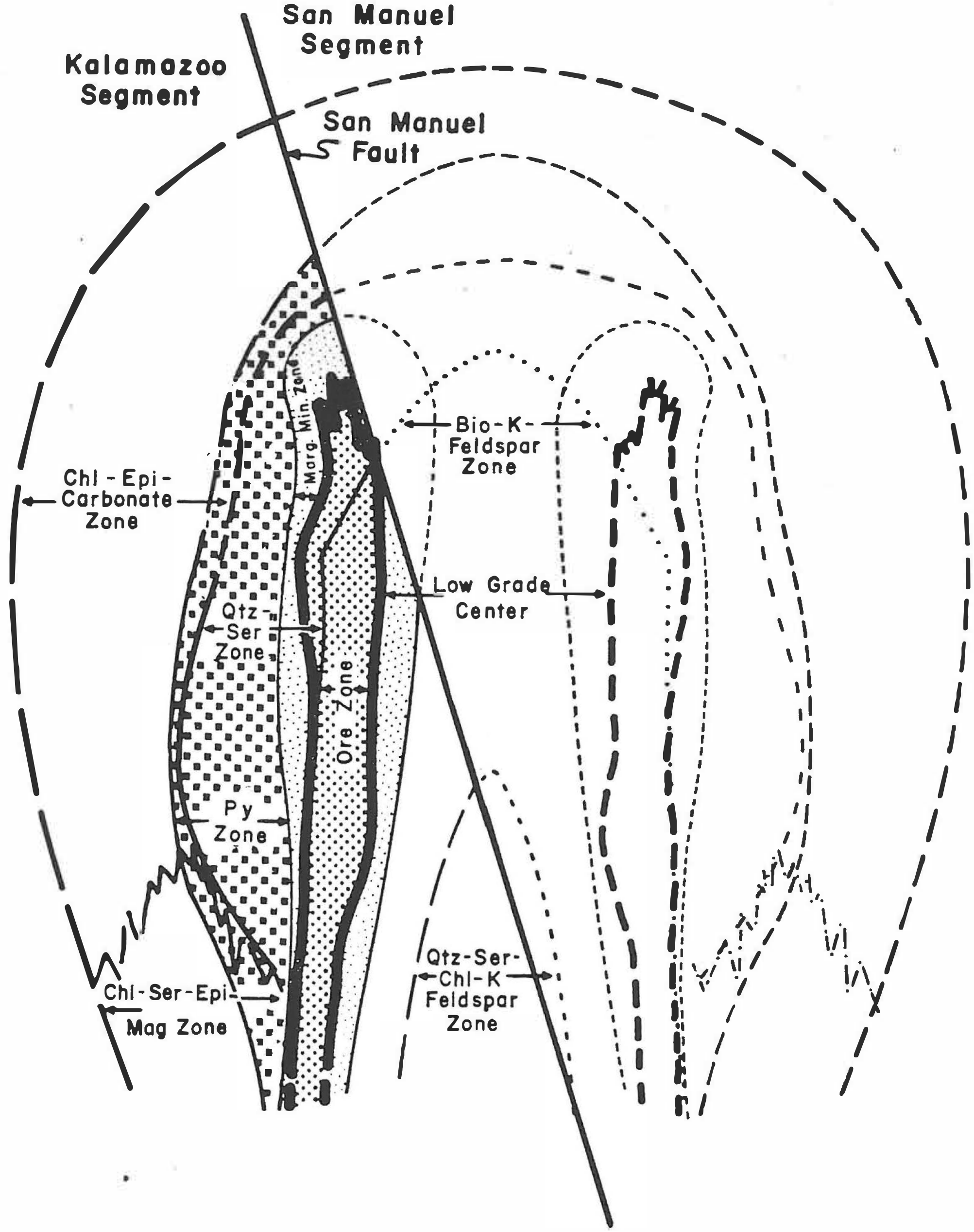


FIG. 7. Schematic section of San Manuel-Kalamazoo orebody showing vertical alteration and mineralization zones. Solid lines and shaded areas represent observed geology, and broken lines indicate extrapolated information. (See Fig. 2 for position of this section relative to final configuration of orebodies.)

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-

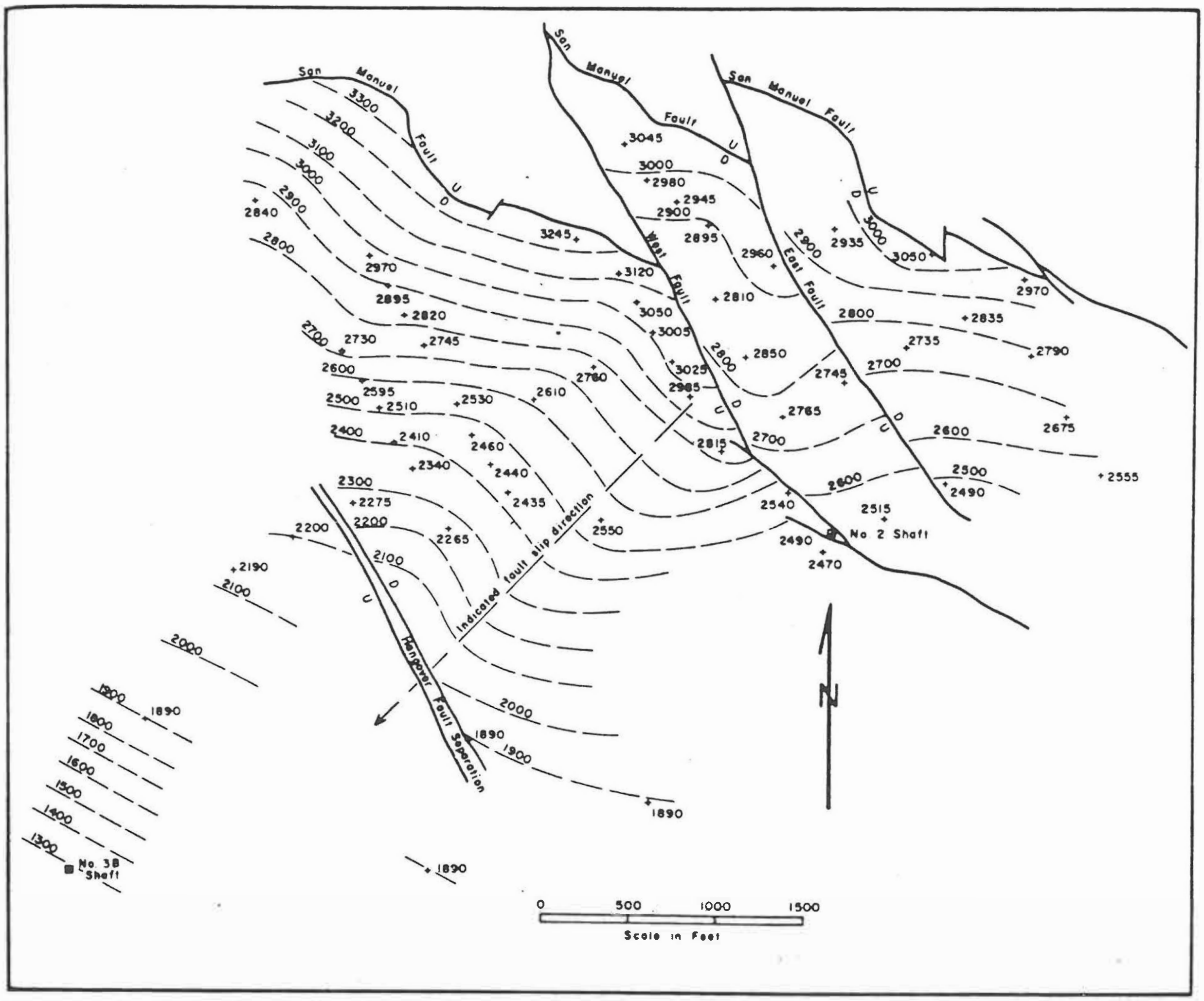


FIG. 8. Structure contour map of the San Manuel fault plane. Elevations are shown in feet above sea level.

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.

CONSULTING GEOLOGIST,
TUCSON, ARIZONA,
March 18; April 20, 1968

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Lateral and Vertical Alteration-Mineralization Zoning in Porphyry Ore Deposits

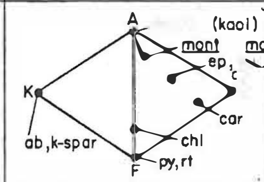
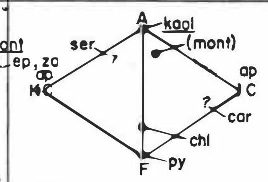
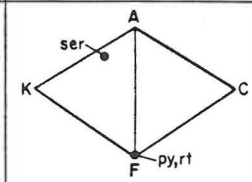
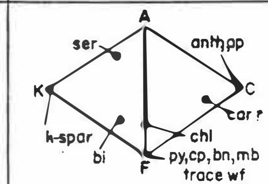
J. DAVID LOWELL AND JOHN M. GUILBERT

Abstract

The geologic history of the San Manuel–Kalamazoo deposit has provided an opportunity for the examination of vertical and horizontal zoning relationships in a porphyry copper system. Precambrian Oracle "granite," a Laramide monzonite porphyry, and a Laramide dacite porphyry are hosts to zones of potassic, phyllic, argillic, and propylitic assemblages shown to be coaxially arranged outward from a potassic core through phyllic, argillic, and propylitic zones. Alteration zones at depth comprise an outer chlorite–sericite–epidote–magnetite assemblage yielding to an inner zone of quartz–K-feldspar–sericite–chlorite. Mineralization zones are conformable to the alteration zones, the ore zone (with a 0.5% Cu cutoff) overlapping the potassic and phyllic zones. Occurrence of sulfides changes upward and outward from dissemination at the low-grade core of the deposit through microveinlet to veinlet and finally vein occurrence indicating the progressively increasing effect of structural control.

Several aspects of San Manuel–Kalamazoo geology suggest that it is exemplary of the porphyry copper deposit group. To test that idea and to evolve three-dimensional aspects of these deposits, a table of geologic characteristics of 27 major porphyry deposits is presented. Consideration of the table indicates that the "typical" porphyry copper deposit is emplaced in late Cretaceous sediments and metasediments and is associated with a Laramide (65 m.y.) quartz monzonite stock. Its host intrusive rock is elongate-irregular, 4,000 × 6,000 feet in outcrop, and is progressively differentiated from quartz diorite to quartz monzonite in composition. The host is more like a stock than a dike and is controlled by regional-scale faulting. The orebody is oval to pipelike, with dimensions of 3,500 × 6,000 feet and gradational boundaries. Seventy percent of the 140 million tons of ore occurs in the igneous host rocks, 30 percent in preore rocks. Metal values include 0.45% hypogene Cu with 0.35% supergene Cu, and 0.015% Mo. Alteration is zoned from potassic at the core (and earliest) outward through phyllic (quartz–sericite–pyrite), argillic (quartz–kaolin–montmorillonite), and propylitic (epidote–calcite–chlorite), the propylitic zone extending 2,500 feet beyond the copper ore zone. Over the same interval, sulfide species vary from chalcopyrite–molybdenite–pyrite through successive assemblages to an assemblage of galena–sphalerite with minor gold and silver values in solid solution, as metals, and as sulfosalts. Occurrence characteristics shift from disseminations through respective zones of microveinlets (crackle fillings), veinlets, veins, and finally to individual structures on the periphery which may contain high-grade mineralization. Breccia pipes with attendant crackle zones are common.

