USGS RESEARCH ON MINERAL RESOURCES—1994

PART B—GUIDEBOOK FOR FIELD TRIPS

NINTH V.E. McKELVEY FORUM ON MINERAL AND ENERGY RESOURCES

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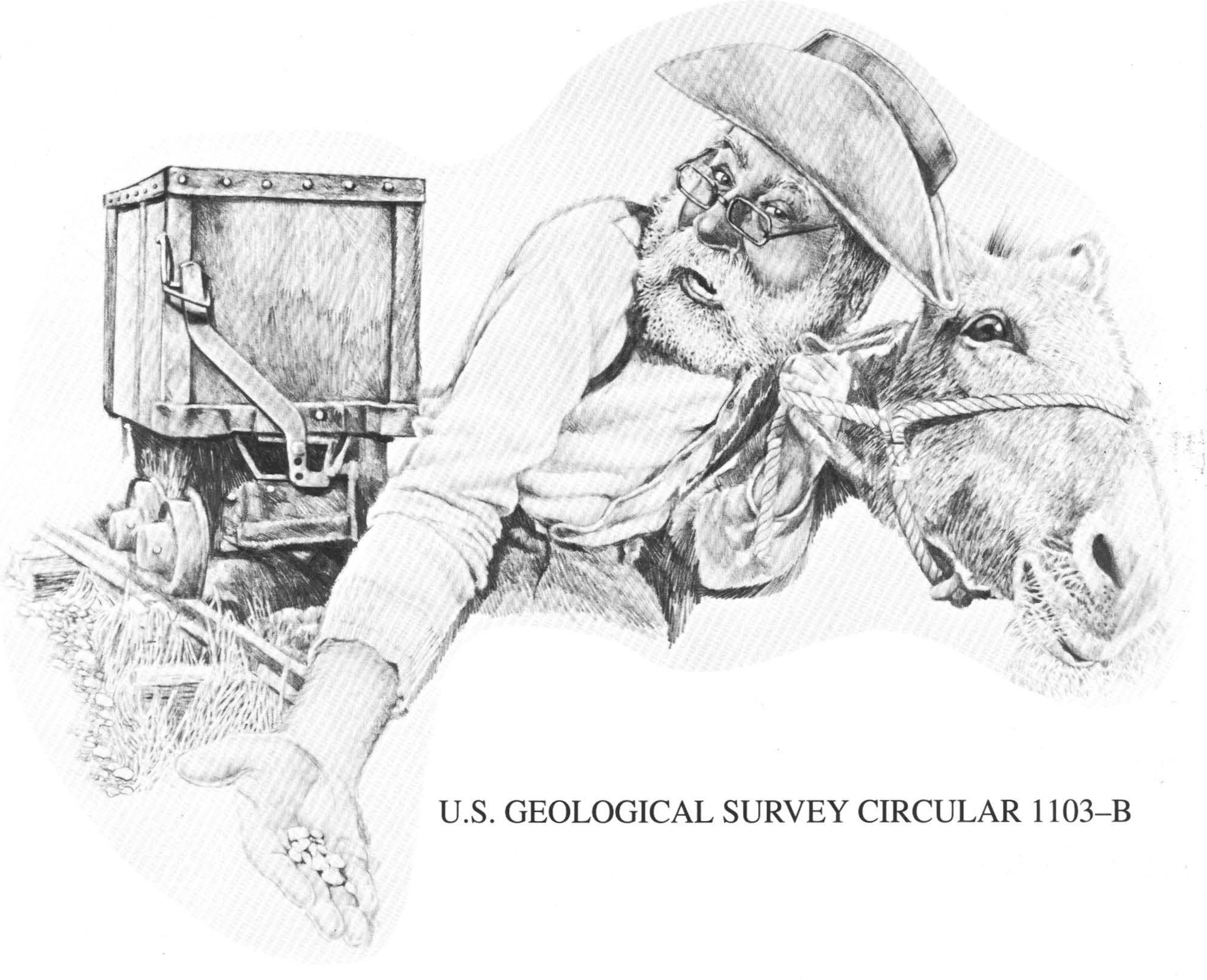

U.S. GEOLOGICAL SURVEY CIRCULAR 1103–B

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PART B—GUIDEBOOK FOR FIELD TRIPS

Edited by Charles H. Thorman *and* Diane E. Lane

NINTH V.E. McKELVEY FORUM ON
MINERAL AND ENERGY RESOURCES

U.S. GEOLOGICAL SURVEY

Cosponsored by

Arizona Geological Society University of Arizona Arizona Geological Survey

9th V.E. McKelvey Forum
Mineral Resources

U.S. GEOLOGICAL SURVEY CIRCULAR 1103–B

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INTRODUCTION TO FIELD TRIP GUIDEBOOK

By Charles H. Thorman[1]

The McKelvey Forum is a public presentation of the results of recent studies on mineral and energy resources by U.S. Geological Survey scientists, commonly in cooperation with their colleagues in academia, other federal and state agencies, and industry. Previous Forums have been held in cities where it was not feasible to include field trips as a part of the program because of weather conditions. However, with Tucson as the site for the 1994 McKelvey Forum, field trips add an important component to the oral and poster presentations. The setting of southern Arizona is ideal for field trips, as it has a spectacular geologic history that is matched by unparalleled beauty of the desert and mountain scenery. Added to that is the fascinating story of the historical development of the region by the American Indians, early Spanish settlers, and the later American settlers, the latter two being driven in large part by the enormous mineral resources of the region, originally silver and lately copper.

In order to provide attendees of the McKelvey Forum with some of the more recent developments in Southwestern United States geology and an overview of the porphyry copper deposits for which the Southwest is famous, this guide book is presented in two parts. The first part comprises three short papers, two on the Jurassic arc in southern Arizona and adjacent areas and the other on the porphyry copper deposits. These papers are presented as background material for the field trips. In the past decade or so, considerable new data have been gathered regarding evolution of the Southwestern United States during the Jurassic, in particular about the development of a magmatic arc that extended from northern Sonora, Mexico, northwest across parts of Arizona and southeastern California, and northward into the Sierra Nevada of California. R.M. Tosdal outlines the concept of this arc, its igneous and sedimentary rock types, and the general settings in which these rocks accumulated. Nancy Riggs, K.A. Hon, and G.B. Haxel present new data regarding the quartz-rich sandstones of southern Arizona and southeastern California that traditionally have been considered correlative with Lower and Middle Jurassic eolian sandstones on the Colorado Plateau. In addition, they discuss the nature of the sandstones and the inferred tectonic setting of Lower and Middle Jurassic intrusive and volcanic rocks as compared with that of middle Tertiary time. The third paper in the first part of this volume, by S.R. Titley, provides an overview of the world-class porphyry copper deposits of the region, the most famous mineral deposit types of the Southwest. In this review of porphyry deposits, Titley reviews the overall tectonic setting of these deposits in the North American cordillera and takes the reader through the evolutionary process of these deposits from plate convergence to late-stage mineralization.

The second part of this guidebook contains the road logs and descriptions for five field trips. Each trip is presented for a one-day excursion and is intended to give the participants a basic introduction to certain areas or geologic topics. B.B. Houser and others will take participants to several historic mining camps south and east of Tucson, the best known and most colorful being Tombstone, a site of famous gunfights and mining activities. While these towns are exciting to visit in order to get a feeling of Southwestern history, they were sites of early geologic studies and provide a basis for our knowledge of economic geology. L.J. Cox will review the geology of the gold placer deposits in the Greaterville District that will be visited on the historic mining camps trip. The trip by Harald Drewes and S.J. Reynolds takes participants to the Helvetia mining district, southwest of Tucson, and the foothills of the Rincon Mountains (Saguaro National Monument), east of Tucson, to show why some structurally complex areas were highly mineralized and others were not. The Saguaro National Monument, in part on the eastern margin of Tucson, is one of the best places to see the saguaro (sah-*war*-oh) flower, which is the state flower of Arizona. The saguaro (giant cactus) is the largest cactus found in the United States; it may grow to a height of 50 ft and may live to an age of 200 yrs. The field trip to be led by S.R. Titley visits the Silver Bell porphyry copper deposit, where participants will view a complex intrusive center associated with several orebodies that still are being mined. Some of the typical

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features of these deposits are still preserved, such as the leached capping and modified hypogene alteration originally exposed at various levels of weathering in orebodies of this region. P.W. Lipman will lead a group to the Tucson Mountains, west of Tucson, to show how a Cretaceous ash-flow caldera is related to the porphyry deposits of the region and how the knowledge gained through studying the middle Tertiary ash-flow calderas of the Western United States may be applied to porphyry deposits. E.R. Force and W.R. Dickinson will lead a trip to the San Manuel and Mammoth mining districts, northeast of Tucson, where they will present results of recent work on the faulting and tilting of these mineralized areas. Concepts developed in the past decade or so on the regional Tertiary basin-and-range structural styles of extensional faulting and tilting have been applied here to provide a new insight into the local geology.

We know you will enjoy these field trips in southern Arizona. The experience of Southwestern scenery and geology plus a day in the field with a group of earth scientists is an ideal combination. Enjoy yourself on these outings. If you are new to the area, please note that the Sonoran Desert vegetation is beautiful but not designed for direct contact by humans or geologists. It is easier to survive in the Southwest if you are thick skinned, as are many of us who work here.

THE JURASSIC ARC IN THE SONORAN AND SOUTHERN MOJAVE DESERTS, SOUTHERN ARIZONA AND SOUTHEASTERN CALIFORNIA, UNITED STATES, AND NORTHERN SONORA, MEXICO

By Richard M. Tosdal[1]

The Jurassic arc in the Sonoran and southern Mojave Deserts of southern Arizona and southeastern California, United States, and northern Sonora, Mexico (fig. 1), formed along the truncated late Paleozoic and early Mesozoic margin of the North American craton and unconformably overlies varied Proterozoic crystalline terranes and Paleozoic and lower Mesozoic cratonic sedimentary rocks. In the Mojave Desert on the northwest, the arc overlies Paleozoic and lower Mesozoic eugeoclinal and miogeoclinal sedimentary rocks. The arc was a topographically low feature during the late Early and Middle Jurassic, but by the late Middle Jurassic the arc had become locally a high-standing area that provided detritus that was shed northeastward into the area now occupied by the Colorado Plateau (Tosdal and others, 1989; Riggs and others, 1993).

Two large "holes" in the arc are present along this segment of the Cordillera where rocks of Jurassic age are the oldest stratigraphic unit exposed and those Proterozoic and Paleozoic rocks that are exposed are allochthonous (fig. 1). One hole in south-central Arizona and northern Sonora is inferred to have formed during Triassic rifting and thinning of the Proterozoic craton (Stewart and others, 1986) prior to the emplacement of Jurassic volcanic and plutonic rocks. The other hole is in southern California and southwestern Arizona where the Mesozoic Orocopia Schist, a section of marine graywacke and minor basalt, chert, limestone, and sparse ultramafic rocks, crops out beneath the Late Cretaceous Chocolate Mountains thrust, a mid-crustal ductile shear zone. Limited chronologic data indicate a late Middle Jurassic age for the protolith of the schist. General agreement on the origin of the basin in which the Orocopia Schist was deposited is lacking, and it has been interpreted to represent a subduction-zone complex that was buried under the leading edge of the continental margin along a flat subduction zone in the Late Cretaceous, or to have been deposited in a transtensional basin along a sinistral strike-slip fault, the Mojave-Sonora megashear, which linked the suprasubduction zone basins in the forearc to the initial opening of the Gulf of Mexico (Tosdal and others, 1989).

Along the arc in the Sonoran and southern Mojave Deserts, magmatic and tectonic activity was concentrated in two areas, which were separated by a gap having no known magmatic or tectonic activity (fig. 1). One area is the Mojave Desert and adjoining parts of the Sonoran Desert in southeastern California and southwestern Arizona; magmatism here was a continuation of the arc that extended southward from eastern California and western Nevada. The other area is in southern Arizona and northern Sonora. Whether the magmatic and tectonic gap is a primary feature of the Jurassic arc or represents the effects of younger tectonism is unknown.

The record of the Jurassic arc is most extensive in southern Arizona and northern Sonora where volcanism, sedimentation, and plutonism occurred throughout most of the Jurassic. Here, extensional basins filled with a thick accumulation of volcanic and sedimentary rocks (Riggs and Busby-Spera, 1990). Eolian dune fields were blown from the cratonic interior into the arc in Early and Middle Jurassic time. Explosive silicic volcanism dominated magmatic activity; alkalic and mafic volcanic rocks are minor constituents. Vent complexes in the Early Jurassic (~190–180 Ma) were associated with rift basins, whereas tectonism associated with large caldera complexes in the late Early and Middle Jurassic (180–170 Ma) was apparently of more limited extent (Lipman and Hagstrum, 1992; Riggs and others, 1993). Stratovolcanic centers dominated

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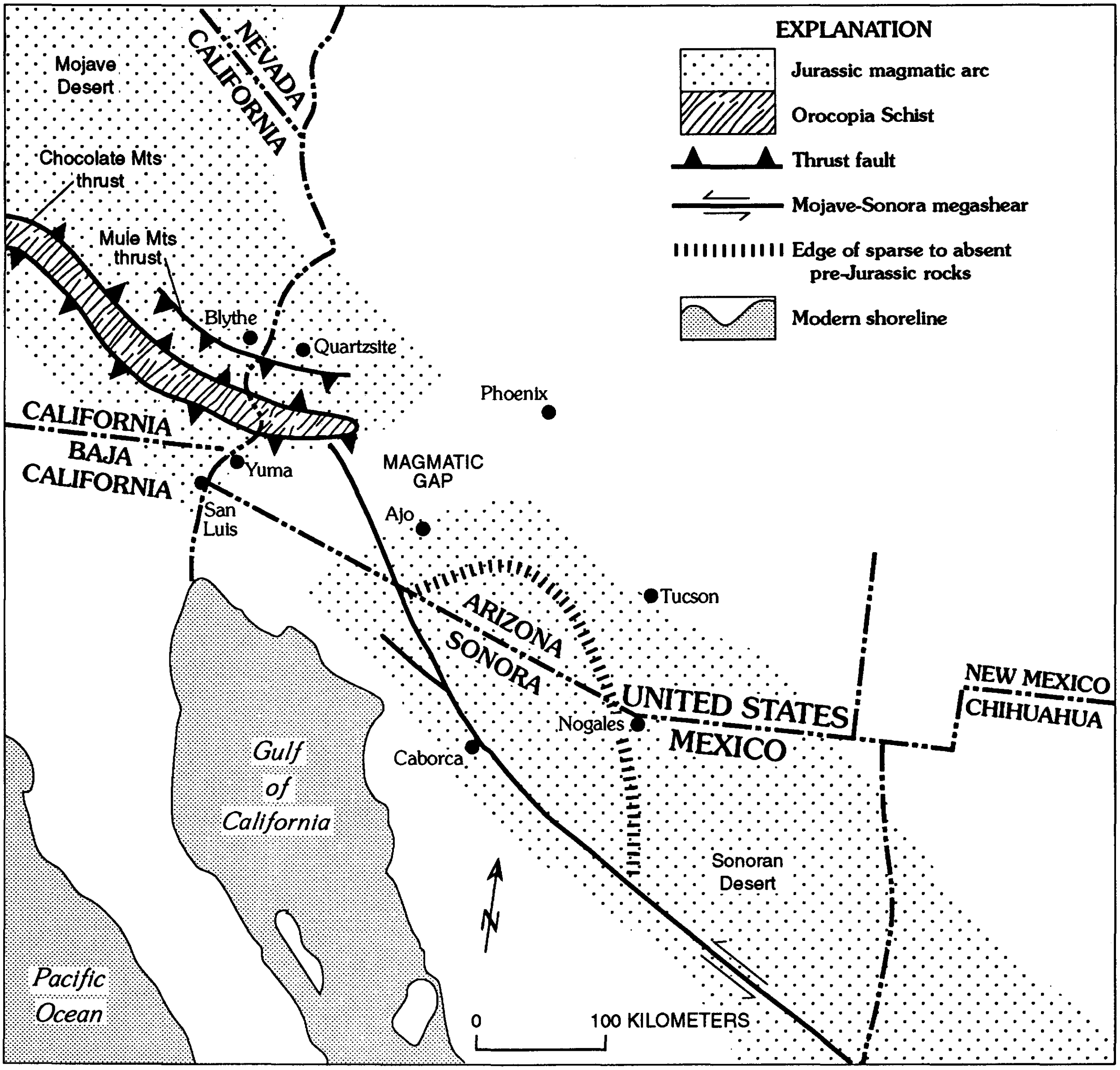

Figure 1. Simplified geologic and index map of the Jurassic arc in the Sonoran and Mojave Deserts of southern and southeastern California, United States, and northern Sonora, Mexico. Modified from Tosdal and others (1989).

volcanism in the latest Middle and Late Jurassic (~160–150 Ma) and were accompanied by limited explosive activity. Subvolcanic plutonic complexes intrude the volcanic rocks.

In southwestern Arizona and adjoining parts of southeastern California, explosive silicic volcanism occurred over a more limited time span. It apparently began in the Middle Jurassic (~175–170 Ma), and there was a second episode in the latest Middle Jurassic (~160–155 Ma) (Reynolds and others, 1987; Busby-Spera and others, 1990; R.M. Tosdal, unpub. data, 1993). Limited evidence indicates that the volcanic rocks were derived from calderas. The volcanic and associated volcaniclastic rocks unconformably overlie Triassic sedimentary rocks along a major unconformity that formed sometime in the Late Triassic to Middle Jurassic (Reynolds and others, 1989). Middle Jurassic eolian quartz arenite is locally present beneath the ash flow tuffs.

Volumetrically significant Middle Jurassic batholithic rocks link the two areas of magmatic and tectonic activity (Tosdal and others, 1989). The plutonic units are compositionally expanded, ranging from gabbro-diorite to granite, and consist of three intrusive units of meta-luminous, potassium-rich, and crustally derived rocks. The oldest, mafic unit was emplaced between ~175 and 170 Ma, the intermediate unit at ~165 Ma, and the youngest, silicic unit between ~160 and 158 Ma (summarized by

Tosdal and others, 1989). The oldest and the youngest units are similar in age to the pyroclastic rocks in southwestern Arizona and southeastern California, but a link between the plutonic and volcanic rocks is uncertain. In this same region, contractile deformation uplifted the arc. This deformation was contemporaneous with plutonism along the edges of the batholith, and is of late Middle Jurassic age (~160 Ma).

The Late Jurassic Mojave-Sonora megashear, a large sinistral strike-slip fault system, transects the southwestern part of the region (fig. 1). Movement on the fault occurred during the latter stages of arc activity. Upwards of 800 km of sinistral displacement has been proposed along the fault system, which probably consisted of a complex and braided fault system like most major continental strike-slip faults. The trace of the megashear is reasonably constrained in Sonora, but its presence and location in the United States is the subject of debate.

Magmatic activity ceased with the onset of syntectonic deposition in rift basins of continentally derived clastic rocks. Mafic magmatism occurred locally during the evolution of the basins. In southern Arizona, these sedimentary rocks are known as the Upper Jurassic and Lower Cretaceous Glance Conglomerate. They form the base of the Upper Jurassic and Cretaceous Bisbee Group, which was deposited in the northwestern extremity of the Chihuahuan Trough, a marine arm of the Gulf of Mexico depression (Dickinson and others, 1989). In southwestern Arizona and southeastern California, Upper Jurassic and Cretaceous sedimentary rocks constitute the lower part of the McCoy Mountains Formation; the upper part of this formation is Late Cretaceous in age and was deposited during shortening at that time. The two units, the lower McCoy Mountains Formation and the Bisbee Group, are generally considered correlative, although the exact nature of the correlation is hindered by the lack of exposure across the magmatic and tectonic gap in the Jurassic arc.

REFERENCES CITED

Busby-Spera, C.J., Mattinson, J.M., Riggs, N.R., and Schermer, E.R., 1990, The Triassic-Jurassic magmatic arc in the Mojave-Sonoran deserts and the Sierran-Klamath region—Similarities and differences in paleogeographic evolution, *in* Harwood, D., and Miller, M. eds., Late Paleozoic and Mesozoic paleogeographic relations, Klamath-Sierra and adjacent regions: Geological Society of America Special Paper 225, p. 325–337.

Dickinson, W.R., Fiorillo, A.R., Hall, D.L., Monreal, R., Potochnik, A.R., and Swift, P.N., 1989, Cretaceous strata of southern Arizona, *in* Reynolds, S.J., and Jenny, J.P., eds., Summary of Arizona geology: Arizona Geological Society Digest 17, p. 447–461

Lipman, P.W., and Hagstrum, J.T., 1992, Jurassic ash-flow sheets, calderas, and related intrusions of the Cordilleran volcanic arc in southeastern Arizona—Implications for regional tectonics and ore deposits: Geological Society of America Bulletin, v. 104, p. 32–39.

Reynolds, S.J., Spencer, J.E., Asmeron, Y., DeWitt, Ed, and Laubach, S.E., 1989, Early Mesozoic uplift in west-central Arizona and southeastern California: Geology, v. 17, p. 207–211.

Reynolds, S.J., Spencer, J.E., DeWitt, Ed, 1987, Stratigraphy and U-Th-Pb geochronology of Triassic and Jurassic rocks of west-central Arizona, *in* Dickinson, W.R., and Klute, M.A., eds., Mesozoic rocks of southern Arizona and adjacent areas: Arizona Geological Society Digest 18, p. 65–80.

Riggs, N.R., and Busby-Spera, C.J., 1990, Evolution of a multi-vent volcanic complex within a subsiding arc graben-depression—Mount Wrightson Formation, Arizona: Geological Society of America Bulletin, v. 102, p. 114–1134.

Riggs, N.R., Mattinson, J.M., and Busby, C.J., 1993, Correlation of Jurassic eolian strata between the magmatic arc and the Colorado Plateau—New U-Pb geochronologic data from southern Arizona: Geological Society of America Bulletin, v. 105, p. 1231–1246.

Stewart, J.H., Anderson, T.H., Haxel, G.B., Silver, L.T., and Wright, J.E., 1986, Late Triassic paleogeography of the southern Cordillera—The problem of the source for the voluminous volcanic detritus in the Chinle Formation of the Colorado Plateau region: Geology, v. 14, p. 567–570.

Tosdal, R.M., Haxel, G.B., and Wright, J.E., 1989, Jurassic geology of the Sonoran Desert region, southern Arizona, southeastern California, and northernmost Sonora—Construction of a continental-margin magmatic arc, *in* Reynolds, S.J., and Jenny, J.P., eds., Summary of Arizona geology: Arizona Geological Society Digest 17, p. 397–434.

EARLY TO MIDDLE JURASSIC MAGMATIC ARC ROCKS OF SOUTH-CENTRAL AND SOUTHEASTERN ARIZONA

By Nancy R. Riggs,[1] Kenneth A. Hon,[2] and Gordon B. Haxel[3]

INTRODUCTION

Early to Middle Jurassic arc-related rocks in southern Arizona are part of a broad belt of exposures of the early Mesozoic magmatic arc that crops out from northern Sonora, Mexico, to western Arizona and eastern California and throughout the Sierra Nevada (fig. 1). The oldest well-developed and best-preserved sequences of arc-related volcanic strata are ~230 Ma (Dilles and Wright, 1988; Wyld and Wright, 1993), but the vast majority of reliable isotopic dates fall between ~195 and ~165 Ma, including most Jurassic rocks preserved in southern Arizona (Wright and others, 1981; Busby-Spera and others, 1990; Walker and Martin, 1991; Riggs and others, 1993).

Mesozoic magmatic arc sequences found from southern Arizona to southeastern California have an unusual association with quartz-rich sandstones. These sandstones have been traditionally considered correlative with Lower and Middle Jurassic eolian sandstones on the Colorado Plateau (Hewett, 1956; Grose, 1959; Drewes, 1971; Haxel and others, 1980b; Bilodeau and Keith, 1986). Many of these sandstones contain small-scale structures indicative of an eolian origin (Porter, 1987; Riggs and Busby-Spera, 1990, 1991), and others are assumed to be eolian only on the basis of the presence of large-scale cross-stratification (Drewes, 1971; Bilodeau and Keith, 1986). The major Lower to Middle Jurassic volcanic and sedimentary units of south-central and southeastern Arizona are summarized here.

SEQUENCES WEST OF THE SANTA CRUZ RIVER VALLEY

BABOQUIVARI MOUNTAINS

Lower Jurassic strata in the Baboquivari Mountains (fig. 2) include as much as 8 km of volcanic and sedimentary rocks deposited between 195 and 185 Ma[4] (Wright and others, 1981; Tosdal and others, 1989; Haxel and others, 1980a,b, 1981). The oldest volcanic rocks (Ali Molina Formation of Haxel and others, 1980a, 1981) are largely ash-flow tuffs that are probably related to caldera-forming events, though no intracaldera source rocks have been identified in the sequence (Riggs and Haxel, unpub. data, 1993). Shallow porphyritic intrusions are locally coeval with the volcanic rocks, but the large intrusion that cuts the volcanic rocks in the northeastern part of the range (fig. 2) is of Middle to Late Jurassic age (Tosdal and others, 1989). This intrusion appears to be part of a much larger zoned granitic to granodioritic batholith (now largely buried in late Cenozoic basins) that varies from hornblende diorite to leucogranite and contains pods of cumulate pyroxenite and hornblendite (Tosdal and others, 1989). Geochronologic studies by Wright and others (1981) suggest that eolian(?) units interstratified with the Lower Jurassic volcanic strata are correlative with the Navajo Sandstone on the Colorado Plateau.

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[4]Unless otherwise noted, ages are U-Pb zircon dates for igneous rocks with errors of about ±5 Ma. Other ages discussed here are K-Ar determinations for biotite or hornblende; these are generally less accurate than the U-Pb ages due to thermal effects of younger tectonic and igneous events. Only approximate age ranges are given for the K-Ar dates; all have been recalculated using 1976 IUGS constants (Marvin and others, 1978).

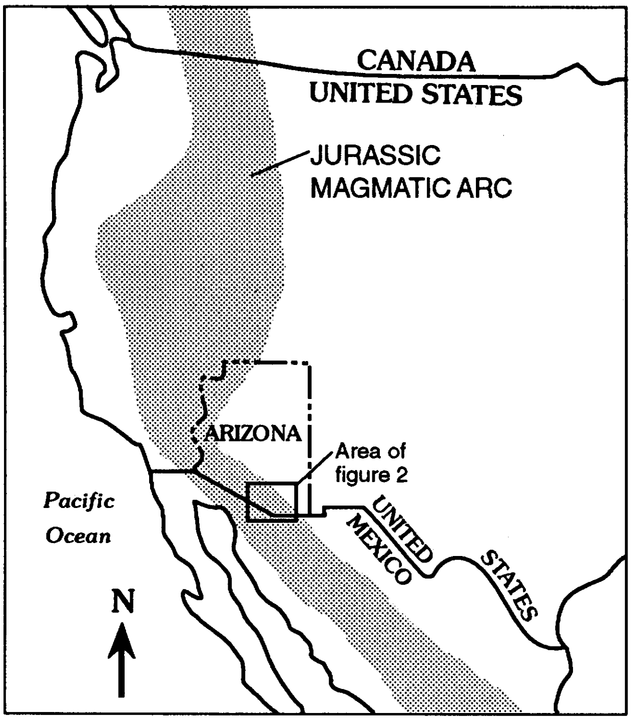

Figure 1. Map showing the distribution of Jurassic magmatic arc rocks in western North America.

A middle epiclastic formation (Pitoikam Formation of Haxel and others, 1980a, 1981) contains thick sequences of breccia, conglomerate, and sandstone that overlie the volcanic strata. The breccias were evidently derived from an Early Jurassic fault scarp (Haxel and others, 1980a) and provide some of the evidence for the presence of an extensional arc graben during the Early Jurassic (Busby-Spera, 1988). Quartzite pebbles in some of the conglomerates are probably of Proterozoic origin and possibly were reworked from once-widespread early Mesozoic conglomerate units (Haxel, unpub. data, 1993). The upper unit, the Mulberry Wash Formation, is a series of poorly known volcanic and sedimentary rocks. Busby-Spera (1988) suggested that this thick sequence of volcanic and sedimentary rocks strongly indicates deposition within a subsiding basin.

ARIVACA REGION

The strata of Cobre Ridge (Riggs and Busby-Spera, 1991) are exposed over several hundred kilometers in between the Santa Cruz River, Arivaca, and into northern Sonora, Mexico (fig. 2). These rocks are products from a complex caldera in which the intracaldera tuff of Pajarito is a crystal-rich rhyolite as much as 3,000 m thick. Initial collapse of the caldera occurred in two major blocks. The southeastern block, now exposed in the Pajarito Mountains west of Nogales, subsided catastrophically, allowing accumulation and preservation of 3,000 m of densely welded intracaldera tuff. The northwestern block, south of Arivaca in the Oro Blanco–Ruby mining area, subsided far less during initial collapse (as much as ~1,500 m of tuff of Pajarito is preserved), but was the locus of continued deformation and eruptions within the caldera. Following the initial caldera-forming eruption, smaller eruptions were interspersed with intracaldera faulting and eolian sedimentation. Finally, another major eruption enlarged the northwestern part of the caldera and deposited a welded tuff about 700 m thick. This tuff caps a 2,500-m-thick sequence in the northwestern block of the caldera.

The Cobre Ridge caldera is thought to have formed about 165–170 Ma (Riggs and others, 1993), but recent additional U-Pb geochronologic work suggests that a granite that intruded the volcanic rocks may be about 175 Ma (Riggs, unpub. data, 1993). Eolian strata within the complex were deposited as sand sheets and are rich in volcanic detritus derived from nearby unconsolidated tuffs. The age of the tuff of Pajarito allows correlation of these sedimentary rocks with the Temple Cap Formation or the Page Sandstone on the Colorado Plateau.

SIERRITA MOUNTAINS

Early Mesozoic strata in the Sierrita Mountains area (fig. 2) comprise the Ox Frame Volcanics and Rodolfo Formation (Cooper, 1971; Drewes and Cooper, 1973). The combined thickness of these units is approximately 2,000 m (Cooper, 1971). These rocks were strongly altered during Late Cretaceous porphyry copper mineralization, making detailed facies analysis difficult.

The volcanic rocks are interstratified with unusually pure quartz arenite sandstone that is cross-stratified, well sorted, and has well-rounded grains (Cooper, 1971). The volcanic and sedimentary units are laterally continuous over tens to hundreds of meters, and most resemble Lower Jurassic strata in the Baboquivari and Santa Rita Mountains (see below and Cooper, 1971), suggesting that units in the Sierritas may be Early Jurassic rather than Triassic in age as thought by Cooper (1971). The Harris Ranch monzonite, which intrudes the Ox Frame Volcanics, has yielded a concordant U-Pb zircon age of 176 Ma (Riggs, unpub. data, 1993). This minimum age for the Ox Frame Volcanics is similar to ages from the youngest part of the Mount Wrightson Formation and supports the correlation between these units. Cross-stratified sandstone within the Ox Frame Volcanics is probably correlative with Lower Jurassic Navajo Sandstone on the Colorado Plateau.

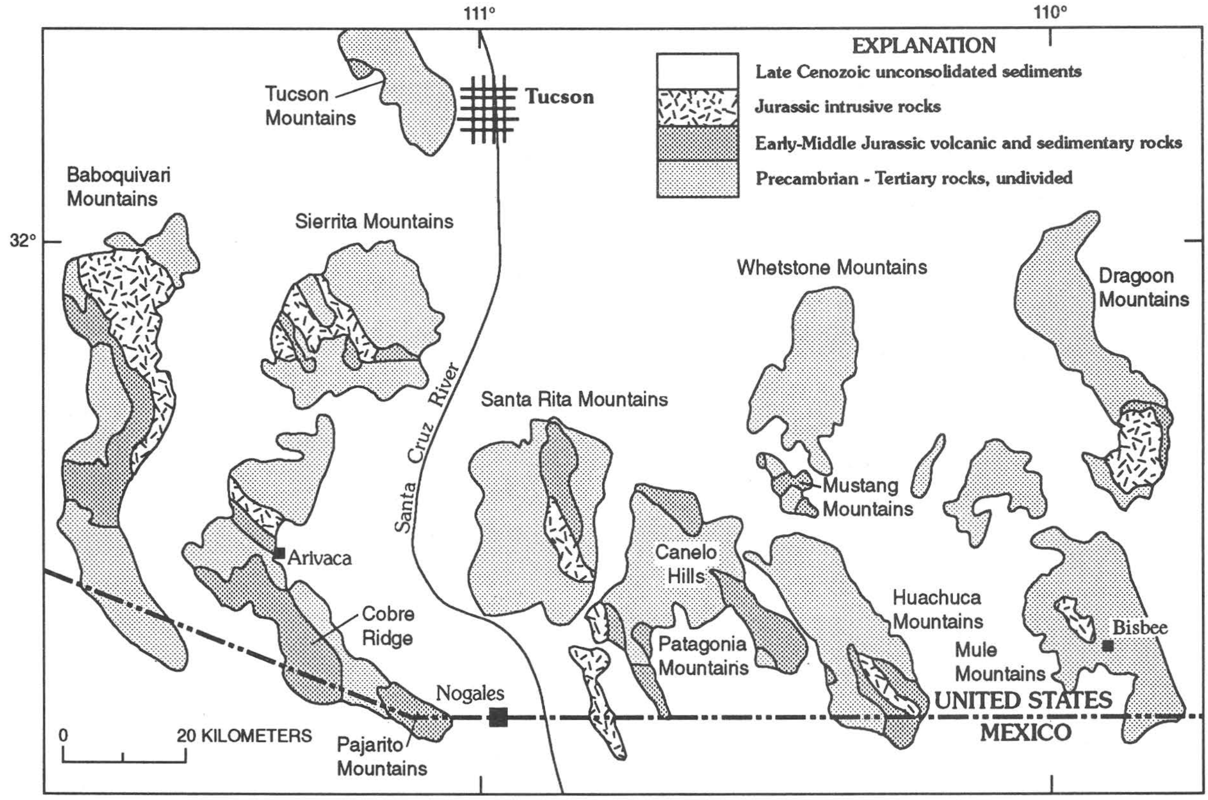

Figure 2. Map showing the location of Jurassic volcanic, sedimentary, and intrusive rocks in south-central and southeastern Arizona.

TUCSON MOUNTAINS

Jurassic strata in the Tucson Mountains comprise volcanic breccia, sandstone, and minor ash-flow tuff. The age of Jurassic strata in the Tucson Mountains is constrained only by cross-cutting dikes dated by K-Ar at about 155 Ma (Shafiqullah and others, 1980). Preliminary reconnaissance work in the Tucson Mountains suggests that the Recreation Red Beds and unnamed volcaniclastic rocks on adjacent Brown Mountain are lithologically similar to the middle part of the Baboquivari Mountains sequence, although the ratio of epiclastic to volcanic rocks is substantially higher in the Tucson Mountains area. The occurrence of eolian(?) quartz-rich sandstone in one fault-bounded outcrop may support correlation of these strata with Lower to Middle Jurassic rocks elsewhere in southern Arizona. Drewes (1981) speculated that the Recreation Red Beds are related temporally as well as genetically to a widespread episode of fluvial sedimentation depicted by the Gardner Canyon Formation in the Santa Rita Mountains, the Rodolfo Formation in the Sierrita Mountains, and possibly the Pitoikam Formation in the Baboquivari Mountains as well.

SEQUENCES EAST OF THE SANTA CRUZ RIVER VALLEY

SANTA RITA MOUNTAINS

The Mount Wrightson Formation in the Santa Rita Mountains (fig. 2) records the evolution of an intermediate to silicic composition, multi-vent volcanic complex that formed within a concurrently subsiding intra-arc basin (Riggs and Busby-Spera, 1990). The 4.5-km-thick Mount Wrightson Formation includes an initial intermediate effusive phase (lower member), followed by a probable short hiatus and a transition to predominantly explosive silicic volcanism mixed with eolian sedimentation (middle member). Eolian sedimentary rocks are more common in the upper member of the formation, suggesting an overall waning in volcanism. Thick welded ash-flow tuffs indicate a nearby source, but, as in the Baboquivari Mountains, no caldera fragments have been identified. U-Pb zircon geochronologic data indicate that the lower and much of the middle member were deposited between about 190 and 180 Ma, but volcanic activity continued to 170 Ma (Riggs and others, 1993). The lower member of the Mount Wrightson

Formation is intruded by a coeval monzonite pluton (Drewes, 1971; Riggs and others, 1993) that has been dated at 188±2 Ma (Asmerom and others, 1990). A much larger granitic intrusion also cuts the Mount Wrightson Formation (Drewes, 1971), but gives a Late Jurassic K-Ar age of about 140–155 Ma (Marvin and others, 1973).

The Mount Wrightson Formation is in part coeval with the Baboquivari Mountains strata, and the combination of age, deposition within a tectonically active basin, and similarity of depositional units suggests the possibility that the two units may have been laterally continuous. Eolian sandstone in the Mount Wrightson Formation may be correlative with the Navajo Sandstone and (or) the Temple Cap Sandstone (Riggs and others, 1993).

The Mount Wrightson Formation is in fault contact with the Gardner Canyon Formation, a primarily fluvioclastic unit (Drewes, 1971; Beatty, 1987) that has a U-Pb zircon age of 200±5 Ma (Asmerom and others, 1990). Much of the volcaniclastic detritus within coarser Gardner Canyon units is intermediate in composition, suggesting erosion of either the lower member of the Mount Wrightson Formation or of an intermediate-composition volcanic complex no longer preserved. This fluvial sedimentation may represent periods of volcanic quiescence in the subsiding arc basin.

PATAGONIA MOUNTAINS

Jurassic volcanic strata within the Patagonia Mountains (fig. 2) have been correlated by Simons (1972) with the Mount Wrightson Formation. Megascopic similarities between some rocks in the Patagonia Mountains and the middle member of the Mount Wrightson Formation in the Santa Rita Mountains support this correlation. Jurassic strata in the Patagonia Mountains are altered and mineralized, but preliminary identification of megabreccia blocks of brecciated Paleozoic limestone within tuff suggests that several caldera fragments may be present in this area (Lipman and Hagstrum, 1992). Several Jurassic granitic to granodioritic bodies intrude the Jurassic volcanic rocks in the southeastern part of the Patagonia Mountains and a largely granitic intrusion that has a K-Ar age of 160–170 Ma (Marvin and others, 1973) makes up much of the western flank of the range (Simons, 1972; Drewes, 1980).

HUACHUCA MOUNTAINS AND CANELO HILLS

Thick sequences of volcanic rocks identified in the southern Huachuca Mountains and Canelo Hills (fig. 2) by Hayes and Raup (1968) were reinterpreted as remnants of major ash-flow calderas by Lipman and Hagstrum (1992). Stratigraphic relations indicate that eruption of the Montezuma caldera in the southern Huachuca Mountains was followed by eruptions from the Turkey Canyon and Parker Canyon calderas in the Canelo Hills to the west.

The Montezuma caldera formed within a cluster of pre-existing andesitic to dacitic volcanoes. Although no intact sections of these early rocks are preserved, large blocks and shattered masses of andesite and dacite form extensive megabreccia lenses that intertongue with caldera-filling dacite tuff. Large areas previously mapped as undifferentiated upper Paleozoic sedimentary rock (Hayes and Raup, 1968) within the caldera-fill sequence and later interpreted as possible caldera floor (Lipman and Hagstrum, 1992) have also been remapped as thick wedges of caldera-collapse megabreccia containing numerous pods of dacite tuff and andesite megabreccia (Hon, unpub. data, 1993). Following collapse, a large composite granitic intrusion (70–76 percent SiO_2) was emplaced into, and probably resurged, the Montezuma caldera (Lipman and Hagstrum, 1992) somewhere between 160 and 175 Ma (K-Ar age; Marvin and others, 1973).

Dacite tuff filling the Montezuma caldera is overlain by thin rhyolitic outflow sheets from the Turkey Canyon and Parker Canyon calderas; these are crystal-poor and crystal-rich welded tuffs, respectively. An identical stratigraphic sequence is preserved within outflow sheets of the same three units 20–30 km to the north in the Mustang Mountains (fig. 2). Some thin sedimentary layers between the two rhyolite tuffs in the southern Huachuca Mountains contain abundant well-rounded quartz and microcline grains, possibly of eolian origin or derived from reworking of nearby eolian sediments.

The youngest of the three calderas, the Parker Canyon caldera, clearly truncates part of the adjacent Turkey Canyon caldera and contains megabreccia largely composed of the crystal-poor rhyolite tuff that fills the Turkey Canyon caldera (Lipman and Hagstrum, 1992).