Expression of zoning is affected by exposure, structural and compositional homogeneity, and postore faulting or intrusive activity. Vertical dimensions can reach 10,000 feet, with the upper reaches of the porphyry environment perhaps only at subvolcanic depths of a few thousand feet. The vertical and lateral zoning described is repeated with sufficient constancy that depths of exposure at many deposits can be cited against the model of San Manuel–Kalamazoo.

SHALLOW–MODERATE DEPTH ASSEMBLAGES					
FRESH QM, PORPHYRIES	PROPYLITIC ZONE	ARGILLIC ZONE	PHYLLIC ZONE	POTASSIC ZONE
Quartz	No Change	Augmented	Augmented	Augmented
Orthoclase–Microcline	No Change	Flecked with Sericite	Sericitized	Recrystallized, in part replaced by alteration K-feldspar–quartz
Plagioclase (An_{35-45})	Tr. Mont, flecks & granules ep, zois, car, chlorite, kaol.	Montmorillonite → Kaolin	Sericitized	Fresh to completely replaced by brn-grn alt'n biotite, K-spar, ser.
Biotite	Chlor, zois, car, leucoxene	Chloritized, + leucoxene, qtz	Sericite, pyrite, rutile	Fresh or recrystallized to sucrose brn-grn granules, ± chlorite
Hornblende	Ep, car, mont, chlor (2 types)	Chloritized	Sericite, pyrite, rutile(?)	Biotite, ± chlorite, rutile
Magnetite	trace pyrite	Pyritized	Pyritized	Pyritized
A–K–C–F A = Al K = K, Na C = Ca salts F = Fe, Mg				
Veinlet Fillings	Q-cal-K-spar-chlor-rare ab–rt	Q–ser–py–chlor	Q–ser–py	Q-K-spar–bi–ser–anhy–cal–ap

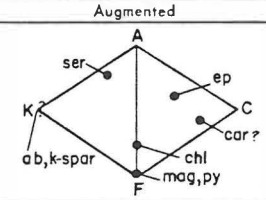
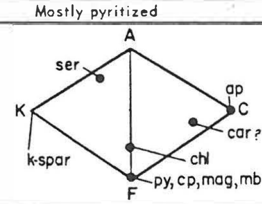
DEEP-LEVEL ASSEMBLAGES		
	OUTER	INNER
Quartz	Slightly Augmented	Augmented
Orthoclase-Microcline	Dusted with trace sericite	Alteration K-spar with sericite, relicts common, minor quartz
Plagioclase (An_{35-45})	Dusted with sericite, chlorite, epidote	Sericitized, with alteration K-spar-quartz, relicts uncommon
Biotite	Largely chloritized, minor epidote mag added	Chloritized, rare primary relicts
Hornblende	Chlorite + Epidote + Carbonate	Chloritized; trace carbonate
Magnetite	Augmented	Mostly pyritized
A–K–C–F A = Al K = K, Na C = Ca salts F = Fe, Mg		
Veinlet Fillings	Q–mag–py ± Q–ser–cal envelopes	Q–K-spar–ser–chl, tr mag, py, cp, mb

FIG. 2. Summary of hydrothermal alteration assemblages at San Manuel–Kalamazoo.

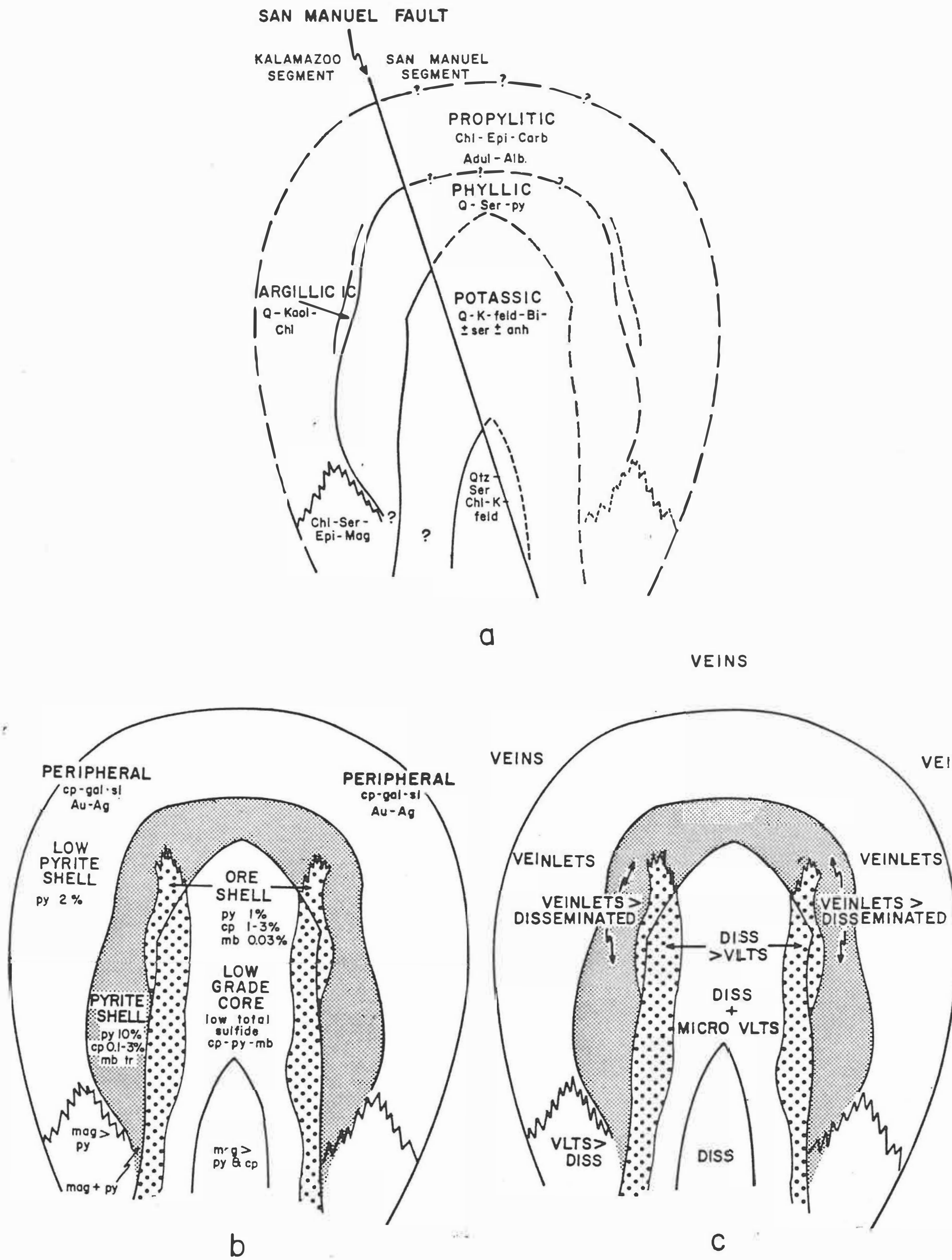


FIG. 3. Concentric alteration-mineralization zones at San Manuel–Kalamazoo. (a) schematic drawing of alteration zones. Broken lines on Kalamazoo side indicate uncertain continuity or location and on San Manuel side extrapolation from Kalamazoo. (b) schematic drawing of mineralization zones. (c) schematic drawing of the occurrence of sulfides.

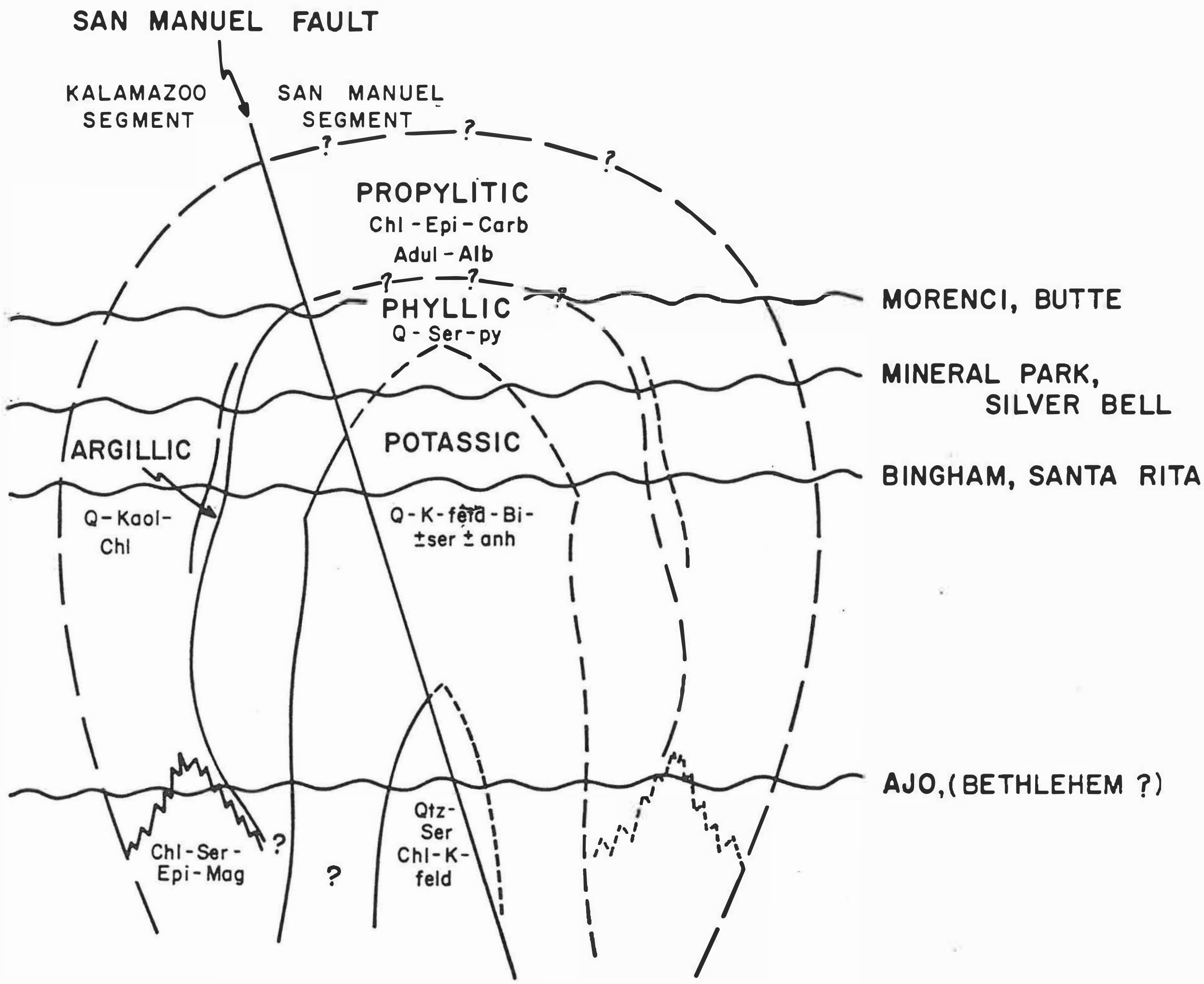


FIG. 13. Schematic drawing of San Manuel–Kalamazoo showing exposure levels of several porphyry copper deposits. Other deposits could be added, but these few serve to show a vertically developed dimension.

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Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona

ABSTRACT

Stratigraphic and structural relations of syntectonic sedimentary sequences associated with Cordilleran metamorphic core complexes provide valuable information about the style and timing of extensional deformation related to tectonic denudation. Adjacent to the Catalina core complex, the San Pedro trough and other nearby depocenters contain multiple tilted half-grabens of conglomeratic mid-Tertiary strata partly buried beneath Neogene basin fill. Major episodes of local geologic history included mid-Proterozoic construction of continental crust, subsequent but intermittent platform sedimentation extending through Paleozoic time, mid-Mesozoic initiation of arc magmatism that persisted at intervals through mid-Tertiary time, complex Laramide orogenic deformation of latest Cretaceous to early Tertiary age, and Cenozoic extensional deformation involving both mid-Tertiary and basin-range phases of development.

Precambrian basement includes lower Proterozoic Pinal Schist intruded by voluminous lower to middle Proterozoic granitic plutons. Pre-Laramide stratigraphic cover includes middle Proterozoic sedimentary strata and intercalated diabase sills, Paleozoic carbonate and clastic units, and Mesozoic volcaniclastic and clastic successions. Laramide assemblages include metaluminous plutons and andesitic to rhyolitic volcanic fields, synorogenic nonmarine sedimentary sequences, and large bodies of peraluminous two-mica granite. Laramide structural features include both premetamorphic and ductile synmetamorphic thrusts within the Catalina core complex, brittle thrusts of uncertain vergence and overall configuration outside the Catalina core complex, and folds of varied geometry related in part to local thrusts exposed nearby. Paleogene erosion had stripped Laramide volcanic cover from wide areas by mid-Tertiary time.

Migratory Tertiary arc magmatism within the intermountain region gave rise to diachronous polymodal igneous suites, represented within and near the Catalina core complex by extensive volcanic fields and local granitic plutons of late Oligocene age. Across the whole Southwest Border region, analogous mid-Tertiary igneous activity was succeeded, following an intra-Miocene tectonomagmatic transition, by basaltic to bimodal suites erupted during subsequent block faulting.

Tertiary intermountain taphrogeny included a mid-Tertiary phase marked by listric or rotational normal faulting associated with tectonic denudation of core complexes along detachment systems, and a later basin-range phase of widespread block faulting. Mid-Tertiary extension was apparently promoted by reduction of interplate shear, kinematic rollback of a subducted slab, lateral spreading of overthickened crust, advective softening of arc lithosphere, and possibly by counterflow of asthenosphere. Basin-range extension was evidently initiated by shear coupling of Pacific and American lithosphere.

The Catalina core complex displays characteristic geologic features: mylonitic fabric overprinted near a detachment fault by brecciation and chloritic alteration, a brittle

detachment surface abruptly separating rock masses derived from different crustal levels, cover strata broken into multiple tilted fault blocks forming a shingled imbricate array, and surrounding syntectonic sedimentary sequences containing intercalated megabreccia horizons. The domical uplift that controls the exposed extent of the Catalina core complex apparently reflects isostatic upwarp of the midcrust in response to tectonic denudation, coupled with rollover arching above listric faults cutting beneath the core complex and with later uplift of crustal masses along steep block faults.

A belt of mylonitic gneiss 10 km wide and 100 km long lies along the southwest flank of the Catalina core complex adjacent to the downdip segment of the detachment fault. Updip segments of the detachment system, across which cumulative displacement is estimated as 20 to 30 km, curve over and around the exposed core complex to merge with an inferred headwall rupture along the trend of the San Pedro trough. The detachment system probably involved a gently dipping aseismic slip surface beneath surficial tilted fault blocks; alternatively, faults now dipping gently may have originated as steep structures that rotated to shallow dips as slip proceeded. Field relations around the Catalina core complex are seemingly more compatible with the former interpretation, but insights gained from the alternate interpretation are useful for structural analysis of rotated tilt-blocks above the master detachment surface. Kinematic considerations imply that displacements within the local detachment system were diachronous during its evolution, but mylonitic deformation and detachment faulting both occurred during late Oligocene and early Miocene time.

Tilted homoclines of syntectonic mid-Tertiary strata and less deformed beds of younger basin fill are both composed dominantly of alluvial fan and braidplain facies that grade laterally to finer-grained fluvial and lacustrine facies. Subordinate deposits include landslide megabreccia, algal limestone, lacustrine diatomite, and playa gypsum. The most voluminous strata are crudely bedded conglomerate and conglomeratic sandstone deposited by braided depositional systems. Clast imbrication is the most widespread and reliable paleocurrent indicator. Mid-Tertiary aggradation in half-graben basins gave rise to sedimentary onlap and overstep of evolving tilt-blocks, intricate local facies relations, and marked stratigraphic contrasts between sequences deposited within partly isolated subbasins. Stratigraphic successions that are concordant within basin depocenters are commonly broken by unconformities and intervals of nondeposition on basin flanks and across crests of bounding tilt-blocks.

Mid-Tertiary strata exposed as tilted homoclines along the flanks of the San Pedro trough and across broad uplands north of the Catalina core complex are assigned to the following formations, each of which includes informal local members and facies: (a) Mineta Formation, mid-Oligocene redbeds including both conglomeratic fluvial and finer-grained lacustrine deposits; (b) Galiuro Volcanics, including lavas and domes, air-fall and ash-flow tuffs, and intercalated volcaniclastic strata of late Oligocene to earliest Miocene age; (c) Cloudburst Formation, also of late Oligocene and earliest Miocene age but including a sedimentary upper member of conglomeratic strata as well as a volcanic lower member correlative with part of the Galiuro Volcanics; and (d) San Manuel Formation, composed of lower Miocene alluvial fan and braidplain deposits that display contrasting clast assemblages in different areas of exposure. Generally correlative Oligocene-Miocene strata exposed south of the Catalina core complex are assigned to the Pantano Formation, which contains similar lithologic components. Less-deformed Neogene strata of post-mid-Miocene basin fill are assigned to the Quiburis Formation along the San Pedro trough, but stratigraphic equivalents elsewhere lack adequate nomenclature. High benchlands mantled by paleosols mark the highest levels of Neogene aggradation. Successive stages of subsequent erosional dissection are recorded by multiple terrace levels incised into basin fill.

Key exposures of syntectonic mid-Tertiary sedimentary sequences in several local subareas reveal typical structural and stratigraphic relationships. Multiple fault blocks expose pre-Tertiary bedrock overlain by tilted mid-Tertiary strata confined to interven-

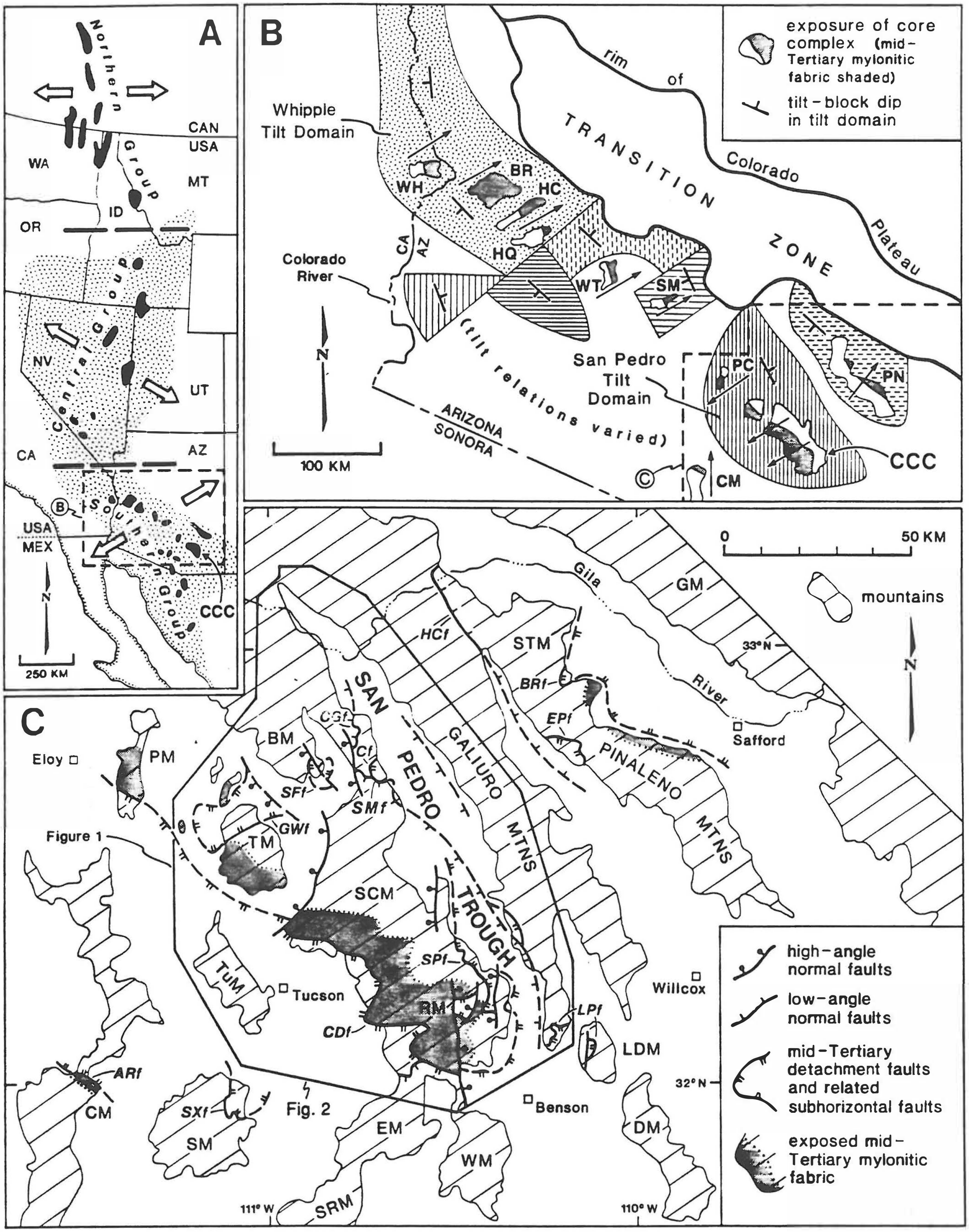
ing half-grabens. Bounding syndepositional faults dip southwest and associated homoclines dip northeast. Fanning dips and buttress unconformities reflect progressive tilt and burial of eroding fault blocks. Dips of block-bounding faults are inversely proportional to the ages of the faults. Steeper dips for younger faults suggest either progressive erosion of successive listric faults or progressive rotation of successive planar faults. Uniformly moderate to steep dihedral angles between fault surfaces and offset homoclinal bedding imply that the faults dipped more steeply near the surface when syntectonic mid-Tertiary strata were subhorizontal. Although the inference of listric faulting best links apparent strands of the Catalina detachment system, the alternate interpretation of rotational normal faulting is compatible with local structural relationships including tilt of porphyry copper orebodies.

Within the San Pedro trough, multiple homoclines of mid-Tertiary strata are exposed locally in tilt-blocks exhumed by Neogene erosion from beneath nearly flat-lying basin fill of the Quiburis Formation. Faults bounding the mid-Tertiary exposures include backtilted strands of the Catalina detachment system, somewhat younger listric or rotational normal faults, and steeper basin-range normal faults that display offsets both synthetic and antithetic to the flanks of the San Petro trough.

In Cienega Gap, flanking the Tucson Basin, multiple tilt-blocks of the Pantano Formation form part of the upper plate of the Catalina detachment system. Initial construction of alluvial fans by generally westward paleoflow was followed by ponding of lacustrine environments along the foot of secondary breakaway scarps that also generated massive megabreccia deposits.