Intrusive and volcanic activity continued in the Huachuca Mountains and Canelo Hills after the caldera-forming events. In the Huachuca Mountains, an east-west-trending rhyolitic dike swarm (>50 dikes) intruded the granite and intracaldera fill of the Montezuma caldera. Both the granite and dikes are unconformably overlain by the Upper Jurassic-Lower Cretaceous Glance Conglomerate of Bilodeau and others (1987), which indicates a Jurassic age for the dikes (Hon, unpub. data, 1993). The upper Glance Conglomerate also contains a thick sequence of interbedded basaltic andesite flows along the western side of the Huachuca Mountains (Hayes, 1970).

In the Canelo Hills, the basal Glance Conglomerate contains thin, local rhyolite ash-flow tuffs and a basalt flow that directly overlie the youngest of the regional ash-flow sheets (Bilodeau and others, 1987). Poorly welded tuff interbedded within lower Glance Conglomerate (Bilodeau and others, 1987) in the Lone Mountain area yielded a Jurassic K-Ar age between 140 and 155 Ma (Marvin and others, 1973). However, conformable relations between the Glance Conglomerate and the underlying crystal-rich rhyolite in the Montezuma Pass area suggest that at least some of this unit may have formed during resurgence of the Montezuma caldera (Lipman and Hagstrum, 1992).

MULE MOUNTAINS

A large Jurassic granite body (the Juniper Flat Granite) and associated dikes intrude the Early Proterozoic Pinal Schist and Paleozoic sedimentary rocks in the Mule Mountains (fig. 2) north of Bisbee (Ransome, 1904; Hayes and Landis, 1964). The Juniper Flat Granite grades downward from a fine- to medium-grained phase quenched against Pinal Schist roof rocks through a porphyritic phase and into coarse-grained equigranular granite. The Juniper Flat granite has been dated by K-Ar methods between 170 and 185 Ma (Creasey and Kistler, 1962; Marvin and others, 1973) and is about the same age as texturally distinct Sacramento Hill stocks (~175–185 Ma by K-Ar methods) that are genetically related to important porphyry copper mineralization at Bisbee (Graeme, 1981).

Although no outcrops of related Jurassic volcanic rocks are preserved in this area, the overlying Glance Conglomerate contains numerous clasts of volcanic rocks, some as much as 1 m in diameter (Bilodeau and others, 1987). The volcanic clasts are lithologically diverse and include rhyolites and intermediate-composition lavas; fragments of rhyolite welded tuff lithologically distinct from those in the Huachuca Mountains and Canelo Hills (40–50 km to the west) are also present. The large size of many of the volcanic clasts and unique compositions of some suggest that they were derived by erosion of a nearby volcanic field whose intrusive remnants may now be covered by Cretaceous sedimentary rocks or Neogene valley-fill deposits.

SOUTHERN DRAGOON MOUNTAINS

A large Jurassic granitic intrusion is exposed in the southern Dragoon Mountains (fig. 2) (Gilluly, 1956) and was dated by K-Ar methods at about 180–190 Ma (Marvin and Cole, 1978; Drewes, 1980). This age range is somewhat older than those determined for the nearby Huachuca and Juniper Flat granitic rocks and may be anomalous. The Gleeson intrusion also differs compositionally from the other granites in that it contains a large central mass of muscovite-bearing aplitic granite enclosed by biotite granite (Gilluly, 1956; Drewes, 1981).

Outcrops of chaotically distributed Paleozoic rock types along the eastern margin of the Gleeson intrusion are commonly separated by pods and films of welded tuff. Originally interpreted as a complex thrust (Gilluly, 1956; Drewes, 1981), these outcrops have been more recently reinterpreted as caldera collapse breccia preserved in a fragment of a Jurassic caldera (Lipman and Hagstrum, 1992). However, significant problems remain to be solved in this area because no primary depositional or intrusive contacts between the chaotic megabreccia and adjacent Jurassic granitic intrusion have been identified.

CONCLUSIONS

We speculate that a temporal pattern exists in southern Arizona that reflects the evolution of the Jurassic magmatic arc and tectonic stabilization of the continental crust. The earliest (180–195 Ma) arc-related volcanic and sedimentary sequences in the Baboquivari Mountains and in the Santa Rita Mountains show a strong interrelationship between active tectonism and volcanism. Synvolcanic faulting can be clearly documented locally in the Baboquivari Mountains (Haxel and others, 1980a; Busby-Spera, 1988), whereas facies analysis of the lower Mount Wrightson Formation in the Santa Rita Mountains indicates that volcanism probably also occurred within an actively subsiding tectonic basin (Riggs and Busby-Spera, 1990).

Subsidence of younger (165–180 Ma) ash-flow calderas in the Arivaca region and Huachuca Mountains–Canelo Hills does not appear to be directly related to active regional faulting or tectonic basin formation. These younger calderas are more typical of calderas erupted through cratonic crust and are more likely related to emplacement of Middle to Late Jurassic granitic batholiths. In particular, the general progression in the Huachuca Mountains and Canelo Hills from early andesitic volcanism to more silicic ash-flow tuff eruptions mimics well-documented patterns seen in many of the middle-Tertiary volcanic fields of the Western United States (Lipman, 1984).

REFERENCES CITED

Asmerom, Yemane, Zartman, R.E., Damon, P.E., and Shafiqullah, M., 1990, Zircon U-Th-Pb and whole-rock Rb-Sr age patterns of lower Mesozoic igneous rocks in the Santa Rita Mountains, southeast Arizona—Implications for Mesozoic magmatism and tectonics in the southern Cordillera: Geological Society of America Bulletin, v. 102, p. 961–968.

Beatty, B., 1987, Correlation of some mid-Mesozoic redbeds and quartz sandstones in the Santa Rita Mountains, Mustang Mountains, and Canelo Hills, southeastern Arizona: Tucson, University of Arizona, M.S. thesis, 105 p.

Bilodeau, W.L., and Keith, S.B., 1986, Lower Jurassic Navajo Aztec-equivalent sandstones in southern Arizona and their paleogeographic significance: American Association of Petroleum Geologists Bulletin, v. 70, p. 690–701.

Bilodeau, W.L., Kluth, C.F., and Vedder, L.K., 1987, Regional stratigraphic, sedimentologic, and tectonic relationships of the Glance Conglomerate in southeastern Arizona: Arizona Geological Society Digest, v. 18, p. 229–256.

Busby-Spera, C.J., 1988, Speculative tectonic model for the early Mesozoic arc of the southwest Cordilleran U.S.: Geology, v. 16, p. 1121–1125.

Busby-Spera, C.J., Mattinson, J.M., Riggs, N.R., and Schermer, E.R., 1990, The Triassic-Jurassic magmatic arc in the Mojave-Sonoran deserts and the Sierran-Klamath region; similarities and differences in paleogeographic evolution, *in* Harwood, D., and Miller, M., eds., Late Paleozoic and Mesozoic paleogeographic relations, Klamath-Sierra and adjacent regions: Boulder, Colorado, Geological Society of America Special Paper 255, p. 325–337.

Cooper, J.R., 1971, Mesozoic stratigraphy of the Sierrita Mountains, Pima County, Arizona: U.S. Geological Survey Professional Paper 658–D, 42 p.

Creasey, S.C., and Kistler, R.W., 1962, Age of some copper-bearing porphyries and other igneous rocks in southeastern Arizona: U.S. Geological Survey Professional Paper 450–D, p. D1–D5.

Dilles, J.H., and Wright, J.E., 1988, The chronology of early Mesozoic arc magmatism in the Yerington district of western Nevada and its regional implications: Geological Society of America Bulletin, v. 100, p. 644–652.

Drewes, Harald, 1971, Mesozoic stratigraphy of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geological Survey Professional Paper 658–C, 81 p.

______1980, Tectonic map of southeastern Arizona: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–1109, scale 1:125,000.

______1981, Tectonics of southeastern Arizona: U.S. Geological Survey Professional Paper 1144, 96 p.

Drewes, Harald, and Cooper, J.R., 1973, Reconnaissance geologic map of the west side of the Sierrita Mountains, Palo Alto Ranch quadrangle, Pima County, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF–538, scale 1:62,500.

Gilluly, James, 1956, General geology of central Cochise County, Arizona: U.S. Geological Survey Professional Paper 281, 169 p.

Graeme, R.W., 1981, Famous mineral localities—Bisbee, Arizona: Mineralogical Record, v. 12, no. 5, p. 258–319.

Grose, L.T., 1959, Structure and petrology of the northeast part of the Soda Mountains, San Bernardino County, California: Geological Society of America Bulletin, v. 70, p. 1509–1548.

Haxel, G.B., May, D.J., and Tosdal, R.M., 1981, Reconnaissance geologic map of the Presumido Peak 15° quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF–1378, scale 1:62,500

Haxel, G.B., Wright, J.E., May, D.J., and Tosdal, R.M., 1980a, Reconnaissance geologic map of the Baboquivari Peak 15° quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF–1251, scale 1:62,500.

______1980b, Reconnaissance geology of the Mesozoic and lower Cenozoic rocks of the southern Papago Indian Reservation, Arizona—A preliminary report: Arizona Geological Society Digest, v. 12, p. 17–30.

Hayes, P.T., 1970, Mesozoic stratigraphy of the Mule and Huachuca Mountains, Arizona: U.S. Geological Survey Professional Paper 658–A, 28 p.

Hayes, P.T., and Landis, E.R., 1964, Geologic map of the southern part of the Mule Mountains, Cochise County, Arizona: U.S. Geological Survey Miscellaneous Geological Investigations Map I–418, scale 1:48,000.

Hayes, P.T., and Raup, R.B., 1968, Geologic map of the Huachuca and Mustang Mountains, southeastern Arizona: U.S. Geological Survey Miscellaneous Geological Investigations Map I–509, scale 1:48,000.

Hewett, D.F., 1956, Geology and mineral resources of the Ivanpah quadrangle, California and Nevada: U.S. Geological Survey Professional Paper 275, 172 p.

Lipman, P.W., 1984, The roots of ash-flow calderas in western North America: Journal of Geophysical Research, v. 89, p. 8801–8844.

Lipman, P.W., and Hagstrum, J.T., 1992, Jurassic ash-flow sheets, calderas, and related intrusions of the Cordilleran volcanic arc in southeastern Arizona—Implications for regional tectonics and ore deposits: Geological Society of America Bulletin, v. 104, p. 32–39.

Marvin, R.F., and Cole, J.C., 1978, Radiometric ages—Compilation A, U.S. Geological Survey: Isochron/West, v. 22, p. 3–14.

Marvin, R.F., Naeser, C.W., and Mehnert, H.H., 1978, Tabulation of radiometric ages—including unpublished K-Ar and fission track ages—for rocks in southeastern Arizona and southwestern New Mexico, *in* Callender, J.F., Wilt, J.C., and Clemons, R. E., eds., Land of Cochise: New Mexico Geological Society, 29th Field Conference, Guidebook, p. 285–290.

Marvin, R.F., Stern, T.W., Creasey, S.C., and Mehnert, H.H., 1973, Radiometric ages of igneous rocks from Pima, Santa Cruz, and Cochise Counties, southeastern Arizona: U.S. Geological Survey Bulletin 1379, 27 p.

Porter, M.L., 1987, Sedimentology of an ancient erg margin—The Lower Jurassic Aztec Sandstone, southern Nevada and southern California: Sedimentology, v. 34, p. 661–680.

Ransome, F.L., 1904, The geology and ore deposits of the Bisbee quadrangle, Arizona: U.S. Geological Survey Professional Paper 21, 168 p.

Riggs, N.R., and Busby-Spera, C.J., 1990, Evolution of a multi-vent volcanic complex within a subsiding arc graben-depression—Mount Wrightson Formation, Arizona: Geological Society of America Bulletin, v. 102, p. 1114–1134.

______1991, Facies analysis of an ancient, dismembered large caldera complex and implications for intra-arc subsidence—Middle Jurassic strata of Cobre Ridge, southern Arizona, USA, *in* Cas, R.A.F., and Busby-Spera, C.J., eds., Volcaniclastic sedimentation: Sedimentary Geology, v. 74, p. 39–67.

Riggs, N.R., Mattinson, J.M., and Busby, C.J., 1993, Correlation of Mesozoic eolian strata between the magmatic arc and the Colorado Plateau: New U-Pb geochronologic data from southern Arizona: Geological Society of America Bulletin, v. 105, p. 1231–1246.

Shafiqullah, M., Damon, P.E., Lynch, D.J., Reynolds, S.J., Rehrig, W.A., and Raymond, R.H., 1980, K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Society Digest, v. 12, p. 210–260.

Simons, F.S., 1972, Mesozoic stratigraphy of the Patagonia Mountains and adjoining areas, Santa Cruz County, Arizona: U.S. Geological Survey Professional Paper 658–E, 23 p.

Tosdal, R.M., Haxel, G.B., and Wright, J.E., 1989, Jurassic geology of the Sonoran Desert region, southern Arizona, southeastern California, and northernmost Sonora—Construction of a continental-margin magmatic arc: Arizona Geological Society Digest, v. 17, p. 397–434.

Walker, J.D., and Martin, M.W., 1991, Style and timing of Middle to Late Jurassic deformation in the Mojave Desert and eastern California: Geological Society of America Abstracts with Programs, v. 23, p. 249.

Wright, J.E., Haxel, G.B., and May, D.J., 1981, Early Jurassic uranium-lead isotopic ages for Mesozoic supracrustal sequences, Papago Indian Reservation, southern Arizona: Geological Society of America Abstracts with Programs, v. 13, p. 115.

Wyld, S.J., and Wright, J.E., 1993, Mesozoic stratigraphic and structural history of the southern Pine Nut Range, west-central Nevada, *in* Dunne, G., and McDougall, K., eds., Mesozoic paleogeography of the Western United States–II: Society of Economic Paleontologists and Mineralogists (SEPM), Pacific Section, Book 71, p. 289–306.

AN ABRIDGED OVERVIEW OF SOME FEATURES OF PORPHYRY COPPER DEPOSITS IN THE AMERICAN SOUTHWEST

By Spencer R. Titley[1]

INTRODUCTION

The region comprising southern Arizona and contiguous parts of New Mexico and Mexico contains an extraordinary abundance of porphyry copper deposits. They have been known here as such since the early part of the 20th Century, when they were first developed as underground operations in rich, mostly secondary ores. Their transition to development as large, low-grade operations proceeded gradually during the first half of the 20th Century in districts and mines such as Ajo, Morenci, Bagdad, Inspiration, Ray, and Chino. By the 1960's, additional discoveries coupled with an evolving and increasingly efficient extraction and beneficiation technology had resulted in full-scale production at 20 separate mineralized centers; mining proceeds at a dozen deposits in the early 1990's in orebodies and mines that survived the economic downturn of the 1980's. These operations are at Sierrita-Esperanza, Twin Buttes, the San Xavier-Mission Complex, San Manuel-Kalamazoo, Ray, Morenci, Chino, the Pinto Valley, and Inspiration in the Globe-Miami center and Bagdad; Lakeshore, Silver Bell, and Mineral Park were in production as active leach operations. An additional 10 known (reported) inoperative or undeveloped orebodies are present in the S outhwestern United States. In 1992, the mines of Arizona continued to be the source of nearly two-thirds of the newly mined copper of the United States, as well as a significant source of byproduct gold, silver, and molybdenum.

Beyond the economic importance of these ores to local and national well-being and wealth, the porphyry ore deposits of the region have been sites of important and fundamental scientific study of hydrothermal processes and ore genesis. The periodical literature of the 1960's, 1970's, and 1980's contains many general and topical papers. In addition, the deposits have been summarized in two general works (Titley and Hicks, 1966; Titley, 1982); during this interval, the porphyry deposits of the Canadian Cordillera were similarly summarized in Sutherland Brown (1976).

Viewed from the perspective of regional geology, studies of districts during the early part of the 20th Century resulted in development of a historical geology and stratigraphic framework of the region, mostly contained in U.S. Geological Survey Professional Papers and Monographs. These fundamental stratigraphic and regional studies remain as sources of basic geological information. In the context of engineering, deposits of Arizona have been sites of development of innovative technology in mineral extraction during the past half century and have served as field laboratories for development of methods and machinery. This evolved technology has resulted in profitable mining (at metal prices of the early 1990's) of some of the lowest copper equivalent grades (Cu percent + NxMo percent) in the world (for example, 0.5 percent).

GENERAL GEOLOGICAL HABIT AND REGIONAL SETTINGS

Most porphyry copper deposits, as well as genetically comparable deposits of other metals such as tin and molybdenum, are believed to be the products of late-stage events of emplacement and cooling of magmas at shallow (<5 km) depths during a volcanic cycle. Rapid rise of magmas in a volcanic environment and consequent rapid cooling is believed to explain the porphyry textures of rocks in these systems. The association with volcanism is seen in youthful deposits, mostly in island-arc regions, and is inferred in older deposits, such as in Arizona, from close spatial and temporal associations of certain volcanic rocks, porphyry intrusions, and mineralization. This association with subaerial volcanic activity links the ores with specific geological settings, most commonly continental margins that have

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undergone the effects of plate convergence, in addition to island arcs. The convergence of oceanic and continental plates results in development of magmatic arcs such as that seen in the Cascade Range of Washington and Oregon.

A magmatic arc evolved in the southern cordillera during the Jurassic, of which Bisbee, Ariz., may be a part, and another evolved in the region during the Laramide. This period of time, between about 75 and 50 Ma, was that of formation of the 40-50 major porphyry deposits and occurrences of Arizona and New Mexico in the United States and of Sonora and Sinaloa in Mexico.

SOUTHWESTERN NORTH AMERICAN SETTING

Deposits of this region lie above the North American craton within about 350 km of the reconstructed Laramide western margin of the craton. None is known to occur within younger accreted and constructed marginal terrane. They are known in two physiographic regions, the southeastern Basin and Range Province, and the Central Mountain Province of Arizona and its extensions to the east. Curiously, and importantly, the porphyry ores of Arizona are only one genetic type of a population of ore deposits of other styles and of other ages in this same region. This phenomenon seems a manifestation, perhaps, of the metallogenetic history of regions where environment and setting are as important as are processes.

Figure 1 (from Titley, 1992) shows the porphyry copper deposits of this southwestern North American region in the framework of various elements of regional crustal geology; the map closes the Gulf of California, restoring Baja California to a likely Laramide configuration of the continental margin. The Laramide pluton-centered ore systems of southeastern Arizona, New Mexico, and contiguous Mexico lie in or above a Proterozoic basement of about 1.7-1.82 Ga, their plutons also invading a superjacent succession of Paleozoic platform strata and widely dispersed, mostly clastic Mesozoic rocks. The Laramide deposits of western Mexico occur in the Cortes (Cortez) Terrane of Coney and Campa (1987), where Paleozoic and Mesozoic strata are present above an unknown basement of either oceanic or cratonic affinity. The Laramide province of Arizona and environs reappears(?) in the Cortez terrane where districts are exposed near the edge of middle Tertiary Sierra Madre Occidental volcanic cover. The distribution of deposits in Mexico raises significant unanswered questions concerning the tectonic and metallogenic history of this region and its relationship to the craton of Arizona and contiguous regions.

Viewed regionally in the American Southwest, the many districts occur in a structurally deformed belt that lies between the Colorado Plateaus to the north and northeast, and the coastal batholiths to the southwest, in Mexico. Most districts in the Basin and Range Province have evolved above a mixed volcanic, clastic, and granite Proterozoic basement in a thin (2-km-thick) section of Paleozoic platform strata and a Mesozoic section dominated by clastic and volcanic rocks of local derivation. The stratigraphic patterns of the Paleozoic reveal general tectonic quiescence, but the geology of many districts reveals preore juxtaposition of Proterozoic and Phanerozoic rocks, suggesting a profound Mesozoic tectonic event, but one whose details remain obscure.

Areal geological associations of many of the relevant Laramide districts reveal close association with Upper Cretaceous andesite-dacite subaerial volcanic flow and pyroclastic complexes. Following their primary formation, the deposits were further modified by supergene processes in the early Tertiary, subsequent burial by rocks of a middle Tertiary volcanic episode, middle to late basin-and-range-forming tectonic phenomena, and subsequent exhumation of the deposits where they are now exposed in many ranges; presumably some still remain buried and undiscovered.