In summary, syntectonic Oligocene to Miocene sedimentation succeeded a prominent pulse of polymodal mid-Tertiary volcanism and was coeval with mylonitic deformation and detachment faulting along the flank of the Catalina core complex. The headwall rupture for the detachment system migrated westward from an initial position along the range front of the Galiuro Mountains. After mid-Miocene time, accumulation and subsequent dissection of essentially undeformed basin fill was accompanied by basin-range block faulting. The most challenging structural issue is whether fault strands of the Catalina detachment system are interconnected or are disconnected rotational segments.

Figure 3. Regional tectonic setting of Catalina core complex (CCC) and San Pedro trough (adjacent on the northeast). A: Schematic distribution of northern, central, and southern groups (delimited by heavy dashed lines) of Cordilleran metamorphic core complexes (solid) in relation to Basin and Range province (stippled). Arrows indicate net direction of crustal extension for each group modified after Wust (1986b). B: Diagrammatic tectonic relations of metamorphic core complexes (see legend) and key tilt domains (variably textured) in southern Arizona. Arrows indicate relative motion of upper or cover plates of core complexes as inferred from S-C and related fabrics in mid-Tertiary mylonitic gneisses below associated detachment faults. Other core complexes shown (in addition to CCC): BR, Buckskin-Rawhide; CM, Coyote Mountains; HC, Harcuvar; HQ, Harquahala; PC, Picacho; PN, Pinaleno; SM, South Mountain; WH, Whipple; WT, White Tank. Modified after Rehrig and others (1980), Rehrig (1986), and Spencer and Reynolds (1986, 1989a, 1989c). C: Patterns of major extensional faults near Catalina core complex (occupying Tortolita, Santa Catalina, and Rincon Mountains) and adjacent San Pedro trough. Key faults: ARf, Ajo Road; BRf, Black Rock; Cf, Cloudburst; CDf, Catalina (main detachment); CGf, Camp Grant; EPf, Eagle Pass; GWf, Guild Wash; HCf, Hawk Canyon; LPf, Lime Peak; SFf, Star Flat; SMf, San Manuel; SPf, San Pedro; SXf, San Xavier. Selected mountain ranges: BM, Black; CM, Coyote; DM, Dragoon; EM, Empire; GM, Gila; LDM, Little Dragoon; PM, Picacho; SCM, Santa Catalina; SM, Sierrita; SRM, Santa Rita; STM, Santa Teresa; RM, Rincon; TM, Tortolita; TuM, Tucson; WM, Whetstone. Modified after Spencer and Reynolds (1989c); base data from Figure 1, Banks (1980), Blacet and Miller (1978), Cooper (1960, 1973), G. H. Davis and Hardy (1981), Dickinson (1984), G. H. Davis and others (1987a, b), Simons (1987), Naruk (1986, 1987a), and Yeend (1976).


A
Northern
CAN
USA
WA
MT
Group
ID
OR
Central Group
NV
UT
CA
AZ
B
Southern Group
USA
MEX
CCC
250 KM
B
exposure of core complex (mid-Tertiary mylonitic fabric shaded)
tilt-block dip in tilt domain
rim of Colorado Plateau
TRANSITION ZONE
Whipple Tilt Domain
WH
BR
HC
HQ
WT
SM
CA
AZ
Colorado River
(tilt relations varied)
ARIZONA
SONORA
100 KM
San Pedro Tilt Domain
PC
PN
CCC
CM
C
0 50 KM
mountains
Gila River
GM
33°N
Safford
STM
HCf
BRf
EPf
PINALENO MTNS
GALIURO MTNS
SAN PEDRO TROUGH
CGf
Cf
BM
SFf
SMf
GWf
TM
PM
Eloy
Figure 1
SCM
SPf
TuM
Tucson
RM
CDf
LPf
LDM
Willcox
high-angle normal faults
low-angle normal faults
mid-Tertiary detachment faults and related subhorizontal faults
exposed mid-Tertiary mylonitic fabric
ARf
CM
SXf
SM
Fig. 2
EM
Benson
32°N
DM
WM
SRM
111° W
110° W

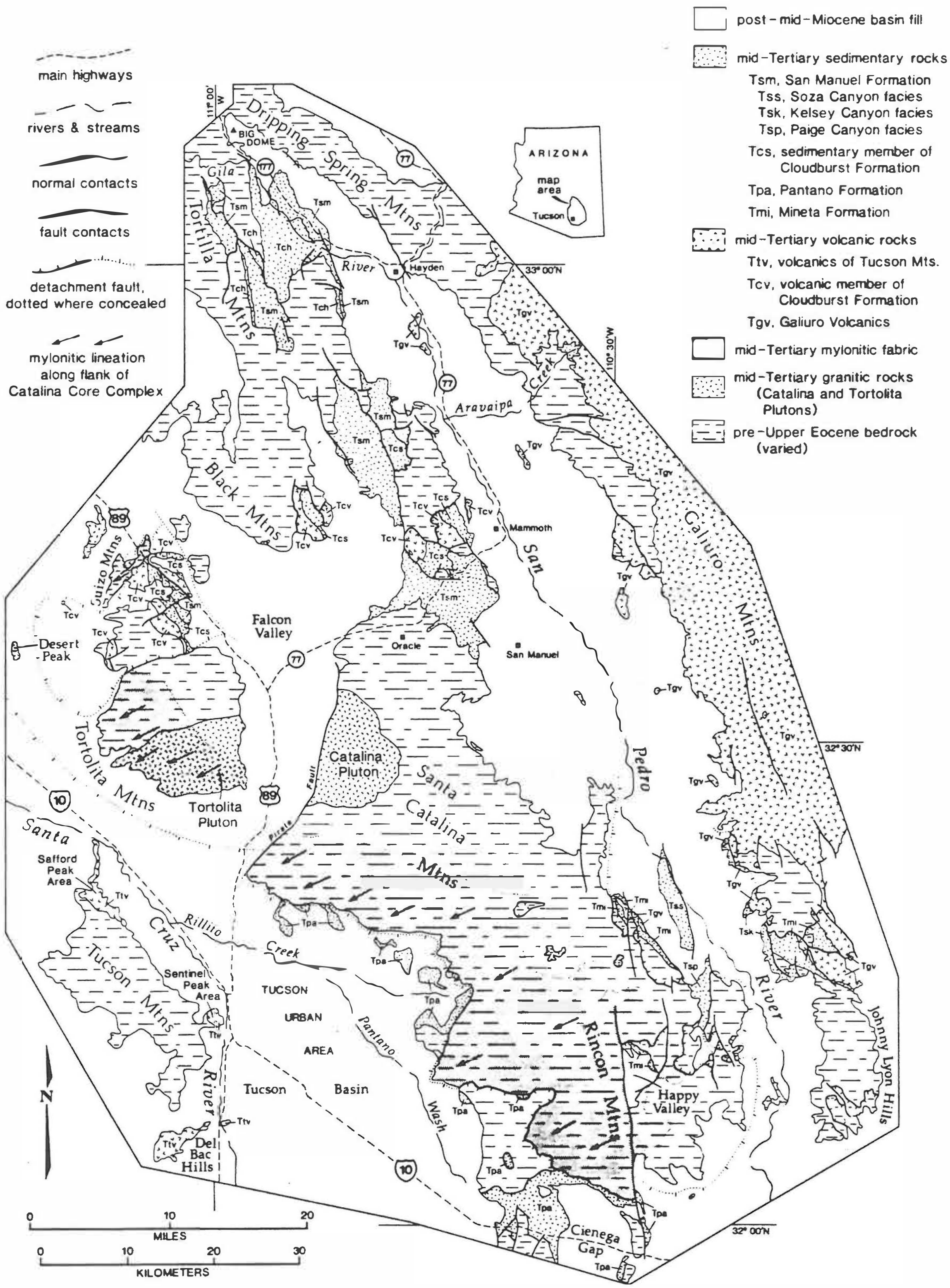


Figure 2. Geologic sketch map of Catalina core complex (mylonitic foliation and lineation along southwest flank) and San Pedro trough (traversed by San Pedro River and by Gila River below their confluence) showing areal distribution of tilted homoclines of mid-Tertiary volcanic and sedimentary successions in relation to exposures of older bedrock and younger basin fill; modified after Dickinson and Shafiqullah (1989).

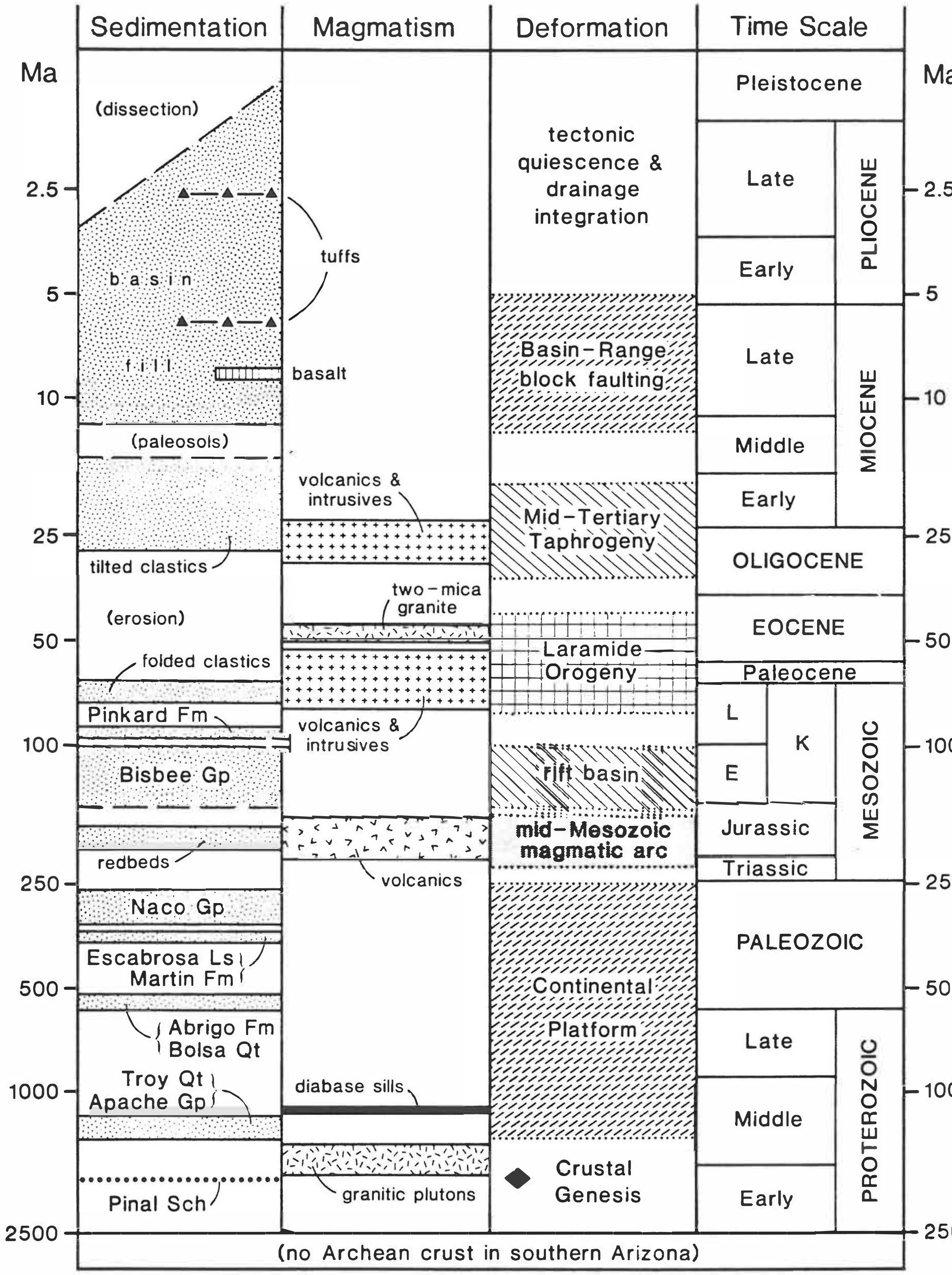


Figure 5. Salient episodes of geologic history in the region of the Catalina core complex and San Pedro trough modified after Coney (1978), Reynolds (1980), and Dickinson (1981). Note logarithmic time scale in Ma; geologic time scale after Palmer (1983). Ages of tuffs in Cenozoic basin fill after Scarborough (1975); slightly older basalt shown with basin fill actually occurs on The Tablelands of the northern Galiuro Mountains (Shafiqullah and others, 1980).