CHARACTERISTIC ELEMENTS OF PORPHYRY COPPER DEPOSITS

A typical porphyry copper deposit is difficult to define in a rigorous way because many important habits vary according to setting, wall-rock contrasts, post-ore histories, and level of exposure. Notwithstanding such variation, members of the genetic class manifest important and fundamental habits and basic geological associations that allow a generalized definition. Viewed in such a way, the porphyry copper deposit is a large (tens of square kilometers), hydrothermally derived ore system. The deposit is centered on, or is close to, an epizonal porphyritic intrusion, around which, or on whose flanks, are stockworks that transgress intrusion

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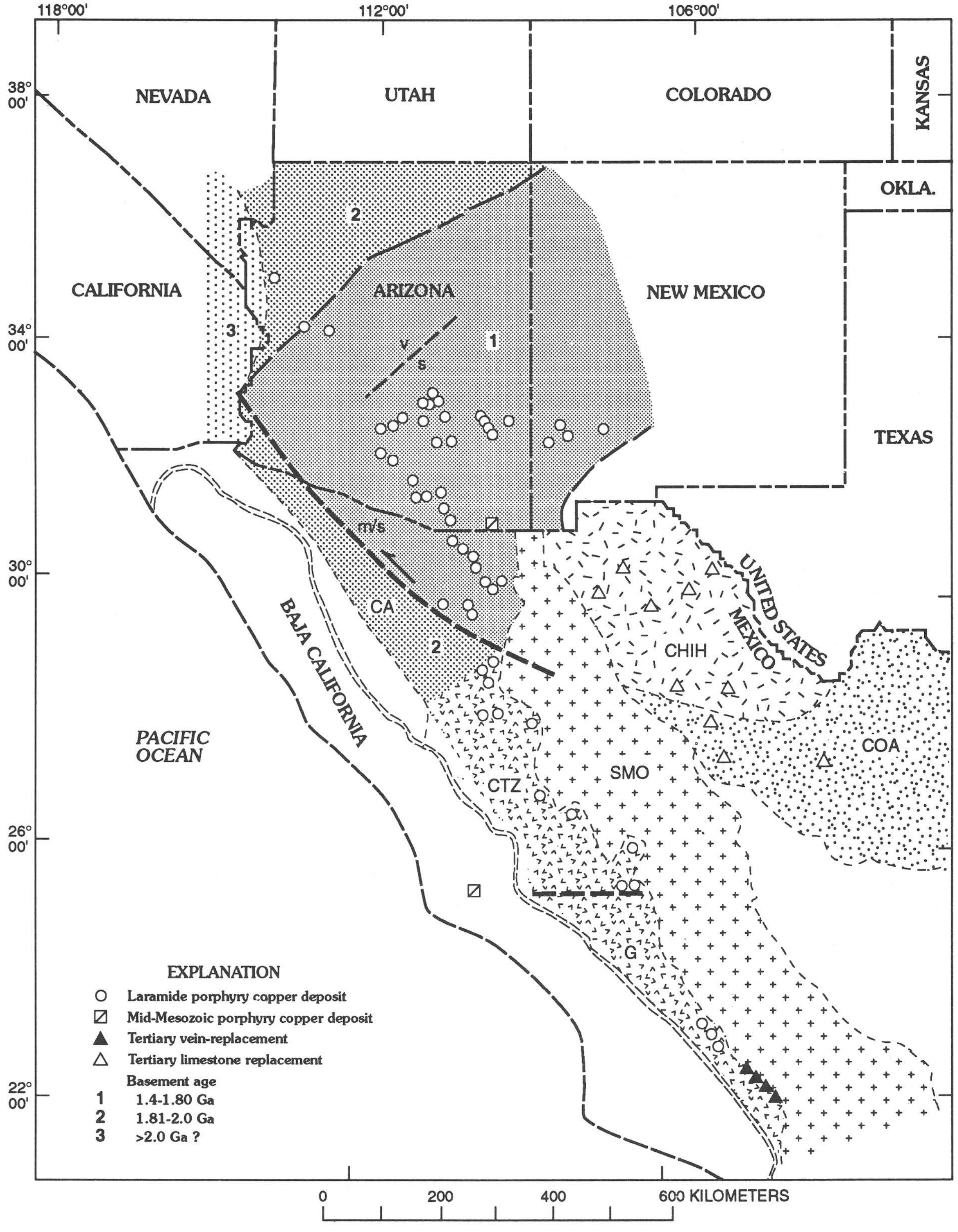
Figure 1 (facing page). Map showing the relationship of porphyry copper deposits and, for contrast, limestone replacement deposits to some crustal rocks in the contiguous regions of Mexico and the Southwestern United States (from Titley, 1992). Patterned area of Arizona is Proterozoic basement of 1.7–1.82 Ga with v/s showing approximate boundary of (older) volcanic rocks (v) with sedimentary rocks (s) of the basement. Stippled patterns of northwestern and western Arizona and southeastern California are of complex basement of age older than about 1.8 Ga. In Mexico, terranes of Coney and Campa (1987) are shown as follows: CA, Caborca; CTZ, Cortes; CHIH, Chihuahua; COA, Coahila; and SMO, younger overlap terrane of the Sierra Madre Occidental; m/s, Mohave-Sonora megashear. Baja California is shown in its prerift position (Miocene).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NEVADA
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UNITED STATES
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BAJA CALIFORNIA
PACIFIC OCEAN
CHIH
SMO
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EXPLANATION
Laramide porphyry copper deposit
Mid-Mesozoic porphyry copper deposit
Tertiary vein-replacement
Tertiary limestone replacement
Basement age
1 1.4-1.80 Ga
2 1.81-2.0 Ga
3 >2.0 Ga ?
0 200 400 600 KILOMETERS

and wall rocks. Mineralized rock is altered, usually into conspicuous zones of specific minerals, and at district scale the occurrence of base and precious metals is commonly zoned.

IGNEOUS ROCK ASSOCIATIONS

On a world-wide basis, the deposits share in common a close temporal and spatial association with porphyritic intrusions, as plugs, stocks, dikes, or sills, usually intrusion complexes. In the American Southwest, the time of this igneous activity is Laramide; Bisbee, Ariz., is the lone known exception and is of older Cretaceous age. In some instances, the porphyry intrusion complexes are late stages of batholith emplacement and cooling; as such, batholiths are host rocks to ore. An important corollary is that non-porphyritic igneous intrusions have not been recognized as progenitors to the porphyry ores. Porphyry intrusions of these systems are a late stage of an igneous cycle that appears to have commenced with volcanic activity, usually andesitic in composition. In island arcs and on cratons, many of the porphyry copper districts expose remnants of this volcanic episode, and, where dated, it is invariably slightly older than the intrusive event most closely related to copper mineralization.

Studies of the ore-related porphyries at Sierrita, Ariz. (Anthony and Titley, 1988), reveal that those intrusions most closely related in time and space to mineralization are cooled from magmas of mostly lower crustal origin. These late porphyries appear to be the end result of a magmatic process that commenced with andesites of significant mantle content and progressed through a process of anatexis of increasing fractions of lower crustal rocks.

FRACTURE-RELATED PERMEABILITY

The process of emplacement and cooling of magmas that become porphyries results in development of large volumes (tens of cubic kilometers) of intense and closely fractured rock. The presence of abundant, closely spaced (on the scale of centimeters) joints in the porphyry ore system is one of its ubiquitous signatures. These fractures were the channels of flow of great volumes of hydrothermal fluid, which resulted in cooling of the pluton and which became sites of precipitation of ore minerals and attendant alteration products. The notion that the porphyry ore system contains disseminated mineralization is a matter of scale and semantics. Mineralization is more or less uniformly dispersed at the scale of truck loads or benches; viewed at the scale of rock samples, most mineralization is localized along fractures that range from hair-width to centimeter-width, and it is their close spacing that results in uniformity of occurrence at a smaller scale.

MINERALIZATION

Seen at the most fundamental level, the porphyry copper deposit occurs as veinlet-localized and veinlet-related copper sulfide mineralization in stockworks in or adjacent to felsic porphyritic intrusions. In some deposits, the porphyritic rocks are mineralized, but in most the wall rocks to porphyry intrusions are mineralized. Mineralized rock in the porphyry copper system contains a low sulfide volume (<5 percent) and is dominated by pyrite and chalcopyrite in ratios (py:cpy) that vary greatly, from 10 to 0.1, in significant volumes of rock. An important economic component of porphyry copper ores lies in accessory metals of the mineral assemblage. These metals vary in a general way with the geological setting, gold being important in island arcs, and molybdenum and silver in cratons, but with some overlap of elements in both settings.

Many porphyry copper occurrences are cores of significant base- and precious-metal districts. Many of these districts in the American Southwest, the Philippines, the Andes, and Australia were originally important for mining of lead, zinc, gold, and silver before recognition of their porphyry copper cores. In most instances mining took place in parts of districts peripheral to the lower grade copper mineralization.

HYPOGENE ALTERATION

The porphyry copper system expresses profound and distinct zoning of hydrothermal alteration. Such zoning is manifest in the expression of these systems at the surface, where the lateral components of changes are conspicuous. Habits of vertical zoning are less obvious because of the generally restricted extent of our knowledge, seldom more than 1 km. However, some information on vertical changes is known from study at Yerington, Nev. (Dilles, 1987), and at San Manuel, Ariz. (Lowell, 1968), where post-ore tilting has resulted in some exposure across an enhanced vertical interval.

The economic mineral assemblages are closely associated in time and space with development of specific groups of hydrothermal alteration minerals whose compositions grossly reflect fundamental chemistry of their host rocks. Thus, potassium-aluminum-dominated alteration assemblages (potassium-silicate) are identified with intrusions, certain clastic strata, and volcanic rocks; calc-silicate alteration, such as skarn, and marble are present in carbonate or other calcium-rich hosts. The style of alteration may be viewed as pervasive, in which significant volumes (tens to thousands of cubic meters) of rock are nearly entirely converted by replacement to the alteration mineral assemblage, as selectively pervasive alteration in which only specific minerals are affected by the process, usually resulting in textural enhancement, or as vein or vein-selvage alteration in which the effects are restricted to the immediate volume of rock traversed by fracture channels.

Potassium-silicate alteration is most commonly manifested by two specific mineral assemblages. One is quartz with biotite and (or) orthoclase, referred to as potassic, which occurs most commonly as vein-filling or vein-selvages. Rarely the assemblage will be pervasive. The other common assemblage is hydrous acid alteration that results in vein or pervasive alteration of host rock to the assemblage quartz-sericite, referred as phyllic. At high or near-surface levels, the acid hydrous alteration may become oxidizing, resulting in evolution of alunite, quartz, and clays. Propylitic alteration is distal and may be the result of heating and movement of fluids previously contained in the host rocks. Calc-silicate or skarn mineralization is manifested in two ways: as pervasive, usually monomineralic replacement of a rock volume and as later vein-related alteration of the early skarn in the same rock.

The different alteration mineral assemblages (types) develop sequentially in the same rock volumes in an environment of declining temperatures as a consequence of the continuing process of pluton cooling; in this sense the alteration and mineralization seen in these systems is thermally retrograde. Sulfide mineralization attends certain of the alteration stages. A result is overprinting of different kinds of alteration on the same rock, within which will also be the precipitated ore minerals. A predominance of one kind of alteration over another gives rise to recognizable zones of alteration at scales of kilometers that may be either symmetrically or asymmetrically zoned with respect to the porphyry body or a district center.

ENVIRONMENT OF FORMATION

The intrusion cores of porphyry copper systems are vertical, long, and tall columns of rock. Although the depths of exploration and knowledge of most deposits is limited to depths of generally less than 1 km, the exposures of tilted systems such as at San Manuel, Ariz. (Lowell, 1968), indicate original column heights of more than 3 km; the tilting and faulting at Yerington, Nev., exposes an original vertical height of possibly 7 km (Dilles, 1987). The porphyry copper deposit, thus, may transgress the range of conventionally considered environments of hydrothermal ore deposit formation, that is, from epithermal through at least part of the hypothermal environments. In the American Southwest, we view deposits at levels of weathering at least 1 km beneath the original surface, and at possibly greater depths; this inference stems from reconstruction of pre-ore strata now weathered and from studies of fluid inclusions in a few deposits where boiling of fluids has been recognized, and hydrostatic column height determined. Thus, not surprisingly, the evidence from mineralogy and textures, as well as temperatures and pressures adduced from studies at these exposed levels reveal habits of the mesothermal environment.

Many studies of fluid inclusions and of the geochemistry of the alteration and mineralization process, together with results of studies of stable isotopes, have been reported. Results of thermometry and mineral chemistry studies indicate continually changing conditions during the evolution of the deposits, a significant property of the mineralization (alteration) process. Yet, even that ubiquitous character of alteration reveals the importance of consideration of dynamic evolution rather than essentially static conditions during their formation.

The nature of evolution of these systems may be read from the habits of crosscutting altered veinlets, which record generally consistent sequences of minerals at generally consistent positions in the paragenesis of hydrothermal events. These data are shown in figure 2, where vein and pervasive alteration mineral assemblages in potassium-silicate rocks are plotted as they relate to temperature (during time and cooling history) and to spatial distribution with respect to an intrusion contact.

Acid sulfate alteration is known at a high level, above copper ore, in the system at Red Mountain, Ariz., and has been reported at corresponding high levels in deposits of the Philippines. Such alteration and its accompanying mineralization are characteristic of the epithermal environment. The nature of the bottom of porphyry systems of this region is less certain, although information from San Manuel (Lowell, 1968) suggests that pyrite gives way to magnetite, and potassium-silicate alteration is confined to development of sericite and clay. In view of the relatively barren properties of both the highest and deepest levels of these systems, hypogene copper concentration is seen to be constrained to some intermediate levels of the original vertical extent of these systems.

POST-ORE MODIFICATION

Porphyry copper deposits of the American Southwest have undergone significant post-ore modification. Uplift and weathering, which may have commenced in the Eocene, have resulted in chemical modification of hypogene ores and their transport to sites of deeper concentration. Still younger middle Tertiary uplift has resulted in fragmentation of orebodies and their transport, displacing

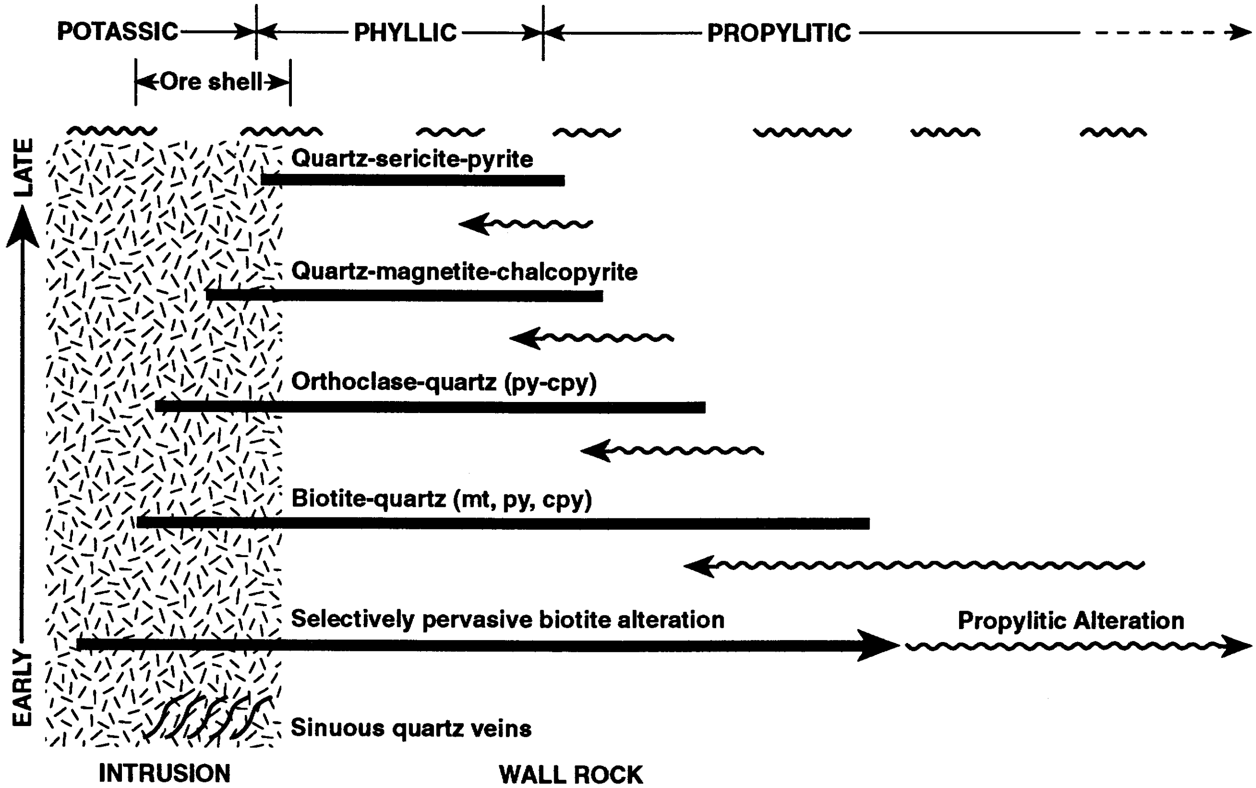


Figure 2. Time and space expansion of alteration stages of a porphyry copper deposit emplaced into potassium-silicate wall rocks (either sedimentary or igneous). The diagram tracks the stages of alteration as manifested in their vein and pervasive styles from oldest (bottom of diagram) to youngest (top of diagram). The oldest is thermally prograde, but each successive stage is thermally retrograde and may be seen at hand specimen scale in sequences of crosscutting altered veins in most ore systems. The existing configuration of alteration zoning is the end product of a process of successive overprinting, with the controlling stage that of quartz-sericite-pyrite alteration (latest) overprinting earlier potassium-silicate alteration types. Wavy lines with arrows show the direction of migration of porpylitic alteration "front," which moves outward in the early stages of alteration and during cooling of the system collapses inward on the earlier stages. Abbreviations: mt, magnetite; py, pyrite; cpy, chalcopyrite. Adapted from Titley (1982).

such bodies as those known in the Pima district and at San Manuel.

SUPERGENE SULFIDE ENRICHMENT

The enrichment of copper ores through weathering was the most significant geological event that resulted in economic development of the porphyry copper ores in this region. Through supergene processes, hypogene copper mineralization of the shallow levels in the original systems was moved downward to be precipitated at greater concentrations in generally flat lying, discoid "blankets" that are probably conformable with the surface of an ancient water table. The process takes place at high levels in the original system where pyrite occurs in sufficient abundance to produce acid, and where, correspondingly, a great abundance of fractures allows flow of significant amounts of the supergene fluids. Production of acid results in solution of hypogene copper sulfides, the copper-bearing, sulfate-dominant (oxidized) solutions moving to an environment where both copper and sulfur are reduced to form chalcocite.

Results of study of the oxidation products of this weathering, those minerals that give rise to the colorful red and yellow hues at the modern surface, reveal that the enrichment processes took place through several stages, each of which may have reflected changes in base level, perhaps adjustments to uplift. When compared with common hypogene grades of 0.05–0.2 percent copper beneath the blankets, enrichment factors of three to six times in polycyclic enrichment are seen in the enriched ores.

SUMMARY

The foregoing has outlined and summarized cogent aspects of the nature of porphyry copper deposits and addressed many habits, both those observable at mesoscopic scale and those interpreted from the results of measurement of habits and composition of the chemistry and mineralogy of rocks, minerals, and fluids present in them. Reported research of the past three decades, while presenting basic geological information and relationships for many deposits, has been mostly focused at the scale of laboratory measurement and interpretation of localized environments and processes. Certain habits of these systems, however, have long been recognized, and it is appropriate here to make some comment on progress.

Figure 3 shows a cross section through a porphyry copper deposit as presented in 1966 by S.E. Jerome (and published by him earlier in 1962), a part of which has been adapted and modified only slightly for further discussion and clarification. The section shows the essential elements of the weathered and enriched porphyry system of this region. The emplacement of magmas into a succession of Phanerozoic strata and volcanic rocks results in different mineralization styles and alteration controlled by original rock compositions. The location of the enriched blanket in most of the porphyry systems is essentially as shown. More important, as Jerome showed in this early diagram, are those distinct alteration assemblages and the characteristic symmetry of alteration of the porphyry copper system. Subsequent modeling of the deposits by numerous workers, mostly ignoring Jerome's basic contribution, has only further strengthened the accuracy of his (illustrated) interpretations of the distribution of alteration types as defined by minerals and their successive evolution and overprinting habits.