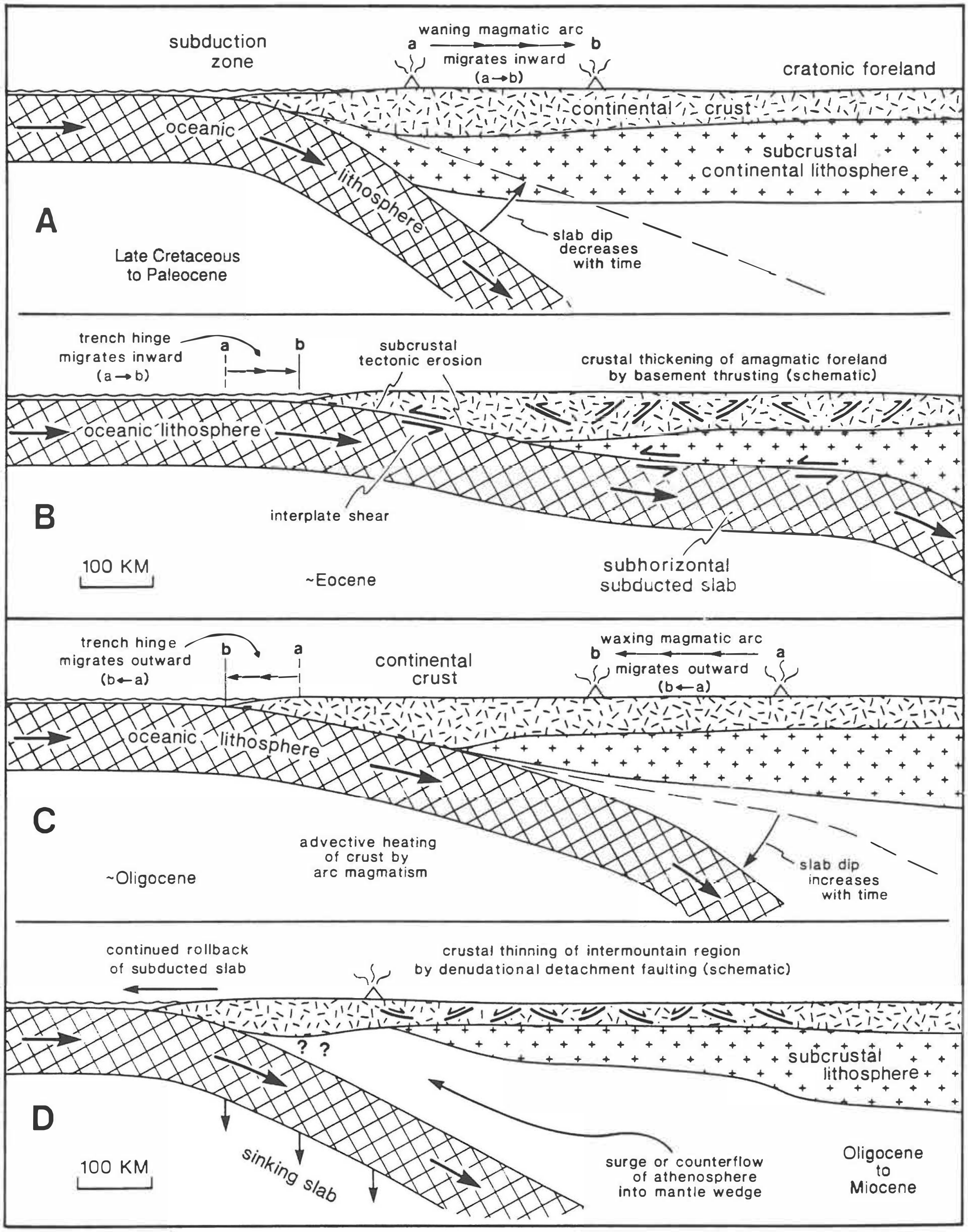


Figure 6. Inferred plate tectonic setting of Laramide and mid-Tertiary deformation in southern Arizona: sequence A to B depicts progressive development of Laramide orogenesis and sequence C to D depicts subsequent development of mid-Tertiary taphrogenesis. Discussions in text amplify concepts illustrated. Recent analysis (Stock and Molnar, 1988) indicates that the Farallon oceanic plate was being subducted during early Laramide orogenesis (A) but that after ~55 Ma the derivative Vancouver plate was being subducted during later Laramide orogenesis and mid-Tertiary taphrogenesis (B-D).

Figure 49. Geologic sketch map of Black Hills area (see Fig. 34 for location) between Oracle and Mammoth; CBW, Cloudburst Wash. Key faults: CBf, Cloudburst fault (detachment fault beneath Cloudburst or Tar Wash allochthon); Tf, Turtle fault (side ramp structure flanking Cloudburst allochthon); Cf/Mf, Cholla or Mammoth fault (basin-range structure). Modified after Heindl (1963), Creasey (1965, 1967), Weibel (1981), and Hansen (1983). See Figure 36 for columnar sections of mid-Tertiary and younger strata exposed along Tucson (column H) and Cottonwood (column I) washes. Legend: 1, Precambrian basement; 2, intrusive Laramide porphyry; 3, volcanic lower member (Tcv) of Cloudburst Formation; 4, sedimentary upper member (Tcs) of Cloudburst Formation; 5, mid-Tertiary rhyolite and rhyolitic breccia bodies (which cut Cloudburst Formation but not San Manuel Formation); 6, San Manuel Formation (Tsm); 7, Quiburis Formation (Tqs) together with overlying terrace and pediment gravels; 8, Quaternary alluvium (Qal) along floodplain of San Pedro River. Internal contact within San Manuel Formation separates Kannally (k) and Tucson Wash (t) Members, which are in part facies equivalents. Asterisks (*) denote subsurface positions of San Manuel (SM) and Kalamazoo (KM) porphyry copper orebodies (SM in the footwall of the San Manuel fault and KM in the hanging wall).

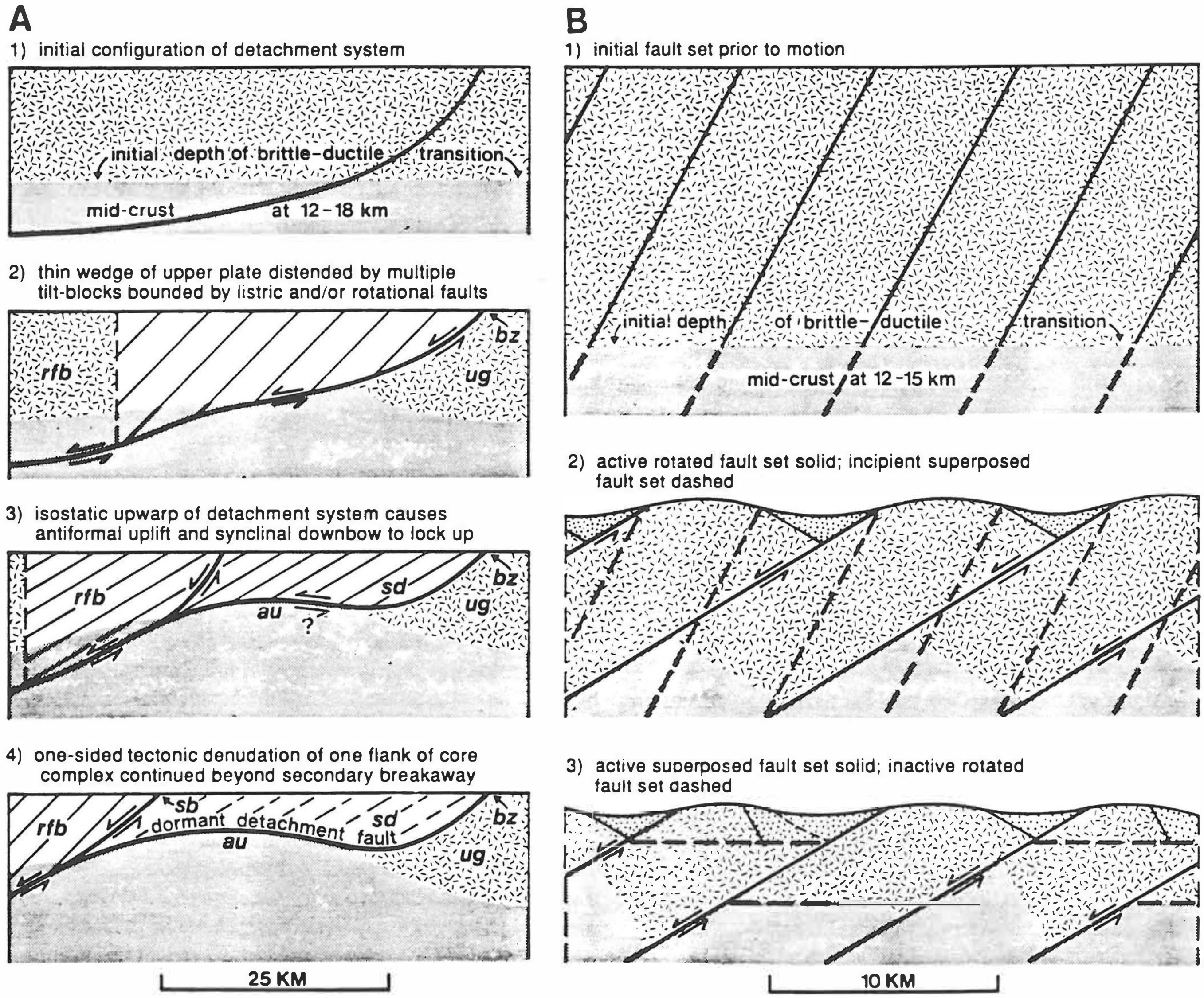
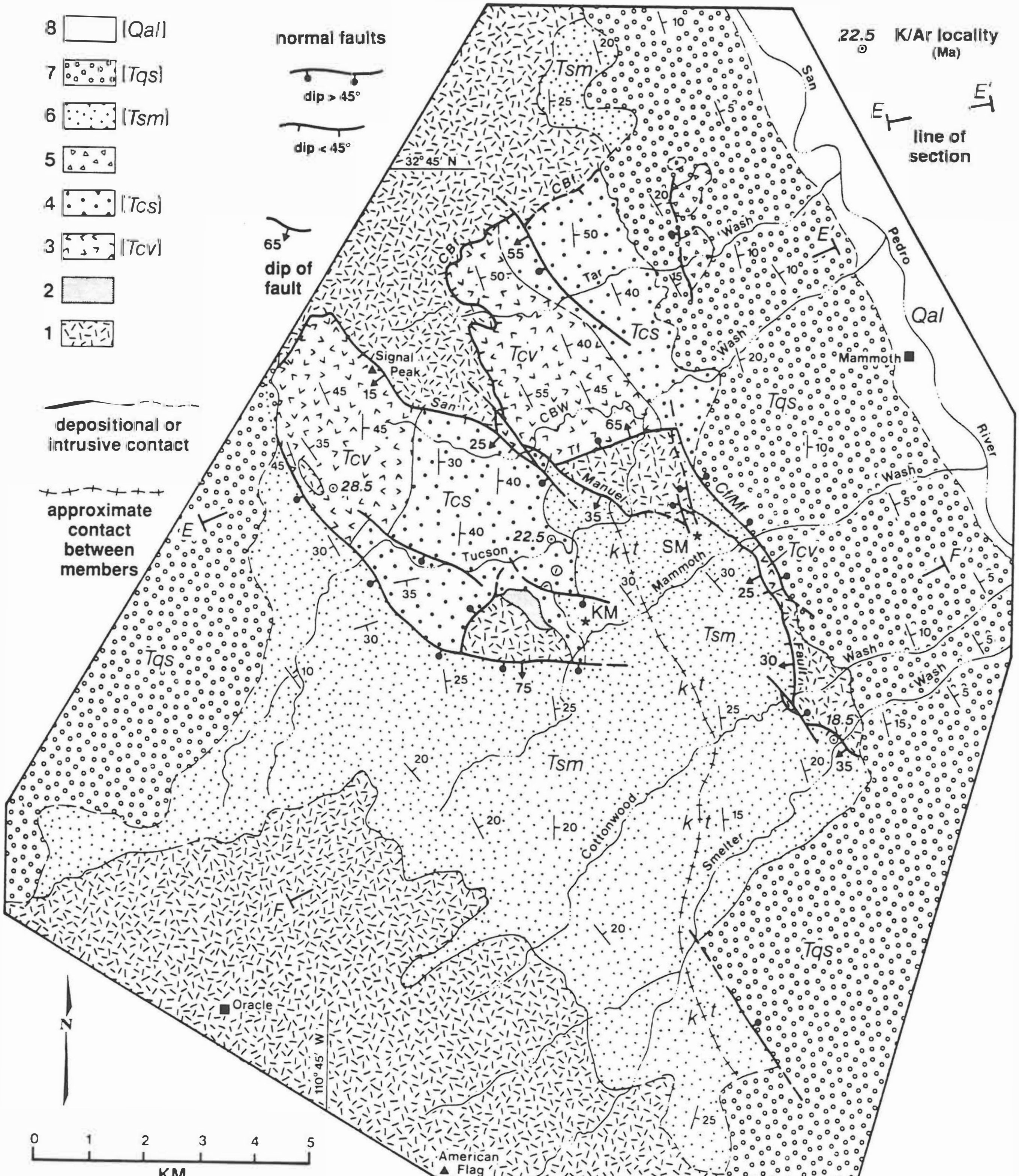