IMPORTANT PROBLEMS REMAINING

The provenance of fluids and metal revealed in the formation of these deposits remains obscure at best and basically unknown. Only one report concerning stable oxygen isotope chemistry addresses deposits of this region (Sheppard and others, 1971), and evidence from sulfur isotopes reveals only complex and changing sources of that metal. Moreover, the porphyry ores are associated with only some Laramide intrusions. The nature of the link of igneous processes with generation of ore fluids and the allied questions of the nature of volatile histories of these magmatic systems remain either unaddressed or unanswered. These enigmas lead directly to the question of why copper was so strongly concentrated in this region during only the Laramide. The widespread intrusions and volcanic rocks of the middle Tertiary are not yet reported as porphyry copper systems in the conventional sense; the middle Tertiary igneous episode is more closely related to precious-metal vein systems and mostly to small (<100,000 tons) copper-zinc-lead bodies in skarn.

Phenomena that may have controlled specific localization of the Laramide ore districts of this region remain mostly unknown. Early notions that linked the occurrence of districts with lineaments have been mostly succeeded by the ideas related to control by subduction of oceanic plates beneath the craton. But lineament controls remain as possible corollaries. At local scales, new ideas concerning associations with calderas pose challenging contrasts to views developed in youthful systems of their association with volcano-tectonic depressions and andesite shield volcanoes. These questions of immediate control and associations of the porphyry copper deposits are of continuing and immediate importance at the scale of search and assessment because they so strongly influence exploration criteria.

REFERENCES CITED

Anthony, E.Y., and Titley, S.R., 1988, Progressive mixing of isotopic reservoirs during magma genesis at the Sierrita porphyry copper deposit, Arizona—Inverse solutions: Geochimica et Cosmochimica Acta, v. 52, p. 2235–2249.

Coney, P.J., and Campa, M.F., 1987, Lithotectonic terrane map of Mexico (west of the 91st Meridian): U.S. Geological Survey Miscellaneous Field Studies Map MF–1874–D.

Dilles, J.H., 1987, Petrology of the Yerington batholith, Nevada—Evidence for evolution of porphyry copper ore fluids: Economic Geology, v. 82, p.1750–1789.

Jerome, S.E., 1966, Some features pertinent in exploration of porphyry copper deposits, *in* Titley, S.R., and Hicks, C.L., eds., Geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 75–85.

Lowell, J.D., 1968, Geology of the Kalamazoo orebody, San Manuel district, Arizona: Economic Geology, v. 63, p. 645–654.

Sheppard, S.M.F., Nielsen, R.L., and Taylor, H.P., 1971, Hydrogen and oxygen isotope ratios in minerals from porphyry copper deposits: Economic Geology, v. 66, p. 515–542.

Sutherland Brown, A., ed., 1976, Porphyry deposits of the Canadian Cordillera: Canadian Institute of Mining and Metallurgy, Special Volume 15, 510 p.

Titley, S.R., 1991, Correspondence of ores of silver and gold with basement terranes in the American Southwest: Mineralium Deposita, v. 26, p. 66–71.

______1992, Evidence for crustal controls of metallogenesis in epigenetic ores of the southern Cordillera, United States and Mexico: Society for Mining, Metallurgy, and Exploration, Preprint 92–210, 11 p.

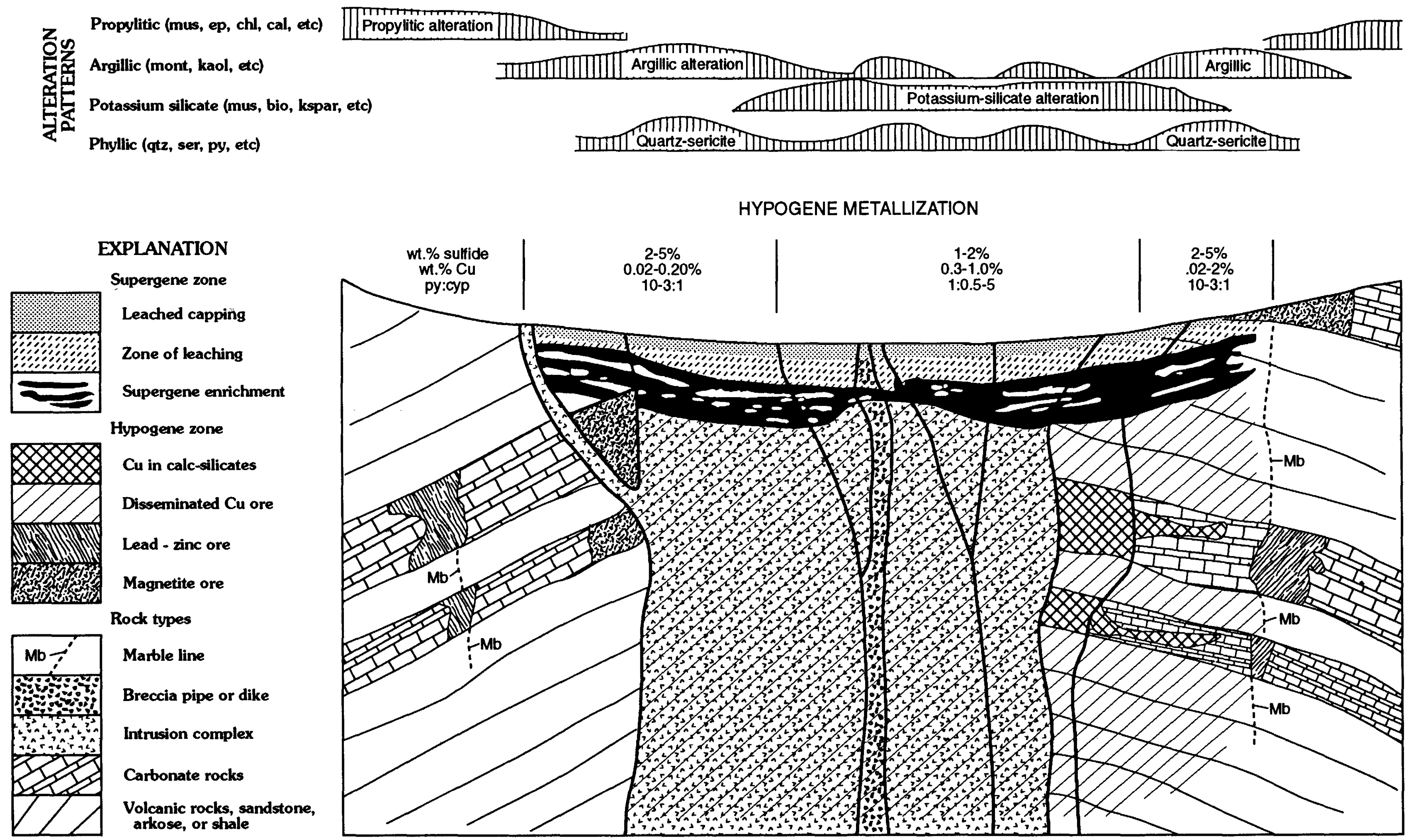


Figure 3. A generalized cross section through a typical weathered porphyry copper system of southwestern North America. This figure is adapted from Jerome (1966) and modified here to include some habits of common hypogene mineralization, as well as modified to include a few additional minerals of the various alteration zones originally described by Jerome. Abbreviations: mus, muscovite; ep, epidote; chl, chlorite; cal, calcite; mont, montmorillonite; kaol, kaolinite; bio, biotite; kspar, potassium feldspar; qtz, quartz; py, pyrite; ser, sericite.

——— in press, Characteristics of porphyry copper occurrence in the American Southwest, *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., eds., Mineral deposit modeling: Geological Association of Canada Special Paper 40.

Titley, S.R., ed., 1982, Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, 560 p.

Titley, S.R., and Anthony, E.Y., Laramide mineral deposits in Arizona, *in* Jenney, J.P., and Reynolds, S.J., 1989, Geologic evolution of Arizona: Tucson, Arizona Geological Society Digest 17, p. 485–514.

Titley, S.R., and Hicks, C.L., eds., 1966, Geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, 287 p.

HISTORIC MINING CAMPS OF SOUTHEASTERN ARIZONA—A ROAD LOG WITH GEOLOGIC AND HISTORIC HIGHLIGHTS

By Brenda B. Houser,[1] Mary M. Farrell,[2] Eric R. Force,[1] James A. Briscoe,[3] Leslie J. Cox,[1] and John Wiens[4]

INTRODUCTION

Arizona's rich mineral endowment, in combination with periodic fluctuations in metals markets, has ensured that Arizona is also richly endowed with historic mining camps and ghost towns. Some mining camps had only a brief existence around the turn of the century, others survived until WW II, and still others have been alive and relatively prosperous for more than a century (although not with mining as the sole economic base). On this trip we will visit four mining camps: Kentucky Camp, Harshaw, Washington Camp–Duquesne, and Tombstone (fig. 1).

Kentucky Camp flourished briefly from 1904 to 1906 as the headquarters site for an engineering endeavor designed to bring water from the Santa Rita Mountains for gold placer mining in the Greaterville district. After the project failed, the land was bought for taxes by a rancher who used the buildings at Kentucky Camp as the ranch headquarters until the 1960's. Thus, the adobe structures here are relatively intact compared to those at other camps.

Harshaw and Washington Camp–Duquesne, both on the east side of the Patagonia Mountains, were camps associated with mines that produced high-grade lead-silver ore. The mineralized deposits here were known to the Jesuits and were worked by the Spanish and Mexicans in the 1800's. Harshaw and Washington Camp–Duquesne date from about 1880. The camps were ghost towns by the 1950's, but exploration continues. The old adobe power house building near Duquesne contains core drilled by Simplot and Rosario in the 1960's and 1970's.

Nearly everyone has heard of Tombstone because of the popularization of some of the town's more notorious early residents, such as the Earps, the Clantons, and Doc Holliday. Mines in the Tombstone district produced chiefly silver, in addition to lesser amounts of gold, lead, zinc, copper, and manganese. Although most mines closed around 1922, the town still survives with tourism as its financial base.

The structures at most of the mining camps are disintegrating rapidly, particularly those made of adobe. At Mowry (a mine and camp about halfway between Harshaw and Washington Camp–Duquesne), for example, Way (1966) said there were half a dozen buildings of frame and adobe and showed photographs of several adobe buildings. There are only a few foundations and crumbling adobe walls there now. Once the roof is gone from an adobe structure, each rain dissolves a bit more of the bricks until, in a few years, nothing is left but a low mound of dirt. Two sections of walls of adobe buildings at Duquesne collapsed as a result of the record rainfall of the winter of 1992–93. The wood frame buildings fall prey to vandals, recyclers, and collectors.

The cultivated plants that were planted by the residents of the mining camps are proving in some cases to be more durable than the buildings. Fruit trees in the valley at Harshaw, where the water table is fairly high, have done quite well with no care for the past 20 years or more. A few introduced cultivars, such as yellow bird-of-paradise and tree of heaven, are even spreading by seed or roots. Spearmint (*Mentha spicata*), naturalized at Paymaster Spring near Mowry, may have been planted by the miners as early as 1860.

There are a number of dates important to the history of mining in Arizona:

[1]U.S. Geological Survey, Gould-Simpson Building #77, University of Arizona, Tucson, AZ 85721.

[2]U.S. Forest Service, Coronado National Forest, 300 W. Congress Street, Tucson, AZ 85701.

[3]JABA, Inc., 2100 North Wilmot Road, #218, Tucson, AZ 85712.

[4]Arizona-Sonora Desert Museum, 2021 North Kinney Road, Tucson, AZ 85743.

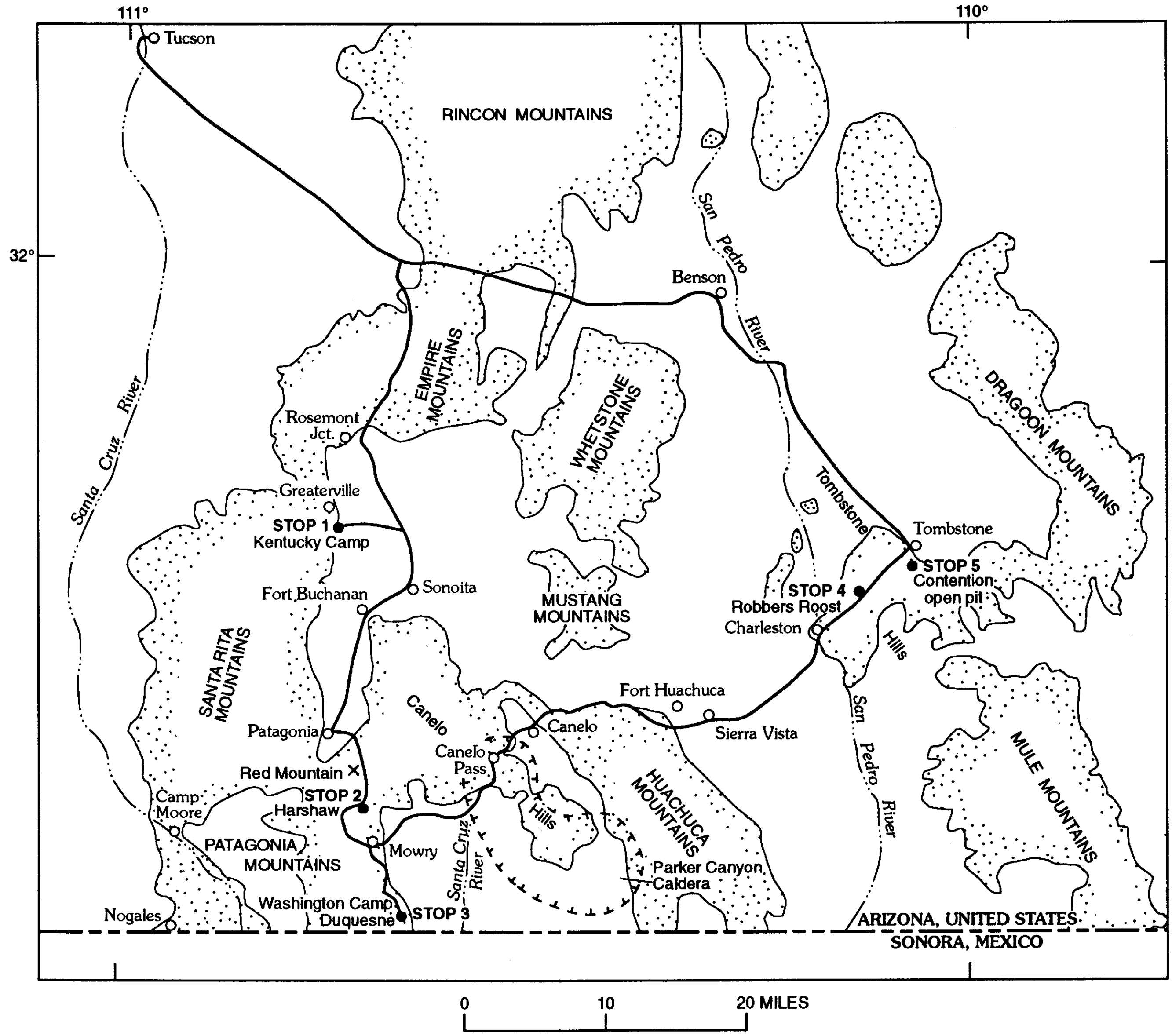


Figure 1. Index map of southeastern Arizona, showing major geographic features, field trip route, and stops.

1853 Gadsden Purchase. Prior to this, the land south of the Gila River was part of Sonora, Mexico.

1861 Beginning of the Civil War. All the Federal troops were withdrawn from Arizona, making it unsafe to be out alone or in small groups because of Apache raids. Pumpelly's account of the hazards of being a miner in Arizona at this time is excellent (Wallace, 1965).

1872 Apache Peace Commission under Vincent Colyer. This first Apache peace made existence a little less precarious for miners, but there was still the threat of Apache raids until about 1876.

1881–84 Railroads completed in southeastern Arizona. Because of shipping costs before this, ore had to be worth at least $100 per ton to be worth mining.

1893 Demonetization of silver. Prior to this time, the price of silver was about $1 per ounce. Afterward, the price dropped sharply (table 1).

1914–17 World War I. Sharp upswing in metals prices.

1921 Collapse of metals prices.

Please be cautioned that in reviewing references and preparing the road log, we noted a number of discrepancies among reference texts as to dates and versions of events. Because this road log is not intended to be a scholarly historical treatise, the date or version was chosen that was known to be correct, or that seemed to be the most likely, or that was the consensus of several sources. For the most part, we did not search newspaper files, court records, or other

Table 1. The price of silver, 1879 to 1901 (Tenney, 1929, p. 154).

Year	Price of silver (dollars)	Year	Price of silver (dollars)
1879	1.12	1891	0.99
1880	1.15	1892	.87
1881	1.13	1893	.78
1882	1.14	1894	.63
1883	1.11	1895	.65
1884	1.11	1896	.68
1885	1.07	1897	.60
1886	0.99	1898	.59
1887	.98	1899	.60
1888	.94	1900	.62
1889	.94	1901	.60
1890	1.05		

original sources to resolve discrepancies. A particularly blatant example of historical misinformation is given by a carved wooden sign at the old post office in Pearce, Ariz., the site of the Commonwealth Mine (not on this field trip). According to the sign, "... Pearce saw its demise when the mine flooded, killing most of the miners. Their families left soon after, leaving behind all but their basic necessities ..." This story of a mine flood has no basis in fact. As recently as 1975, the 800-ft level (the deepest level) of the Commonwealth Mine was dry and accessible according to John M. Guilbert, University of Arizona (oral commun., 1992). One can only surmise that the person who took the trouble to carve this misinformation in wood either believed the story or perhaps thought it was the sort of thing that tourists wanted to hear.

ROAD LOG AND GEOLOGIC AND HISTORIC HIGHLIGHTS

Miles

Depart from Holiday Inn on Congress Street, Tucson, Ariz. Go west on Congress Street to Interstate 10 (I–10).

0.0 Junction of Congress Street and I–10. Take I–10 East to Arizona State Highway (SH) 83 (exit 281, Sonoita Road).

22.8 Junction of I–10 and SH 83. Take SH 83 south toward Sonoita.

28.8 Empire Mountains to the east.

EMPIRE MINING DISTRICT

The Empire mining district is to the southeast in the Empire Mountains (fig. 1). Deposits of argentiferous lead and copper ores were first discovered in the Empire district in the late 1870's, but mining became economically feasible only after the railroad was built in the early 1880's. The principal camps in the district were California Camp, Total Wreck, and Copper Camp.

The highest and most rugged part of the Empire Mountains consists of generally southeast-dipping Paleozoic carbonate rocks and quartzite that were intruded by early and late Laramide-age granitoid plutons. Precambrian granitoid rocks are exposed on the north flank of the Empire Mountains. Sedimentary rocks of the Lower Cretaceous Bisbee Group surround the Empire Mountains and overlap both the Paleozoic and Precambrian rocks (Finnell, 1974; Drewes, 1980).

The mineralization of the Empire district is probably genetically associated with intrusion of Laramide age granitoid rocks into the Paleozoic carbonate rocks. The mineral deposits are chiefly oxidized silver-lead and copper minerals contained in vein and replacement deposits. Some mines in the district produced small amounts of gold.

For a time, Total Wreck was the leading silver bullion producer in the Arizona Territory. The name "Total Wreck" came from the description of the site of the first silver mining claims on the Richmond lode in the Empire Mountains, given by John T. Dillon, who discovered the deposits in 1879. He said the site was ". . . a big ledge, but a total wreck, the whole hillside being covered with big boulders of quartz which have broken off the ledge and rolled down" (Granger, 1960, p. 284). By 1883 the camp had 200 inhabitants and the *Tucson Weekly Star* reported that there were five saloons, three general stores, a butcher shop, a shoemaker shop, and from eight to ten Chinese laundries. By 1884, the mines had produced about $500,000 worth of silver bullion. Mining continued into the 1890's, but has been sporadic since the early 1900's, with peaks during World War I and in the late 1920's. In 1926 the mill tailing pile was leased and more than 1,000 tons of low-grade material was shipped as flux (Tenney, 1929). The district was worked for zinc in the 1940's, but there has been little activity since 1950. Keith (1974) gave the total estimated and recorded production of the Empire district as more than 34,000 tons of ore containing 206,400 ounces of silver, 744 ounces of gold, 8,334 tons of lead, 372 tons of zinc, 172 tons of copper, 76 tons of molybdenum, and a minor amount of tungsten. The total value of production from the district has been about $1,178,000.