Figure 16. Alternate (A and B) structural models (stages 1 to 4 and 1 to 3, respectively) for tectonic denudation of midcrustal rocks in Cordilleran metamorphic core complexes (note different scales): A, isostatic upwarp of lower plate of gently dipping detachment fault during progressive unloading of midcrust by lateral transport of upper plate internally distended by either curviplanar listric or rotational planar normal faults denoted schematically only; B, successive rotation of multiple tilt-blocks bounded by superposed generations of rotational normal faults accommodating bulk crustal extension. Geometric display of both sets of sequential diagrams adjusted to allow uplift of midcrustal rocks to one-third of their initial depth (nominally 4 km versus 12 km). Actual position of brittle-ductile transition within crust during structural evolution of alternate systems depicted would depend largely on strain rate. Sy;mbols for A: bz, breakaway zone; ug, unextended ground; rfb, rooted fault block; sd, synformal downbow; au, antiformal uplift; sb, secondary breakaway. For B, stipples denote sedimentary fill of tilted half-graben basins for which sediment volume shown is balanced with the amount of material removed by erosion from tilt-block crests (note that different spacing of faults and/or different placement of superposed faults could yield markedly different inferred geometry).



8 [Qal]
7 [Tqs]
6 [Tsm]
5
4 [Tcs]
3 [Tcv]
2
1
normal faults
dip > 45°
dip < 45°
65 dip of fault
depositional or intrusive contact
approximate contact between members
22.5 K/Ar locality (Ma)
E E' line of section
32° 45' N
110° 45' W
N
0 1 2 3 4 5
KM
San Pedro River
Qal
Mammoth
Tqs
Tsm
Tcs
Tcv
CBf
CBW
Tar
Signal Peak
San
Manuel
Cf/Mf
Tucson
Mammoth
Wash
SM
KM
Fault
Cottonwood
Smelter
Oracle
American Flag Hill
28.5
22.5
18.5

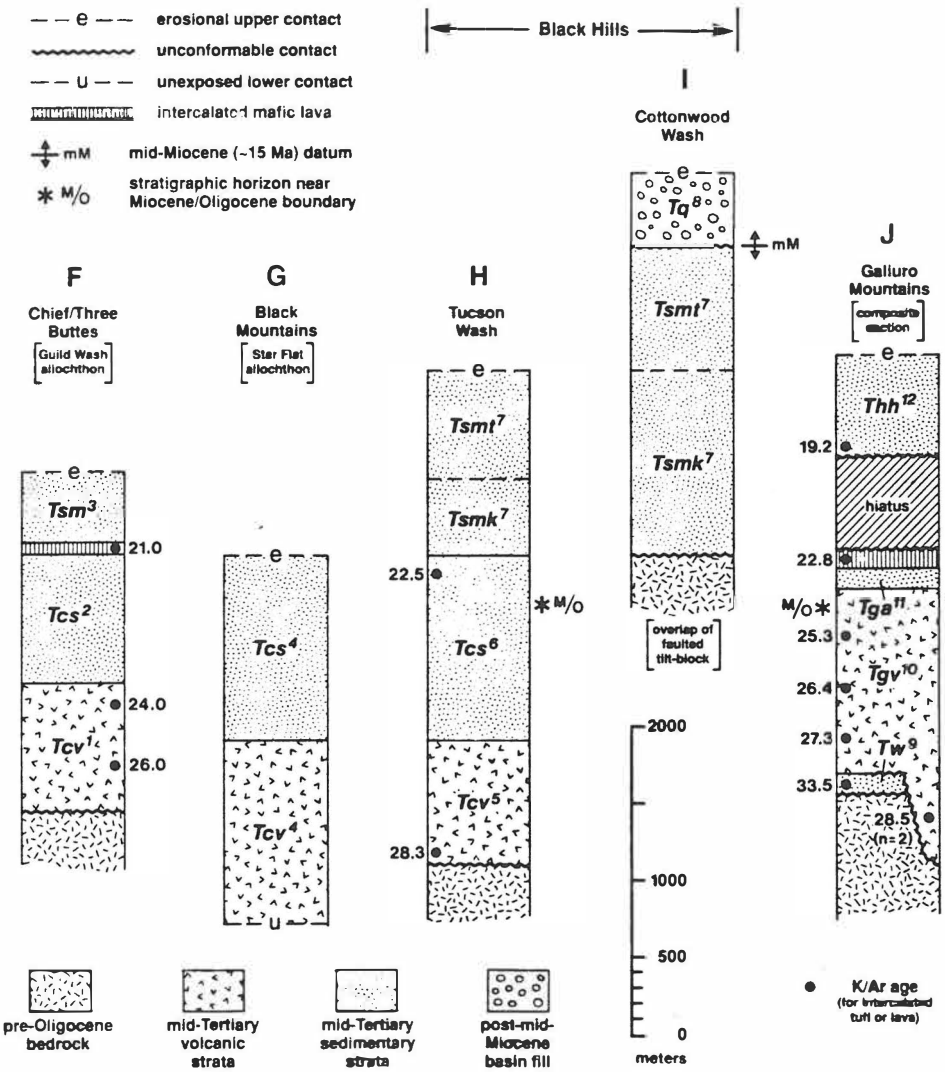


Figure 36. Schematic correlations of post-mid-Oligocene strata of Guild Wash allochthon, Star Flat allochthon (Fig. 46), Black Hills (Fig. 49), and Galiuro Mountains in central part of study area (see Fig. 34 for locations of columns). Radiometric ages after Dickinson and Shafiqullah (1989). Legend: Tw, Whitetail Conglomerate; Tgv, Galiuro Volcanics; Tcv, volcanic lower member of Cloudburst Formation; Tcs, sedimentary upper member of Cloudburst Formation; Tga, Apsey Conglomerate Member of Galiuro Volcanics; Tsm, San Manuel Formation; Tsmk, Kannally Member of San Manuel Formation; Tsmt, Tucson Wash Member of San Manuel Formation; Thh, Hell Hole Conglomerate; Tq, Quiburis Formation (overlain locally by younger terrace and pediment gravel cover). Footnotes: 1, "Tertiary volcanic rocks" of Banks and others (1977) assigned here to volcanic lower member of Cloudburst Formation by analogy with equivalent strata mapped as Cloudburst Formation by Krieger (1974d) at Star Flat (column G); 2, "older Tertiary sedimentary deposits" of Banks and others (1977) formerly referred to correlative Pantano Formation by Barter (1962); 3, "younger Tertiary sedimentary deposits" of Banks and others (1977) formerly referred to correlative Pantano Formation by Barter (1962); 4, first mapped as Cloudburst Formation by Krieger (1974d); 5, "volcanic unit" of Heindl (1963) or "volcanics" of Creasey (1965, 1967) in Cloudburst Formation as mapped by Weibel (1981); 6, "fanglomerate unit" of Heindl (1963) or "fanglomerate" of Creasey (1965, 1967) in Cloudburst Formation as mapped by Weibel (1981); 7, members of San Manuel Formation of "Gila Group" as mapped locally by Heindl (1963), but regarded jointly by Creasey (1965, 1967) as "lower member of Gila Conglomerate," although usage of either "Gila Group" or "Gila Conglomerate" was later abandoned for local usage by Krieger and others (1974); 8, as proposed by Heindl (1963) and discussed by Ladd (1975), but regarded as "upper member of Gila Conglomerate" by Creasey (1965, 1967); 9, as mapped by Krieger (1968b); 10, complex internal stratigraphy discussed by Creasey and Krieger (1978) and by Creasey and others (1981); 11, as mapped by Krieger (1968b) beneath overlying dated "andesite of Table Mountain" named by Krieger (1968c); 12, as mapped by Simons (1964) and Walsh (1989).

TERTIARY STRUCTURES AND STRATIGRAPHIC UNITS IN THE BLACK HILLS BETWEEN ORACLE AND MAMMOTH, PINAL COUNTY, ARIZONA

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Department of Geosciences, University of Arizona

[Arizona Geological Society field trip guide of March 1993]

Tertiary stratigraphic units of the Black Hills include (a) Upper Oligocene to lowermost Miocene redbeds of the Cloudburst Formation (volcanic lower member and sedimentary upper member), (b) Lower Miocene San Manuel Formation (basal Kannally Member overlain by but also locally grading laterally into Tucson Wash Member) of gray to tawny hue, and (c) Upper Miocene to Pliocene(?) basin fill of the Quiburis Formation along the San Pedro trough. Upper Oligocene and/or Lower Miocene rhyodacitic to rhyolitic felsite domes and plugs cut Cloudburst Formation but not San Manuel Formation. Pliocene(?) "gravels of Camp Grant Wash" west of the Black Hills are probably equivalent to some part of the Quiburis Formation.

Principal structures include (a) the gently dipping Upper Oligocene Cloudburst detachment fault, which underlies the Tar Wash allochthon; (b) the Lower Miocene San Manuel fault, now a low-angle normal fault which probably dipped more steeply when active; (c) steep basin-range normal faults of post-mid-Miocene age; and (d) steep oblique-slip faults, which were synchronous in part with displacements along the Cloudburst fault and in part with displacements along the San Manuel fault.

Quaternary units include (a) floodplain alluvium of the San Pedro River valley, (b) alluvial fans built onto the flank of the river floodplain from the mouths of major washes draining the Black Hills, and (c) remnants of San Pedro River terrace gravels capping low hills near the river floodplain. Lateral erosion by the San Pedro River channel has locally truncated fan toes at steep cutbanks, and has thus triggered incision of fan channels. Thin pediment gravel caps, which blanket many gently inclined interfluves within the Black Hills, formed during badland-style degradation of the landscape that accompanied lowering of local base level as downcutting by the San Pedro River proceeded.

KEY EXTENSIONAL STRUCTURES

A. Cloudburst fault: backtilted detachment structure, now dipping (from structure contours) about four degrees to N65-75E, but upper plate moved toward WSW; slip at least 3500-4500 m but probably about 7500 m; floors Tar Wash allochthon bounded on SE by Turtle fault, interpreted as steep oblique-slip side ramp striking N70E subparallel to slip vector of Catalina detachment system; offset by San Manuel fault and steep basin-range faults; in hanging wall of San Manuel fault, offset Turtle fault bounds

"Purcell Window" on NW but offset Cloudburst fault is entirely hidden in subsurface; uppermost Oligocene to lowermost Miocene strata of Cloudburst Formation overstep Turtle fault to rest unconformably on basement south of Tar Wash allochthon; slip on Cloudburst fault interpreted as synchronous with eruption and deposition of much of the Cloudburst Formation.

B. San Manuel fault: rotated (?) low-angle normal fault, now dipping 25-45 degrees WSW (ave 30-35 degrees) but probably dipping about 60 degrees during displacement; slip about 2500 m based on offset of porphyry copper orebody from San Manuel mine to its Kalamazoo extension; offset by steep basin-range normal faults; lower or Kannally Member of San Manuel Formation occurs only in hanging wall but upper or Tucson Wash Member oversteps San Manuel fault to rest on basement in footwall; slip on San Manuel fault interpreted as synchronous with deposition of much of the San Manuel Formation.

C. Post-mid-Miocene basin-range normal faults (Mammoth and Cholla faults and others unnamed): northerly strikes trend N10-40W; steep dips average perhaps 60 degrees, mainly easterly (Mammoth-Cholla system) to downdrop axial basin fill of San Pedro trough, but antithetic faults are also present; estimated maximum individual displacements less than 250 m; slip on basin-range normal faults interpreted as synchronous with deposition of much of the Quiburis Formation, which is offset by many of the faults but also locally onlaps eroded fault scarps.

D. Oligocene-Miocene oblique-slip tear faults (multiple ages): (a) ENE-trending faults (i.e., Turtle fault) interpreted as synchronous with slip on Cloudburst fault, and overstepped locally by stratal horizons within Cloudburst Formation, display apparent sinistral slip; (b) WNW-trending faults (Black Canyon and Red Rock faults) interpreted as synchronous with slip on San Manuel fault, and overstepped locally by stratal horizons within San Manuel Formation, display apparent dextral slip with wrench folds adjacent to Red Rock fault; (c) both sets of faults dip 60-75 degrees, with hanging wall downdropped in normal sense of displacement; (d) conjugate extensional geometry of the two sets of oblique-slip faults has uncertain significance, given their apparently different ages.

KEY STRATIGRAPHIC UNITS

1. volcanic lower member of Cloudburst Formation: lavas and polygenetic volcaniclastics (flow-breccia, pyroclastic and laharic breccia, volcanic conglomerate and sandstone) containing subordinate intercalated beds and intervals of polymictic breccia and conglomerate (including granitic clasts); generally andesitic to latitic but ranging basaltic to dacitic; Upper Oligocene (28 Ma WR K-Ar age near unconformable base above Precambrian granitic rock in hanging wall of San Manuel fault); partial sections are 1200-1500 m thick; interpreted as partial lateral equivalent of pre-ignimbrite sequence of Galiuro Volcanics east of San Pedro

trough.

2. sedimentary upper member of Cloudburst Formation: fanglomerate (alluvial fan and braidplain facies) with volcanic clasts from mid-Tertiary successions like rocks of lower member and granitic clasts from Precambrian basement; gradational with volcaniclastics of lower member (contact where intercalated lavas and pyroclastics disappear); uppermost Oligocene and lowermost Miocene (22.5 Ma sanidine K-Ar age from felsic volcaniclastic bed near top); paleocurrents from imbrication indicate net paleoflow to N25E in Cloudburst and Tucson Washes (and "Midway Wash" in between), but net paleoflow is N45W in area west of "Purcell Window" block south of Black Canyon fault, and multiple lenses of debris-avalanche "megabreccia", composed entirely of granodiorite debris, in Tar Wash and "Northside Wash" (near edge of map) imply sediment transport to WSW off active Cloudburst fault scarp (no reliable imbrication observed in Tar Wash or "Northside Wash"); maximum thickness about 1750 m.

3. Post-Cloudburst and/or syn-Cloudburst (but pre-San Manuel) rhyodacitic to rhyolitic felsite domes and plugs: exposed in drainages of Tucson, Tar, and "Northside" Washes where exhumed from beneath cover of Quiburis Formation and pediment terraces; contain entrained inclusions of sedimentary upper member of the Cloudburst Formation; Lower Miocene age (23 Ma biotite K-Ar) for similar rhyolitic dike in Putnam Wash 15 km NW of Mammoth.

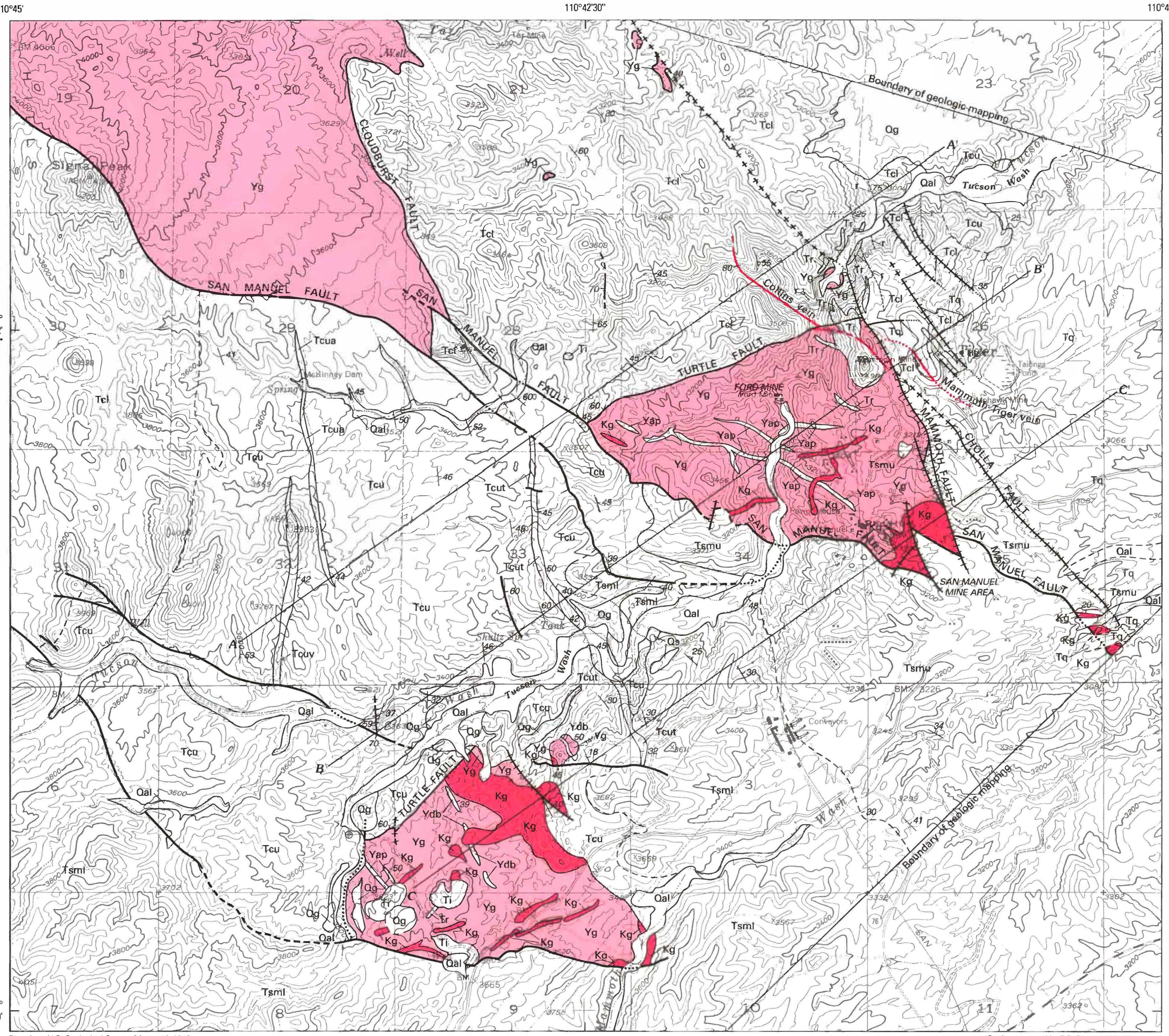
4. Kannally Member of San Manuel Formation: fanglomerate (alluvial fan and braidplain facies) composed mainly of granitic (Oracle/Ruin) detritus, with boulders up to 2.5 m in basal part; rests concordantly (with local scour up to 5 m) on sedimentary upper member of Cloudburst Formation but also overlaps Cloudburst Formation to rest nonconformably on Precambrian granite over wide areas in hanging wall of San Manuel fault; Lower Miocene in age; paleocurrents from imbrication indicate net paleoflow to N60-65E (away from sources near Oracle); debris-avalanche "megabreccia" bodies in area south of Red Rock fault contain debris from the Cambrian Bolsa and Abrigo Formations and the Precambrian Apache Group, but the exact location of their source block is uncertain; estimated thickness 750-1750 m.

5. Tucson Wash Member of San Manuel Formation: fanglomerate (alluvial fan and braidplain facies) with prominent reworked clasts of volcanic and volcaniclastic rocks from Cloudburst Formation (or similar Galiuro Volcanics); rests gradationally upon (but locally grades laterally into) Kannally Member (record of superimposed and locally intertonguing fans), but also oversteps San Manuel fault to rest nonconformably on basement in footwall block; Lower Miocene in age (imprecise FT age of 15-20 Ma from an intercalated ashfall tuff near uppermost exposed horizon); paleocurrents from imbrication in Mammoth, Cottonwood, and Smelter Washes indicate paleoflow to S55W (away from sources in footwall block of San Manuel fault); maximum thickness 750-1000 m.