34.9 Road to Rosemont Junction and Camp, 2.5 mi to the southwest.

Rosemont Camp, the site of the Rosemont Mining and Smelting Company, was a thriving village in the Helvetia district in the 1880's and 1890's (fig. 1). There were about 150 residents, a school, a hotel, and some stores (Sherman and Sherman, 1969). The claims and smelter were acquired by Lewisohn

Brothers of New York City in 1896. Subsequently, the mines were worked on an exploratory basis until 1907, when finally they were closed and the smelter was shut down. After that, Rosemont was more or less deserted (Schrader, 1915).

There are at present two houses at Rosemont—one at Rosemont Junction and the other at Rosemont Camp—but it is not known if they date to the days of the mining camp or not. At Rosemont Junction, the remnants of a poured concrete foundation and porch indicate that there was at least one substantial dwelling here. A slag dump apparently marks the location of the smelter, and there are a number of level places nearby along the creek where there were probably various structures.

40.0 Junction of SH 83 and Greaterville Road.

Placer gold was discovered on the east side of the Santa Rita Mountains in 1874 by a prospector named Smith. Smith was soon joined by his partners from New Mexico, and a moderate-sized gold rush ensued (Schrader, 1915). Some large nuggets were found, and by 1878 there were about 400 Mexicans and nearly 100 Americans in the new community of Greaterville (fig. 1). There were several dance halls, saloons, and stores; the jail was a round hole dug in the ground into which prisoners were lowered by rope (Sherman and Sherman, 1969). Schrader (1915) reported that by 1909 Greaterville had a store, a post office, and tri-weekly mail service from Helvetia (on the west side of the Santa Rita Mountains) by way of Rosemont.

The Greaterville placer district suffered from a problem common to many southwestern placer deposits—lack of water. Placers were worked by rocker and long tom (cradles or troughs of various lengths for washing gold-bearing material). Mexican entrepreneurs brought water 4 mi from Gardner Canyon in canvas and goatskin bags on burros, charging about 3 cents a gallon for it.

The camp gradually declined as the richer gravels were worked out and attacks by Apaches continued to be a threat. From 1873 to 1875 the Greaterville placers yielded about $250,000 worth of gold, but by 1883 the yearly yield had dropped to $12,000. The total production from the placers through 1929 was about $680,000 worth of gold (Tenney, 1929).

The search for lode deposits in the Greaterville district was disappointing. A few lodes were located and some rich pockets were mined, but there was little production from them. The Conglomerate Mine, which contains lead and silver-gold ore in limestone and adjacent granite, was the most important mine in the area, but it is 2 mi south of the placer area and was probably not a source of gold for the placers (Tenney, 1929). L.J. Cox discusses (this volume) the geology of the Greaterville district in relation to the source of the placer gold.

There was a revival of interest in the Greaterville placers between 1900 and 1905, when there were several attempts to bring water in by ditch and pipeline. The center for one of these operations was Kentucky Camp in Kentucky Gulch (**STOP 1** of this field trip). From 1905 to about 1930, various companies attempted to work the gravels with a steam shovel, drag-lines, and a dredge; all failed because of insufficient water and poor sampling (Tenney, 1929). The current (early 1990's) price of gold ($300–400 per ounce) assures that nearly every weekend a number of people will be working the gravels in Ophir Gulch just west of the site of Greaterville.

43.7 Junction of SH 83 and Gardner Canyon Road (Forest Road (FR) 92). Turn right on Gardner Canyon Road.

44.5 Junction FR 92 and FR 163. Take FR 163 to the right and continue on FR 163 to FR 4113.

48.0 Junction FR 163 and FR 4113. Take FR 4113 to the right.

49.2 Go left at Y-intersection.

49.3 **STOP 1.** Park at locked gate and walk about 0.2 mi down the hill to Kentucky Camp, a U.S. Forest Service Stabilization Project.

KENTUCKY CAMP AND THE GREATERVILLE PLACER DISTRICT

Stop Leaders: Mary M. Farrell and Leslie J. Cox

Once the scene of a grandiose engineering scheme and optimistic activity, Kentucky Camp, a small gold mining camp in southeastern Arizona, fell into lonely abandonment for decades. But recently this camp in the Coronado National Forest (fig. 1) has come alive once more as several groups have joined with the Forest to preserve the site for the future.

More than a century ago, the Greaterville gold placers on the east slope of the Santa Rita Mountains were alive with activity. Gold had been discovered in 1874 in the Greaterville mining district, which proved to be the largest and richest placer deposit in southern Arizona. In 1875, an *Arizona Citizen* article reported that one ". . . Horace

Arden, not noted for working imprudently hard . . ." was recovering an ounce of gold a day, even though he had to pack the pay dirt to water for washing. Such success stories brought more than 200 miners to the Greaterville mining district in the 1870's. But by the end of the 1880's the Greaterville placers were "worked out," all the easily obtainable gold had been recovered, and the population began to decline. One claim named "Burro Placer" is suggestive of the major difficulty in mining the Greaterville placers—lack of water. Most gulches flowed only intermittently, and water for the placer washing was packed in on mules and burros from wells in the vicinity.

At the turn of the century, a millionaire and an engineer teamed up in an effort to solve the mining area's incessant water shortage. In 1904, a mining engineer from San Jose named James Stetson conceived a grand scheme to channel runoff from the Santa Ritas' spring snowmelt into a reservoir that would hold enough water to last ten months. With that, he could keep a mine operating. Stetson convinced George McAvery, also of San Jose, to invest in the plan, and together they formed the Santa Rita Water and Mining Company to make it work. From 1904 to 1906, the buildings at Kentucky Camp served as the headquarters for dam builders, ditch diggers, and miners. They employed 40 men in building Kentucky Camp and in constructing miles of pipeline.

In spite of optimistic reports on their preliminary work, the Santa Rita Water and Mining Company failed. Tragedy struck in 1905, the day before a meeting with stockholders, when Stetson was killed in a fall from a third-story hotel window in Tucson. McAvery died shortly thereafter. Arguments among McAvery's heirs kept the estate tied up and, although other partners tried to keep the operation going, it soon died. The buildings and land at Kentucky Camp were sold for back taxes at a sheriff's auction in 1906. An attorney bought the property, and his family used Kentucky Camp as a base for cattle ranching until the 1960's.

Thanks to the care bestowed on the buildings by the ranchers, the site was in much better condition than most turn-of-the-century mining camps in the area, with standing adobe buildings (fig. 2), pieces of the pipeline, and the hummocky landscape of placering. But decades of abandonment and weathering, vandals, and recyclers had taken their toll on the site by the time it was acquired by the Coronado National Forest, in 1989. One structure had collapsed, and leaky roofs threatened the remaining four buildings. Broken glass, rusty nails, and crumbling walls seemed to invite lawsuits as much as they did inquisitive visitors.

The buildings that remain at Kentucky Camp were built about 1904. The largest was probably used as an office by the Santa Rita Water and Mining Company (fig. 2). Later, it was the main ranch house. The iris beds at the west corner of the building probably date from its occupation as a ranch house. The small building behind was used to process the gold ore. A large barn lies in ruins opposite a small house where Stetson may have lived, and another small house lies at the far end of the site (fig. 3).

Because many of the old mining ghost towns have been completely obliterated or are inaccessible to the public, Kentucky Camp appears to offer an excellent opportunity for interpretation. As a development engendered and abandoned with the changing fortunes of a large engineering project, Kentucky Camp illustrates the crucial role water has played in mining this arid region of Arizona. Furthermore, the site is only a little more than an hour from Tucson, with most of the drive along an Arizona scenic highway.

The U.S. Forest Service (Coronado National Forest) contracted with Ryden and Associates, of Phoenix, to prepare a historic-building analysis. The basis of a site stabilization plan, the analysis describes and ranks the steps needed to preserve the buildings and to restore them for future use. The U.S. Forest Service will restore the buildings to the way they appeared in the mining era. Until Kentucky Camp is restored, you should keep certain things in mind. The buildings are old and deteriorated, so care should be taken when inside—floorboards may give way, and some ceiling boards hang low. **And please do not remove anything from Kentucky Camp**. Although they may appear old, broken, and abandoned, all the artifacts will be useful in reconstructing life in the camp.

In the spring of 1991, Passport in Time, a volunteer group, helped document architectural and archaeological features and drew room plans. With patience and care, scattered trash and fragments of lumber were transformed into clues about the doors, windows, porches, and other features that once graced the buildings. Their work aided not only in preservation efforts, but also allowed the initial cleanup of safety hazards.

The Nogales Ranger District fire crew, with an archaeologist who specializes in historic buildings, made adobe bricks to rebuild a collapsed wall, and replaced wooden beams that had been "salvaged" during Kentucky Camp's abandonment. The fire crew re-roofed the standing buildings with wooden shingles acquired through a cooperative agreement with the Young Riders film company, which shoots episodes of the television series in the vicinity.

Public interpretation requires public facilities, such as toilets and picnic tables, so an interdisciplinary team has begun an interpretive plan to guide future design and to ensure that developments do not detract from the historic setting. The interpretive plan outlines U.S. Forest Service priorities, identifies research needs and possible interfaces with other interpretive opportunities, targets audiences, and develops themes for future booklets, living history, tours, and trails. The gradual phasing in of projects will allow

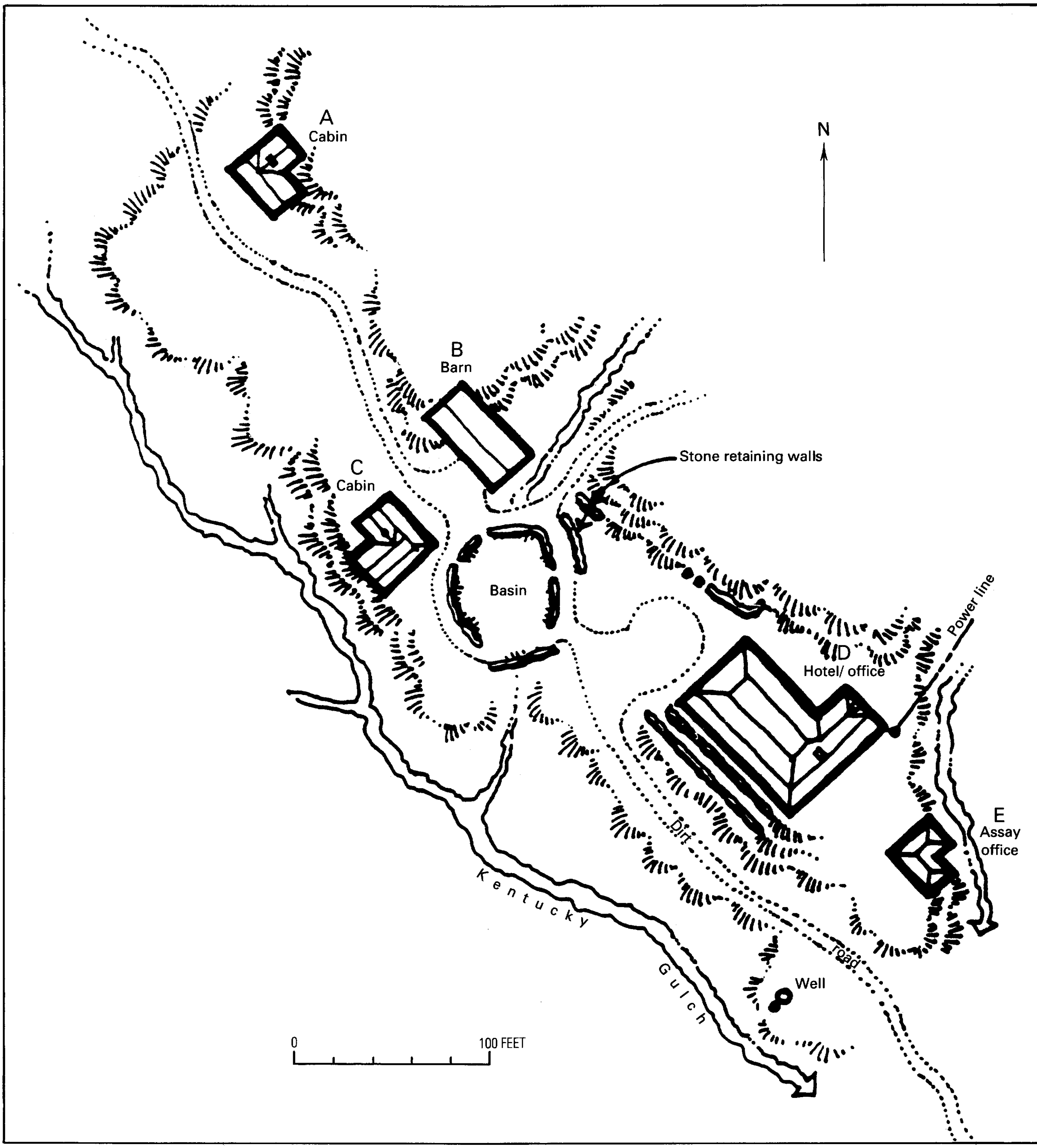


Figure 2. Site plan of Kentucky Camp, near Greaterville, Ariz. (illustration courtesy of U.S. Forest Service).

some interpretation to begin soon, while options for accomplishing long-term goals can be explored.

Tours led by the U.S. Forest Service and outreach have generated a pool of other interested volunteers, and the Nogales Ranger District is committed to pursuing the preservation of Kentucky Camp for future generations. Twenty-one volunteers donated more than 500 hrs in a Passport in Time project in June 1992, and a Friends of Kentucky Camp group is forming (1992) in order to collect donations and coordinate volunteer activities.

Figure 3. Adobe structure at Kentucky Camp, southeastern Arizona, dating from about 1904, with a reconstructed roof (building C on site plan, fig. 2). Photograph by B.B. Houser, 1993.

Return to SH 83.

54.6 Turn right (south) toward Sonoita.

58.7 Junction of SH 83 and SH 82 in Sonoita.

Turn right on SH 82 toward Patagonia. Sonoita was established in 1882 on the newly built Mexico and Arizona Railroad, which was completed through the Sonoita Creek Valley to Nogales in 1884. The old railroad grade can be seen alongside the road between Sonoita and Patagonia. The name Sonoita comes from the Tohono O'Odham word meaning "place where corn will grow" (Granger, 1960).

61.6 The site of Fort Crittenden is about 0.2 mi north of the road.

Camp (Fort) Crittenden was established March 4, 1867, on a hill overlooking the old site of Fort Buchanan. It was named for General Thomas Leonidas Crittenden, military commander for southern Arizona from 1867 to 1868. The camp was abandoned in the summer of 1872 because of unhealthy conditions, probably malaria (Granger, 1960).

62.2 The former site of Fort Buchanan is near here, about 0.1 mi north of the road (fig. 1).

In 1856, Major Enoch Steen was ordered to set up a permanent military post in Tucson to protect the settlers of southern Arizona. Steen was unimpressed with the "miserable huts" he found in Tucson and the lack of grass and grain in the area for horses, so instead he chose a site for the post (called Camp Moore) 60 mi to the south up the Santa Cruz River Valley (fig. 1). When his superiors in Santa Fe ordered him to relocate the post closer to Tucson, Steen replied that in the Sonoita Valley he was protecting miners and ranchers, whereas in Tucson he would be protecting only "whiskey peddlers." Nevertheless, another site for the post was chosen 20 mi to the northeast of Camp Moore, and construction on Fort Buchanan was begun in the summer of 1857 (although Tucson residents pointed out in a petition that the new site was even farther from Tucson than the old site had been).

Morale was low at Fort Buchanan because of poor accommodations, lack of troop rotation, Apache raids, and the prevalence of malaria that had its source in nearby swamps. Rafael Pumpelly, a mining engineer who visited the post, described it as follows (Wallace, 1965, p. 37):

> This fort . . . consisted simply of a few adobe houses, scattered in a straggling manner over a considerable area, and without even a stockade defense. The Apaches could, and frequently did, prowl about the very doors of the different houses. No officer thought of going from one house to another at night without holding himself in readiness with a cocked pistol.

The fort was burned and abandoned July 21, 1861, when the soldiers were withdrawn to help repel the Confederates on the Rio Grande (Wagoner, 1975).

71.0 Junction of SH 82 and the road to Harshaw and Lochiel at the Patagonia post office just west of Sonoita Creek. Turn left, go one block, and turn left again onto McKeown Ave.

Patagonia was established in 1898, when Rollin Rice Richardson decided to move the town of Crittenden about 3 mi south to a marshy area that he owned at the present site of Patagonia (fig. 1). Richardson, a rancher, had previously owned much of the land in the area and had bought out the squatters at old Camp Crittenden. (There must have been both a military Camp Crittenden and a town named Crittenden about 5 mi apart.) Richardson had wanted to call his town Rollin, but the residents of the new town chose the name "Patagonia" from the name of the mountains to the south. Because the petition for a post office had to be signed by the residents, Richardson had little say in the matter of the town name (Granger, 1960).

In 1909, Patagonia was an active mining center having about 200 residents. Two daily passenger and mail trains stopped there, and daily stage and mail service was maintained between Patagonia and Harshaw, Mowry, Washington Camp, and Duquesne to the south (Schrader, 1915). Nowadays, ranchers, retirees, hunters, and bird watchers provide much of the economic base for Patagonia.

We are in the Harshaw mining district, which comprises the northeastern quarter of the Patagonia Mountains and extends about 7 mi south of the town of Patagonia. The principal camps of the district were Harshaw, World's Fair, Wieland, Elevation, Standard, and Thunder. Early mines in the Harshaw district produced large amounts of high-grade lead-silver ore. The ore is usually in vein deposits in Mesozoic granitoid and silicic volcanic rocks that were intruded by younger rocks (Schrader, 1915).

Through 1972 the total estimated and recorded production of base and precious metals from the 21 mines of the district was 1.3 million tons of ore containing about 86 thousand tons of zinc, 72 thousand tons of lead, 3 thousand tons of copper, 9.2 million ounces of silver, and 4.3 thousand ounces of gold for a total value of $41.5 million (Keith, 1975).

Figure 4 shows the geology of the trip route through the Harshaw district and the Patagonia district to the south. The eastern two-thirds of the Harshaw district is underlain by lower Paleocene silicic to intermediate volcanic rocks intruded by upper Paleocene granitoid stocks at Red Mountain and Saddle Mountain, 4 mi to the east. The western one-third, which includes much of the mineralized area, is underlain by granitoid stocks and chiefly silicic volcanic rocks of Mesozoic age. A small exposure of Paleozoic carbonate rocks and limestone and conglomerate of the Lower Cretaceous Bisbee Group extends up into the southern part of the district. The north-northwest-trending Harshaw Creek fault (fig. 4) forms part of the boundary between the eastern and western terranes. Simons (1974) presented evidence that the Harshaw Creek fault has at least 4 mi of left-lateral displacement.

74.3 According to local tradition, the smaller rock on the northwest side of the large rock on the left side of the road broke off during the 1887 earthquake. The tradition further holds that the rock landed on top of an immigrant family camped at the base of the large rock, but it seems unlikely that the smaller rock would have covered all traces of the family (Robert Lenon, oral commun., 1992).

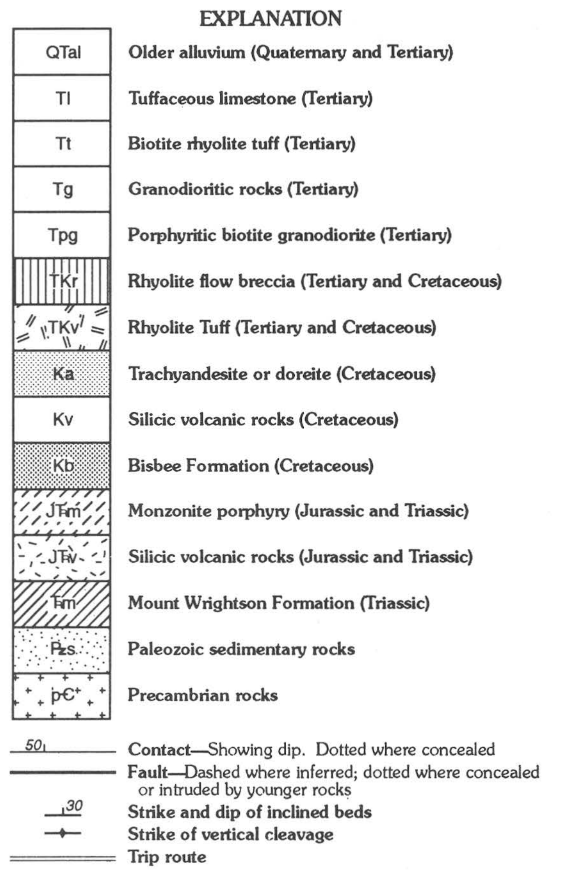
74.5 Red Mountain (elevation 6,350 ft) is to the west (fig. 4).