6. Quiburis Formation (basin fill of San Pedro trough): alluvial fan and braidplain facies with clasts of local bedrock transported to NE and ENE off paleotopography of Black Hills, except that sandflat facies marginal to playa lacustrine axial deposits of San Pedro trough exposed near mouth of Tucson Wash and in roadcut within Mammoth; post-mid-Miocene (probably <12 Ma) with tuffs exposed at San Pedro River level dated as latest Miocene (5.4-6.4 Ma WR K-Ar on glass shards); thickness about 500 m in subsurface beneath San Pedro trough east of Mammoth.

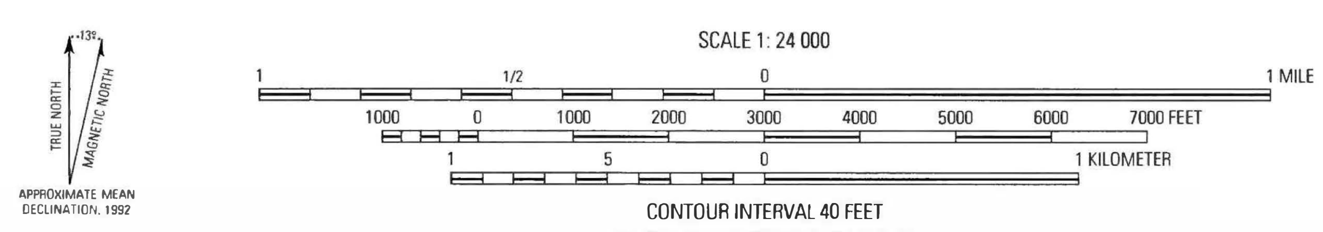
FIELD TRIP

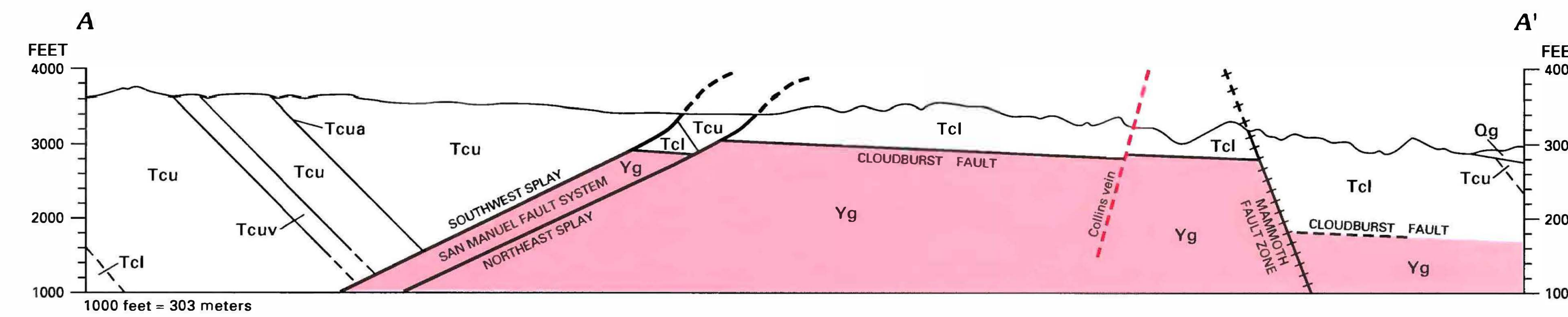
HANDOUTS

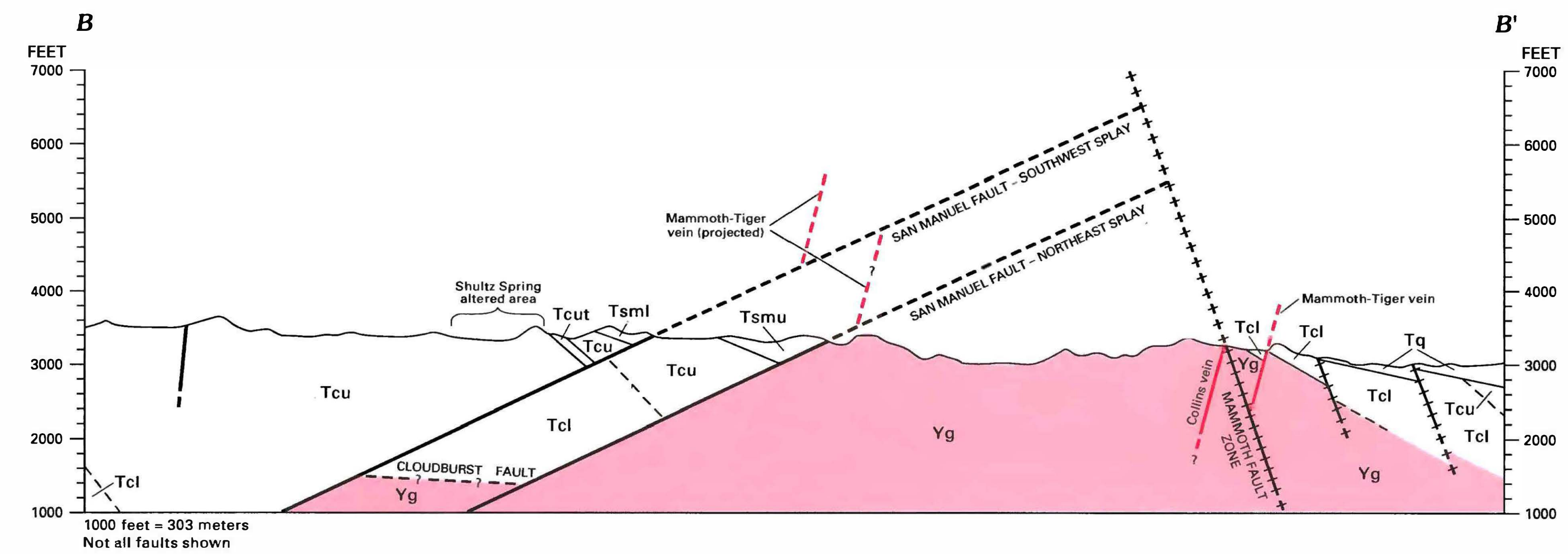


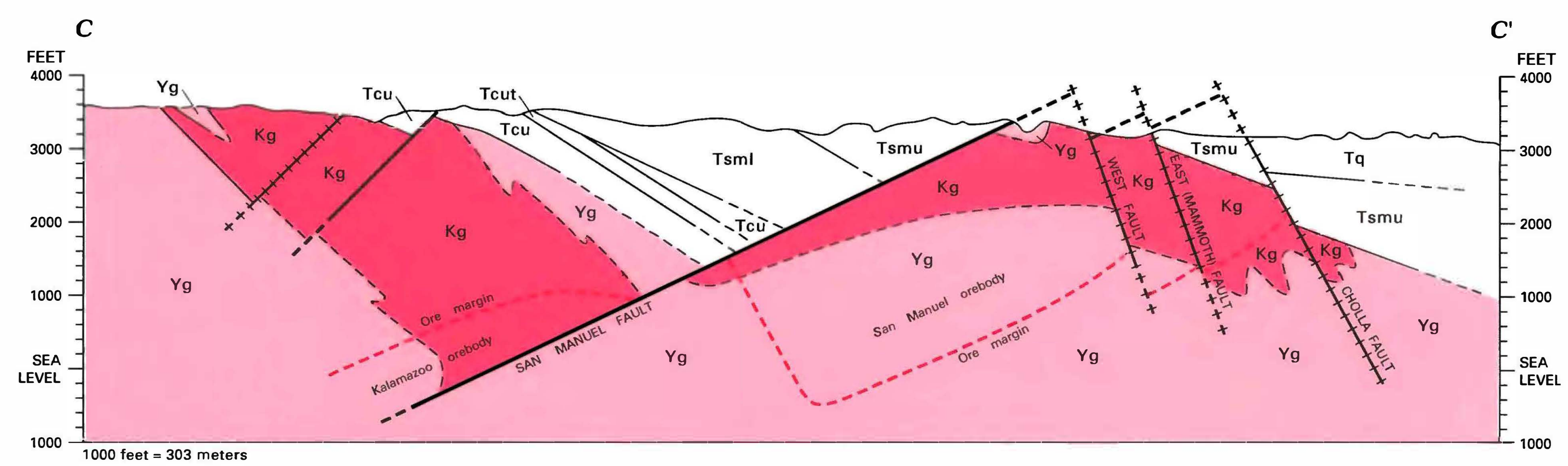
Base from U.S. Geological Survey, Mammoth 1948; Photorevised 1972

Geology mapped by E.R. Force, 1989–91, modified from Creasey (1965) and Weibel (1981)









GEOLOGIC MAP AND CROSS SECTIONS, MAMMOTH-SAN MANUEL AREA, SOUTHEASTERN ARIZONA

By

Eric R. Force

1992

CORRELATION OF MAP UNITS

Qal — Unconformity — Qg — Unconformity — QUATERNARY

Tq — Upper Miocene or Pliocene — Unconformity

Tsmu, Tsml — Lower Miocene — Unconformity — TERTIARY

Tcu, Tcua, Tcl; Ti, Tr, Tcut, Tcuv, Tcl — Lower Miocene and upper Oligocene

Kg — Upper Cretaceous? — CRETACEOUS?

Ydb, Yap, Yg — MIDDLE PROTEROZOIC

DESCRIPTION OF MAP UNITS

Qal **Alluvium (Quaternary)**—Fills present valleys

Qg **Gravel (Quaternary)**—Forms terraces

Tq **Quiburis Formation (Pliocene or late Miocene)**—Gravel. Crops out east of and locally overlaps the Cholla and Mammoth faults

San Manuel Formation (early Miocene)—Conglomerate. Divided into:

Tsmu **Tucson Wash Member**—Contains an upper and lower part

Tsml **Kannally Member**

Tr **Rhyolite (Tertiary)**—Intrusive in all units predating San Manuel Formation; extrusive (r) in lower member of Cloudburst Formation

Ti **Intrusive rocks (Tertiary)**—Mostly porphyritic rhyodacite

Cloudburst Formation (early Miocene and late Oligocene)—Divided into:

Tcu **Upper member**—Mostly conglomerate; also includes:

Tcut **Tuff**

Tcua **Arenite**

Tcuv **Volcanic flow**

Tcl **Lower member**—Interlayered volcanic rocks and conglomerate

Kg **Granitic porphyry of San Manuel mine (Late Cretaceous?)**—Known as San Manuel porphyry of Laramide age

Ydb **Diabase dikes (Middle Proterozoic)**—In Oracle Granite

Yap **Aplite dikes (Middle Proterozoic)**—In Oracle Granite

Yg **Granitic rocks (Middle Proterozoic)**—Includes Oracle Granite (Peterson, 1938), generalized in northern part of area

50 **Contact**—Showing dip; dashed where approximately located; dotted where concealed

25 **Faults approximately contemporaneous with accumulation of the Cloudburst Formation (oldest faults)**—Showing dip; dashed where approximately located; dotted where concealed

25 **Faults approximately contemporaneous with accumulation of the San Manuel Formation**—Showing dip; dashed where approximately located; dotted where concealed

25 **Faults approximately contemporaneous with accumulation of the Quiburis Formation (youngest, basin-range faults)**—Showing dip; dashed where approximately located; dotted where concealed

Strike and dip of beds

45 **Inclined**

Vertical

Horizontal

35 **Mammoth vein set**—Showing dip; dashed where approximately located; dotted where concealed

Force, E.R. and Cox, L.J., 1992, Structural context of mid-Tertiary mineralization in the Mammoth and San Manuel Districts, southeastern Arizona: U.S. Geological Survey Bulletin 2042–C