RED MOUNTAIN

Red Mountain overlies a porphyry copper sulfide deposit that is about 5,000 ft below the top of the mountain. This deposit was extensively explored by the Kerr-McGee Corporation from 1960 through the late 1970's. The company drilled more than 60 holes, many to depths of about 5,000 ft. They abandoned their unpatented claims in 1992, but they hold about 400 acres of patented claims above the orebody on the west side of Red Mountain (Richard Ahern, oral commun., 1993).

Rock exposed on Red Mountain consists of three Cretaceous through lower Tertiary volcanic sequences that have undergone various degrees of alteration associated with the formation of the porphyry copper deposit. The volcanic sequences dip to the east at about 15° and are cut by porphyritic granitic dikes and small intrusive bodies of Laramide age. Corn (1975) thought the thick sequence of silicic volcanic rocks and underlying porphyritic granitic intrusions might represent a caldera-type subsidence structure.

Simons (1974) described the upper sequence of volcanic rocks as white, light-gray, yellowish-gray, or pale-red, massive, very fine grained to sparsely porphyritic, silicic flow breccia and tuff. It forms most of the upper part of the mountain and is as thick as 2,400 ft. These rocks locally



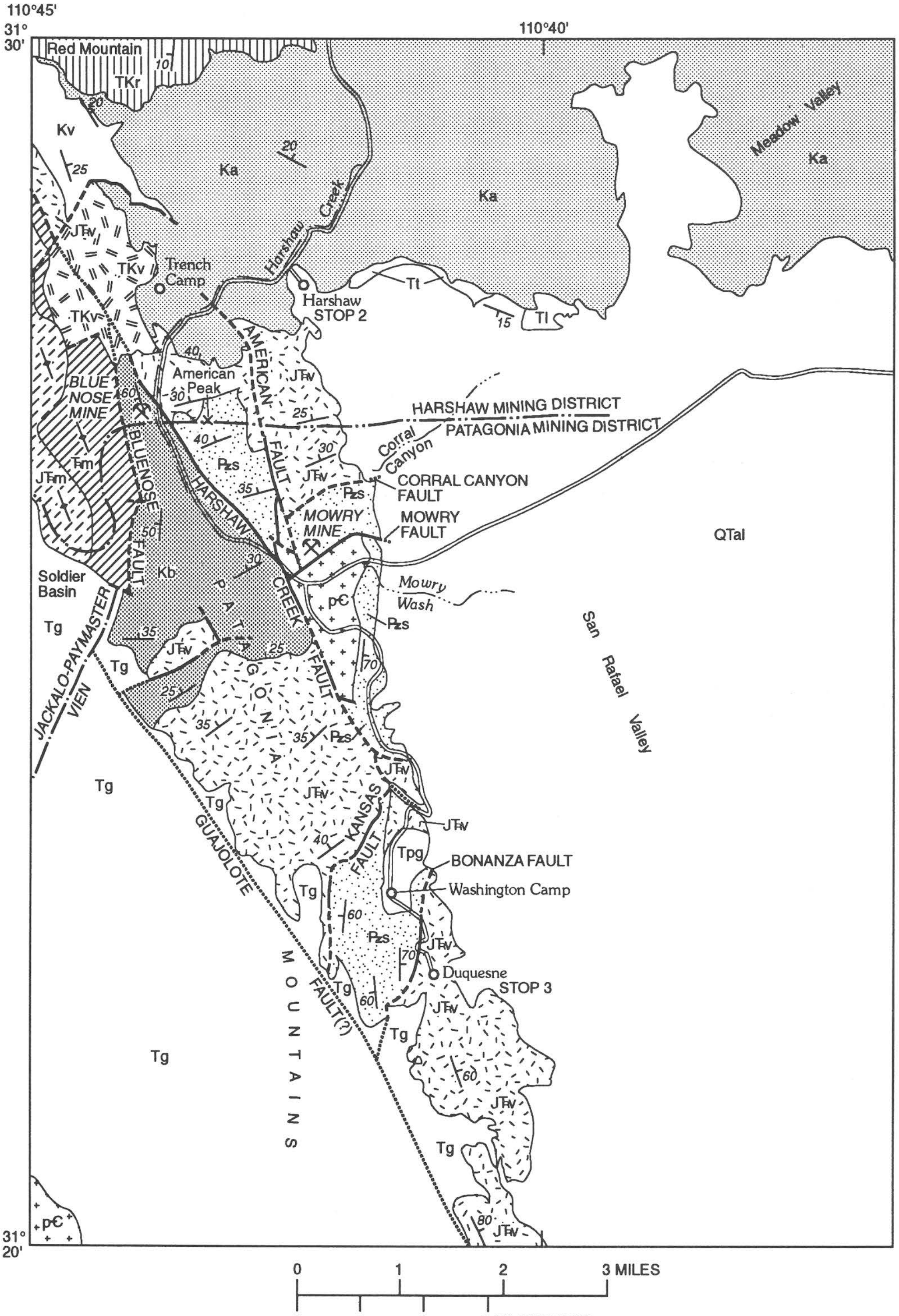


Figure 4 (above and facing page). Simplified geologic map of part of the Patagonia Mountains showing the field trip route and locations of **STOPS 2** and **3** (modified from Simons, 1974).

form cliffs, and outcrops are stained with iron oxide. Alteration to quartz, kaolinite, sericite, and limonite is common. Alteration to alunite and zunyite is locally common. Schrader (1915) reported that the tuff is profusely impregnated with pyrite, chalcopyrite, and chalcocite disseminated in crystals and grains. Drewes (1980) gave the age of the rock as Paleocene(?).

The middle volcanic sequence is andesite and trachyandesite about 3,000 ft thick that crops out on the flanks of Red Mountain. This sequence was dated at 72 Ma (Simons, 1974). Hornfels bands occur at the base (Quinlan, 1986). Rocks of the lower sequence are chiefly latitic volcanic conglomerate and breccia, and silicified tuff and flows(?) interlayered with and cut by latite sills and dikes (Quinlan, 1986). This sequence is exposed on the south side of Red Mountain in Alum Gulch. It correlates with the Upper Cretaceous silicic volcanics of Simons (1974).

Quinlan (1986, p. 294) described the silicate-alteration zoning at Red Mountain. The abstract of his paper is given below:

The Red Mountain porphyry copper deposit located in southeastern Arizona occurs within an altered complex of volcanic and intrusive rocks of Cretaceous and early Tertiary age. Silicate alteration, sulfide distribution, and assay data have been used to define the deposit.

As presently outlined, the deposit is divided into three parts: (1) a small, near-surface chalcocite blanket, (2) a near-classic, porphyry copper bulk sulfide deposit, 5,000 ft below the summit of the mountain and 3,500 ft below the chalcocite blanket, and (3) a deep-level breccia pipe in the core zone of the bulk sulfide deposit.

At least three major and distinct alteration and mineralization pulses are recognized at Red Mountain. Much of the alteration at the surface is the result of the supergene modification of a zoned and virtually copper-barren hypogene alteration system. Superimposed on the early hypogene system and recognized at depth is a smaller, more intense near-classic porphyry copper alteration zone with a partially defined copper-sulfide shell. The breccia pipe occurs within the core area of the shell and represents a later, even more restricted hydrothermal event. Silicate and sulfide zoning within the breccia pipe indicates that the pipe itself is a miniature zoned porphyry copper deposit.

The most obvious clue to the deep-level orebody at Red Mountain is the near-surface chalcocite blanket. The blanket deposit formed by secondary enrichment of copper in a low-grade halo or plume which extended upward from the deep-level deposit to the present surface, or at least 5,000 ft. Pyrite, largely from the phyllic zone of the early and virtually copper-barren alteration system, not only provided a favorable host environment in which the blanket could form, but also on oxidation, provided much of the acid needed for the secondary enrichment process.

76.7 End of pavement. Junction of Harshaw Road (FR 49) with FR 58. Take FR 49 to the right.

77.0 This was the patented mill site for the American mine. In the 1882 patent survey, the large sycamore tree by the creek on the right side of the road was surveyed in and was described as being about 3 ft in diameter. In the course of resurveying in 1972, the same tree was identified and had grown to 4 ft in diameter (Robert Lenon, oral commun., 1992).

78.9 **STOP 2**. Park along road at Harshaw town site.

HARSHAW TOWN SITE AND CEMETERY

Stop Leaders: Mary M. Farrell and John Wiens

During 1988, a cultural resources investigation that includes much of the Harshaw town site (figs. 1, 5) was undertaken by the U.S. Forest Service. The purpose of the investigation was to evaluate a small land parcel that was proposed for interchange. One of the houses on the parcel, the James Finley House (figs. 5, 7), is listed on the National Register of Historic Places. In June 1993, a botanical survey was done to inventory the exotic plants in the vicinity of the town site to see which species have survived since the town was abandoned about 20 years ago. The exotic plants are listed and their locations are keyed to the locations of the structures and cultural features shown in figure 5.

ENVIRONMENTAL AND CULTURAL BACKGROUND

The land parcel that was investigated is in Hermosa Canyon at its junction with Harshaw Creek and includes both the level canyon bottom and steep adjacent slopes. The elevation ranges from about 4,800 to 4,900 ft. Cottonwood and sycamore trees grow along the stream bed, and oak, mesquite, and juniper on the terraces and slopes. Grasses, prickly pear cactus (*Opuntia*), and small shrubs form the understory in most of the parcel; dense manzanita thickets occur on slopes in the southern part.

Prehistoric use of the area is poorly known because of the general lack of archaeological information. Prehistoric occupation of the nearby Sonoita Valley has generally been attributed to the Hohokam on the basis of investigations near Sonoita and Patagonia. Occupation of the area in early historic times by Sobaipuri groups was documented in Spanish accounts of Father Kino's time (a Jesuit missionary who worked in southeastern Arizona and northern Sonora, Mexico, from the mid-1690's until his death in 1711).

Earliest records suggest that there was a small Mexican settlement named Durazno along Harshaw Creek in the vicinity of the Harshaw town site. Durazno, which means peachtree in Spanish, reportedly refers to fruit trees planted by an early Spanish missionary. Historic use of the area has been related primarily to mining ventures. However, neither Spaniards nor Mexicans were able to develop the mining potential of the region because of Apache dominance of the area. After the Gadsden Purchase in 1853, the establishment of Fort Buchanan encouraged mining activity.

Two of the earliest claims in the Harshaw district were the Flux and the Trench, located west of Harshaw. Together these mines produced almost 85 percent of the estimated 1.3 million tons of ore yielded by the mines of the Harshaw district through 1964. These mines were allegedly worked by the Spanish and were rediscovered in 1858. However,

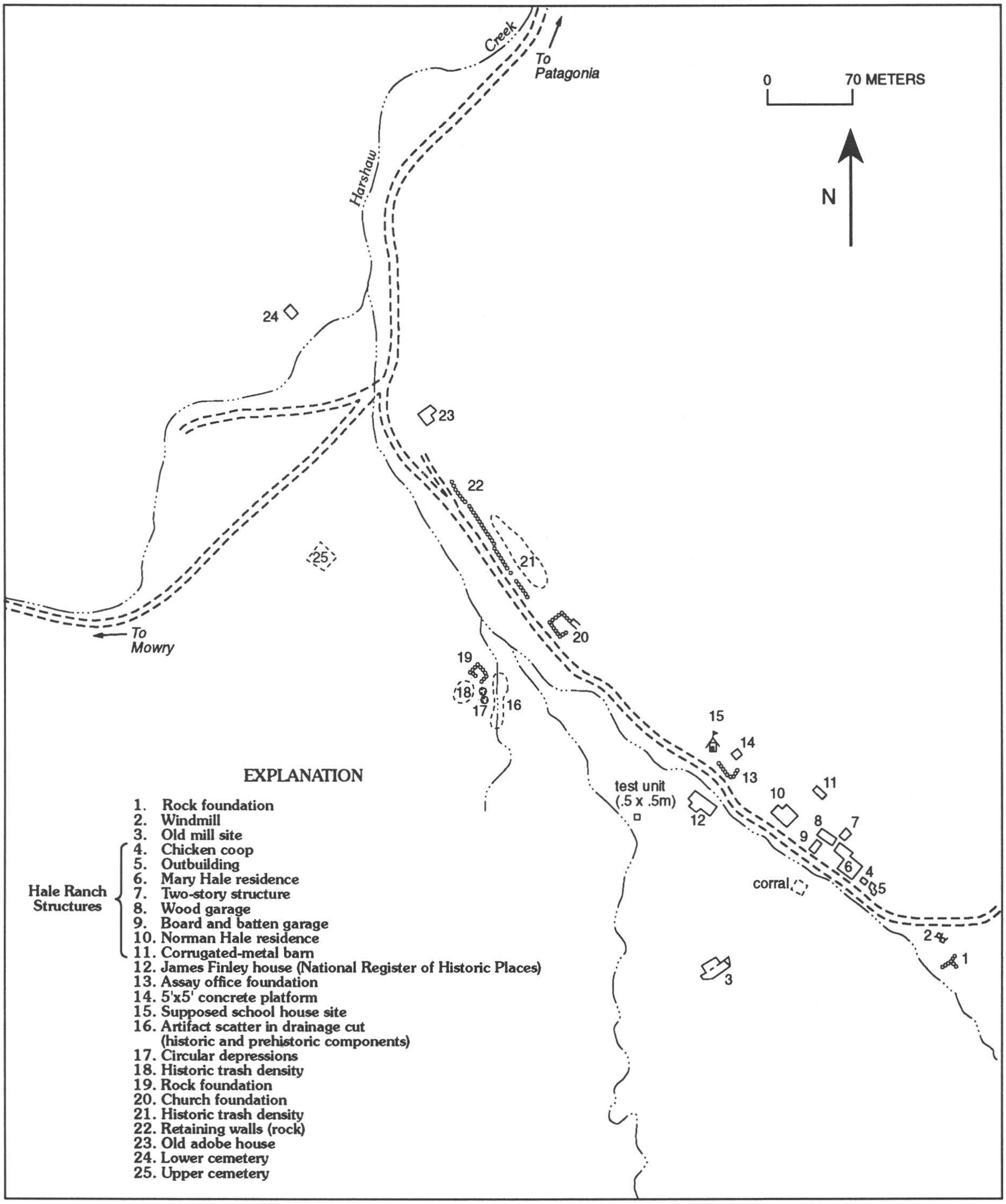


Figure 5. Site plan of Harshaw, Ariz., showing location of structures and other cultural elements. Plants listed in the botanic survey are located with reference to features on the site plan. Map by M.M. Farrell and Chris Schrager, U.S. Forest Service.

most mining activity was suspended at the onset of the Civil War (when Federal troops were withdrawn from the area) until General O.O. Howard's peace treaty with the Apache leader Cochise in 1872.

David Tecumseh Harshaw staked several silver claims in the Patagonia Mountains in the 1870's. About 1879, the Hermosa Mining Company acquired one of his properties, the Hermosa Mine. They constructed a 100-ton, 20-stamp amalgamation mill (fig. 6) and had the mine in production by October 1880. The Hermosa Mine and mill became the nucleus for the town of Harshaw. The 1880 census reported some 600 people there, including miners, laborers, merchants, and blacksmiths, with restaurants, lodging houses, saloons, and livery stables (Wilson, 1988). When the population reportedly peaked at about 2,000, the main street was 0.75 mi long (Varney, 1980). Wehrman (1965, p. 30–32) provided a summary of the nationalities and occupations represented in the population, and the *Arizona Daily Citizen* ran an article in 1880 describing several of the businesses of the town.

The mine closed in late 1881, and a few months later the mill stopped operations. The mill was sold in 1885 and was dismantled and moved to the western part of Pima County (Wehrman, 1965, p. 33–35). In 1890 James Finley of Tucson reopened the Hermosa Mine, installed a small mill, and carried on operations until the price of silver dropped in 1893. All work stopped in 1903 following the death of Mr. Finley and a further decline in the market value of silver. The Harshaw post office was discontinued in 1903 (Wilson, 1988).

In addition to the Hermosa Mine, the Harshaw district included numerous other mines that operated into the 1970's (Wilson, 1988, p. 254). The district reached its peak as a major metal producer between 1930 and 1970, zinc, silver, lead, and gold being the major metals (Wilson, 1988, p. 256–257). By 1939, the American Smelting and Refining Company (ASARCO) had gained control of the Trench, Flux, and other mining properties in the district and constructed a 200-ton/day flotation mill at Trench Camp, located about 1 mi west of Harshaw (fig. 4). Production increased to 50,000–60,000 tons/year of zinc, lead, and copper ore having high silver values (Keith, 1975, p. 12–13).

According to Norman Hale (one of the current residents of the Harshaw town site), this renewed activity at nearby mines once again inspired settlement at Harshaw and several new buildings were constructed, including a church and a school. By the late 1950's, however, the major deposits were becoming depleted of ore and the total output of the district had declined. Since 1965 there has been little or no production (Keith, 1975). In the 1960's the U.S. Forest Service began to remove buildings from the area. Some inhabitants remained at Harshaw. The nomination of the Finley House for the National Register of Historic Places, prepared in 1974, notes that at that time the town had "about 70 inhabitants, many of whom are on welfare." Most of the buildings were removed by the owners or the U.S. Forest Service by the mid-1970's. Usable building material was taken for reuse elsewhere, foundations were bulldozed, and trash was carried out.

Figure 6. Hermosa mill in Harshaw, Ariz., taken about 1880 (photograph reproduced courtesy of the Arizona Historical Society, Tucson, Ariz.; accession number 28130).

CULTURAL SURVEY

The survey of the site consisted of traverses at 10- to 15-m intervals in level areas having a slope less then 25 percent. Steeper areas were surveyed with traverses at 20- to 25-m intervals. Dense brush restricted access in small parts of the survey area; however, ground visibility was good in most of the area. Some of the cultural features identified in this survey are described below; the numbers refer to their locations shown in figure 5. The cultural features were designated U.S. Forest Service site AR03–05–03–133.

3. Hermosa mill site. The mill site is within an amphitheater excavated into a ridge. Three rock walls are built stair-step fashion against the ridge to form part of the millworks foundation. The largest wall is at least 30 ft wide and 10 ft high. Parts of a stamp and unidentified round metal discs are eroding from the slope adjacent to the walls. A graded road or trail leads from the valley bottom to the site and up to the ridge behind the walls. Much of this trail has been eroded. To the north there are two flat areas apparently formed from the excavated fill, with a few fragments of broken glass, wire, and wire nails. The Arizona Archaeological and Historical Society archives contain photographs of the mill during construction (1879) and when completed (fig. 6).
6. Mary Hale residence. Plastered adobe walls, hip roof. Two additions, one gabeled, one shed-roofed, both board and batten with poured concrete foundations. Screened shed porch on three sides of house and on one side of gable addition.
7. Small two-story structure. First story is constructed of dressed fieldstone and mortar. Wooden plates at the top of the first story appear to have carried

original roof. Upper story is adobe; gable roof is tin. Door and window are framed in wood.

10. Norman Hale residence, constructed of plastered adobe brick. The gable roof is covered with corrugated sheet metal. There is a wood frame shed porch on the southwest side of the building and a concrete retaining wall in front. The yard is fenced. Although modified through the years, parts of the structure date to the 1880's (Norman Hale, oral commun., 1988).
12. James Finley House (AR03–05–03–07) (fig. 7). The property was listed on the National Register of Historic Places of 1974 because of its architectural and historical significance relating to late nineteenth century mining in the Patagonia Mountains near Harshaw.
13. Rock alignment, approximately 3 ft long. According to Norman Hale, this was the location of an assay office. No artifacts in vicinity.
15. According to Norman Hale, this is the site of a two-room schoolhouse built in the 1940's. The frame structure was removed in the 1960's, and the cement slab foundation covered over. No other artifacts or features were observed in the vicinity.
20. Location of Catholic Church built in the 1940's. The church was a simple, but attractive building; a photograph of it appears in "Ghosts and Ghost Towns" (Way, 1966). The Hale family has a photograph of the church showing (where the stucco had chipped away) that it was constructed of cut blocks of volcanic tuff. The tuff was probably quarried a mile or two to the east from exposures of thick-bedded biotite rhyolite pumice lapilli tuff. The tuff and associated tuffaceous lacustrine and fluvial sedimentary rocks were mapped by Simons (1974), who reported K-Ar ages on biotite and hornblende ranging from 23 to 26 Ma. Minimal foundation remains and a leveled area suggest the building was approximately 45 ft on a side. A small concrete foundation along the east side of the terrace at a cut in the hillside may have been for a small addition or outbuilding.

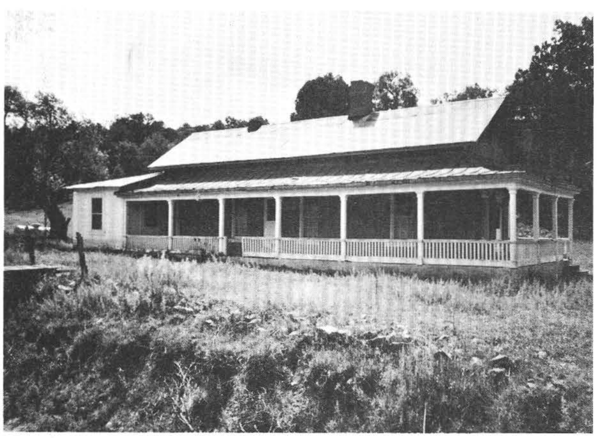


Figure 7. The James Finley House, Harshaw, Ariz. This house is on the National Register of Historic Places. Photograph by F.N. Houser, 1993.

23. Standing adobe brick structure, depicted in "Arizona's Best Ghost Towns" (Varney, 1980). The original one-room adobe building measures approximately 17×25 ft. Additions have been constructed of adobe, wood, and concrete block. There is a rock-lined well near the northwest corner. The building was vandalized recently: the well pump was stolen and part of the northeast wall was pushed in. The building is owned by Norman Hale and straddles the boundary between his private land and the public land administered by the U.S. Forest Service.
24. Cemetery, predominantly Mexican-American. There are some good examples of wrought iron crosses in this cemetery.
25. Cemetery, commonly referred to as the "American cemetery" to distinguish it from the chiefly Mexican-American cemetery north of the town across the road. Headstones date to 1880, 1898, 1911, 1922, 1930, and 1964. In addition, there are at least ten graves marked only by piles of rock. Some of the graves are fenced. One of the graves is that of Norman Hale's grandfather, Richard Farrell.

BOTANIC SURVEY OF HARSHAW TOWN SITE

In looking at abandoned or nearly abandoned mining communities, we see that structures and mine workings are not the only evidence of human activity that persists. People in mining camps, as elsewhere, tend to use vegetation around their homes both in a functional way (edible plants), and aesthetically (ornamental species). Many of these plants have persisted or have become established and spread, and are now viewed as permanent, exotic members of Arizona's flora.

Harshaw is in the biotic community of Madrean Evergreen (oak) Woodland bordering on Semidesert Grassland, well represented at Sonoita (Brown, 1982). A variety of oak species, junipers, mesquite, and manzanita shade the grass-covered hills. Annual precipitation is 17.46 in., according to records kept at nearby Patagonia (Sellers and Hill, 1974). About 60 percent of the precipitation falls as rain during the mild summers and 40 percent as rain and not infrequent snow during the winters, which can be cold from time to time. The winter cold, along with a seasonal dry spell from mid-April through late June, is a barrier to the escape and establishment of some ornamental plants.

In preface to discussing persistent and established ornamental plants that are present at some former mining communities and not at others, mention needs to be made of species involved, climate, and duration of habitation of the site. For example, finding salt cedar (*Tamarix ramosissima*) in Harshaw might be considered unremarkable because it has become an aggressive exotic species in drainages and riparian situations in much of Arizona. However, salt cedar's preferred habitats are at lower elevations, and its occurrence at Harshaw represents its limits for high elevation and winter cold. The same species is well established at the former Arizona mining town of Silver Bell, in northwest Pima County (Wiens, 1991). Abandoned in 1984, the Silver Bell site is lower (1,700 ft) and has much milder winters than Harshaw.

The plant list indicates that there are a number of exotic plants at the old adobe house (23), but that many of them are not doing very well compared to plants of the same species at other parts of Harshaw town site, particularly those closer to the wash. The advantage of proximity to the wash is obvious. A second factor affecting the health of the plants at the old adobe house is that the structure has been abandoned for about 40 years (Nancy Hale, oral commun., 1993), and, thus, the plants have had no care for that length of time. The Finley House has been unoccupied for only about 15 years.

Of the species of exotic (non-native) plants persisting or becoming established in Arizona, many were introduced not as ornamentals but as soil binders, as fodder, or as accidental byproducts of human activity. Of the non-natives in and around the Harshaw site, many fall into the latter of these categories and are noxious weeds. For example, Bermuda grass (*Cynadon dactylon*), originally from Africa and currently used ornamentally, was probably accidentally introduced through cattle ranching and thrives in Harshaw along the stream banks. Plants in this category do not appear on the plant list.

The following are exotic plants observed around the town site, excluding the yard of the currently occupied Norman Hale residence (10). The plant locations are keyed to the numbered structures and cultural features shown on figure 5. Unless otherwise noted, plants seem to be original plantings and are not spreading.

Tree of heaven (*Ailanthus altissima*)—Most abundant of escaped exotics, clumps of this suckering tree can be seen throughout the town site, as well as downstream. This tree is native to China and has been widely planted in urban areas because of its adaptability and resistance to pollution.

Hollyhock (*Alcea rosea*)—One plant in fair condition on the south side of the Finley House (12).

Yellow bird-of-paradise (*Caesalpinia gilliesii*)—Though not seen in the town site, it is abundant along the road just south of the intersection next to the old adobe house (23). It is reproducing by seed.

Trumpet creeper (*Campanis radicans*)—A group of three sprouts doing poorly in the yard of the old adobe house (23). This is a woody vine native to the Eastern United States.

Locust (*Gleditsia triacanthos*)—Suckering trees wickedly armed with thorns, scattered along drainages northwest of the Finley House. Possibly reproducing by seed.

Apple (*Malus* sp.)—Six trees: three trees doing fair to poorly, at a structure foundation on the side drainage just northwest of the test unit; two large trees doing very well along the main drainage across the road from the historic trash density (21); and one tree doing poorly in the yard of the old adobe house (23).

Chinaberry (*Melia azedarach*)—One medium-sized tree growing across the road from the rock retaining walls (22). This Asian native is an aggressive weed-tree in many situations. Perhaps the cold winters prevent this species from spreading here.

Black mulberry (*Morus nigra*)—Six trees: three doing poorly in the yard of the old adobe house (23); one doing poorly at the base of the east-facing slope below the cemetery (25); and two doing very well indeed along the road across from the retaining walls (22).

Mountain cottonwood (*Populus monticola*)—Two robust trees by the corral across the road from the Mary Hale residence (6). They were brought as cuttings from Santa Cruz, Sonora, Mexico, 25–30 years ago by Nancy Hale's uncle (Nancy Hale, oral commun., 1993). The trees are about 40 ft tall and have trunks 30 in. in diameter.

Peach (*Prunus persica*)—One plant barely hanging on in the yard of the old adobe house (23). A plant across the road from the Mary Hale residence (6) appears to be a recent planting.

Apricot (*Prunus* sp.)—Six trees: two doing fair in the meadow across the road from the Hale residence (10); one doing very well near the drainage across the road from the supposed schoolhouse site (15); one in good condition next to the foundation of a structure just northwest of the test unit; one in fair condition where the drainages converge across the road from the church foundation (20); and one doing well at the south end of the rock retaining walls (22).

Pomegranate (*Punica granatum*)—One plant in poor condition, just northwest of the test unit in a grove of trees that surrounds the rock foundation of a structure not designated on the map. Pomegranate is a semitropical tree or shrub native to Asia.

Pear (*Pyrus* sp.)—Five trees: three in fair condition in the meadow across the road from the Mary Hale residence (6); and two large trees in good health just northwest of the Finley House (12).

Rose (*Rosa* sp.)—A depauperate plant in the yard of the adobe house (23) and a beautiful specimen by the wash across the road from the retaining walls (22) near the huge mulberry tree. This second plant was probably planted, not escaped.

Bouncing Bet (*Saponaria officinalis*)—Shrubs growing on the south side of the Finley House (12) and minimally escaping into the adjacent wash. This European/Asian native was grown for medicinal- and soap-producing aspects. All previously known collections of this plant naturalizing in Arizona have been from the northern third of the state.

Salt Cedar (*Tamarix ramosissima*)—One small tree in poor condition under the canopy of the huge mulberry tree across the road from the retaining walls (22). Although the seeds are wind-blown, this tree could have been planted as an ornamental.

Elm (*Ulmus* sp.)—Three small- to medium-sized trees, in fair condition, in the yard of the old adobe house (23).

Return to cars and continue south on Harshaw Road.

79.7 The adobe ruin on the left was the Hardshell store (Robert Lenon, oral commun., 1992). Ore was discovered in Hardshell Gulch in 1879 by Jose Andrade and David Harshaw, and the claim was bought in 1880 by Rollin R. Richardson (Granger, 1960).

Flux Canyon Road (FR 812), on the right, goes to the Trench and World's Fair Mines (fig. 4). The Trench Mine is one of the oldest mines in Arizona, dating back to the Spanish era, and was the site of Asarco's 200-ton/day flotation mill. The mill was closed around 1956, and ASARCO is currently undertaking remediation work at the site.

Of the 40 or so mines in the vicinity of Harshaw, the Flux, Trench, Hardshell, World's Fair, and Hermosa were among the most important. On the basis of the descriptions of the mineralization at these mines given in Schrader (1915) and Tenney (1929), we know the ore deposits were chiefly lead-silver vein deposits associated (1) with a brecciated shear zone in rhyolite and limestone in the case of the Flux Mine, (2) with a fissure vein in diorite intruded by rhyolite at the Trench Mine, (3) with the contact between diorite and intrusive rhyolite at the World's Fair Mine, (4) with a shear zone in rhyolite and interbedded quartzite at the Hardshell Mine, and (5) with a shear or fault breccia zone in an altered, brecciated rhyolite at the Hermosa Mine. Simons' geologic map (1974) shows that these mines are at the southwest edge of a Laramide volcanic pile consisting chiefly of trachyandesite to rhyolite flows (fig. 4). Simons did not recognize any diorite, so the rock termed diorite by Schrader (1915) may be trachyandesite. The outcrop pattern of the rocks shown by Simons, along with mapped faults and the proximity to the northwest-trending Harshaw Creek fault, suggests that the mines are in a northwest-trending shear zone 1–2 mi wide. Of the 20 mines in this area described by Schrader (1915), the mineralized veins trend generally northwest in 13 of them. At Red Mountain to the north, the volcanic pile is underlain by a granitic intrusion capped by a porphyry copper deposit (Quinlan, 1986). It is possible that the mineralization in the vicinity of Harshaw also was related to hydrothermal systems associated with the granitic intrusion beneath Red Mountain, the northwest-trending shear zone acting as the plumbing system for the upward movement of fluids.

80.5 Contact between Cretaceous trachyandesite to the north and Triassic or Jurassic silicic volcanics to the south (fig. 4).

Lipman and Hagstrum (1992) suggested that part of the thick pile of Triassic or Jurassic silicic volcanic rocks in the Patagonia Mountains may be caldera fill on the basis of Simons' (1972) description of these rocks. Simons described sections of rhyolite, tuff, and welded tuff several thousand feet thick that contain blocks of sandstone, quartzite, and Paleozoic limestone breccia as much as 0.5 mi long. Lipman and Hagstrum (1992) thought that the tuff and exotic blocks of rock might be caldera-fill megabreccia. The larger blocks are shown on Simons' map (1974).

80.9 Contact between silicic volcanic rocks on the north and a large block of brecciated Paleozoic limestone on the south.

The approximate contact can be traced up the hill to the east for about 0.4 mi, but is nowhere exposed. The lack of exposure of the tuff-limestone contact may indicate that the tuff is not welded adjacent to the limestone. This tends to support the possibility that the limestone block is part of a caldera-fill megabreccia because the megabreccia blocks that collapse into intra-caldera tuff are cold and, thus, prevent the adjacent tuff from welding (Kenneth Hon, U.S. Geological Survey, oral commun., 1992).

81.0 Southern contact of the brecciated limestone block and silicic volcanics.

81.1 We are now in the Patagonia mining district, which takes in the southern part of the Patagonia

Mountains south to the international border (see Schrader, 1915, and Tenney, 1929, for descriptions of the Patagonia district).

Schrader (1915) reported that in 1909 Mowry, Washington Camp, and Duquesne were good-sized settlements in the district, having telephone lines and with daily stage and mail service. Both Mowry and Washington Camp had concentrating mills and smelters. Post offices had been established at Mowry, Lochiel (La Noria), Washington Camp, Duquesne, and Luttrell (Granger, 1960).

The field trip route is through the eastern part of the Patagonia district (fig. 4). The rocks here consist of an eastern belt that includes exposures of Precambrian crystalline rocks overlain by Cambrian sedimentary rocks south of the Mowry mine; Paleozoic carbonate and clastic rocks; Triassic or Jurassic silicic igneous rocks including plugs, dikes, and volcanic rocks; and the Lower Cretaceous Bisbee Formation. The Harshaw Creek fault cuts diagonally through the eastern belt.

The western belt is a large intrusive body of biotite-hornblende granodiorite composition dated at 58 Ma (Simons, 1974; Drewes, 1980). A small stock of porphyritic biotite granodiorite in the vicinity of Washington Camp probably was emplaced at the same time.

The mineral deposits of the Patagonia district are mostly silver and lead with some copper and occur as veins and as contact metamorphic deposits. Some of the mineral deposits are spatially and probably genetically related to the granodiorite intrusions. Others, however, farther removed from the Tertiary intrusive contacts, may be genetically related to the volcanism and hydrothermal systems associated with the proposed Triassic or Jurassic caldera.

81.2 Cross Harshaw Creek fault (fig. 4).

We will be traveling over exposures of the Bisbee Formation for the next 1.9 mi. Simons (1972) described the Bisbee here as siltstone and mudstone with intercalations of limestone, sandstone, epiclastic volcanic sandstone and siltstone, and conglomerate. He estimated that the total thickness is more than 3,000 ft and noted that the Bisbee in the Patagonia Mountains contains considerably more volcanic material than elsewhere, chiefly in the form of reworked volcanic ash in the matrix of the clastic rocks.

We are familiar with tales of the violence and murder that were apparently commonplace in the early days of mining camps. This antisocial behavior has had a veil of romanticism thrown over it by the distance of time and by the Hollywood renditions of some of these Old West tales. An act of violence that took place near here in the waning days of a mining camp seems prosaic by comparison. A German named Herman Bender who owned a store nearby was murdered around 1942 by his two companions as they were returning from an evening of drinking. The murderers threw his body down the shaft of the Blue Nose Mine about a quarter of a mile up the hill to the right (Robert Lenon, oral commun., 1992).

82.4 The Morning Glory Mine, which is about 0.5 mi up the small valley on the right, produced high-sulfide silver-copper-zinc ore.

During the rainy season, sulfate-rich water from the Morning Glory Mine flows down the valley and mixes with the stream on the left side of the road, which drains carbonate bedrock on American Peak to the east (the headwaters of Harshaw Creek). At the confluence of the two streams, a soapy gray-white precipitate forms and white froth is rafted along the stream surface (Robert Lenon, oral commun., 1992). X-ray diffraction analysis confirms Lenon's suggestion that the precipitate and froth are gypsum.

83.1 Guajolote (turkey) Flat Road to the right. The flat was named for the Guajolote Mine, located in the 1860's. Continue straight on the Harshaw and Lochiel Road.

83.8 Mowry Road (FR 214) on the left.

84.5 On the right, between the road and the wash, was the site of the smelter for the Mowry mine and of a village named Commission. Fifteen houses were reported to be here in 1864 (Granger, 1960), and Allison's store was here in about 1886 (Robert Lenon, written commun., 1992).

84.8 Along the creek on the left side of the road is a small-scale placer mining area. There is enough water in the creek at times for panning. Schrader (1915) said of this area, "The production is small, as the deposits are worked only when in need of money. The average earnings are about 75 cents a day for each man . . . The deposits at this place seem to be about five feet thick. The known production in 1909 was two ounces of gold. In 1906, when, after the closing of the Mowry Mine, many unemployed men were in the country, the production was about $200." Butler (1937) reported that in the summer of 1933, when water was scarce, five men were carrying on rocking operations and earning less than 50 cents a day. (Recalculated at a gold price of $350 per oz, this is about $9 a day—still not very good wages.) One 2-oz nugget and several smaller nuggets had been found, but most gold was small angular particles.

86.3 View of San Rafael Valley.

The Santa Cruz River has its headwaters in this valley, flows south into Mexico, then turns back north and reenters Arizona east of Nogales (fig. 1). On the west side of the road about 1.5 mi north of the International Border there is a monument to Fray Marcos de Niza, constructed by the Civilian Conservation Corps in 1939. The inscription reads, "By this valley of San Rafael Fray Marcos de Niza, vice-commissary of the Franciscan order and delegate of the Viceroy in Mexico, entered Arizona, the first European west of the Rockies, April 12, 1539."

87.5 The mountain to the right topped by the light-gray marble outcrop was given the name "El Caloso" in the Spanish land grant surveys of the San Rafael Valley prior to 1830 (Robert Lenon, oral commun., 1992). Now it is called Lime Peak.

87.7 Junction with road to Nogales. Continue straight on FR 61.

88.1 Site of Washington Camp (fig. 4).

WASHINGTON CAMP

In 1889 George Westinghouse of the Westinghouse Electric Company came into the area and began acquiring properties, developing mines, and building various processing facilities. In 1910 the Duquesne Mining and Reduction Company, which was organized by Westinghouse, built housing and a reduction plant at Washington Camp (fig. 8). Earlier, this had been the site of the plant and mill of the Pride of the West Mining and Smelting Company. The company headquarters was 1 mi to the south at Duquesne, near the Bonanza Mine. Each town had a population of about 1,000. Both places have been ghost towns since the 1950's, but there was a store here as late as the early 1950's. The green stucco house on the left was the site of the Wonder Bar until about 1980 (Mara Grodzicki, local resident, oral commun. 1992).

The present residents of Washington Camp number about 20, and a large percentage of them are retirees. One resident, Refugio Granillo, who was born in Washington Camp in 1913, claims to have worked in every mine in the Washington-Duquesne area (there are about 20). The Majalca family lives on the west side of the road; Manuel Majalca was foreman at the Indiana Mine in 1973 during the Simplot-Rosario exploration program.

Not all of the residents of Washington Camp, however, have been sympathetic to the needs of mining. Under the headline "Armed Woman Keeps Miners From Work" the *Arizona Daily Star* reported the following story on September 9, 1969:

> Mining explorations by J. R. Simplot Co. were halted yesterday by a woman determined to keep unauthorized people and cattle off her property (at Washington Camp) 18 miles south of Patagonia.
>
> Mrs. Rose Bagley smilingly greeted all miners who tried to use the road across her property with, 'Sorry, no mining today, fellow.' Her gentle persuasiveness was reinforced by the presence of a black dog and a double-barreled shotgun at her side as she reclined on a chaise lounge a few feet from her gate.
>
> She is under court order to keep the road open to all bona fide employees, but yesterday she turned away 15 men when they could not prove they were employed by J.R. Simplot Co., which is conducting mining explorations around her property.

88.4 Take the Duquesne Road (FR 128) to the right.

As you drive up the hill, the A-frame house that can be seen in the valley on the left is near the site of the former Washington school.

88.9 Bonanza Mine on the right (fig. 9).

The adobe structure was a power house. Ore was taken from the mine to the Washington Camp smelter by a 3,000-ft aerial tramway. Ore was dumped from the ore buckets into large chutes, then fed into the smelter. The old power house was used for core storage during the Simplot and Rosario exploration program in the late 1960's and early 1970's.

Note the extent of the deforestation at Washington Camp–Duquesne in the early 1900's, shown in figures 8 and 9. The trees were cut probably both for mine timbers and for charcoal. The recovery of the oak-juniper forest in the past 70 years is remarkable and encouraging.

89.1 **STOP 3.** Duquesne town site (fig. 1). Park along the side of the road.

DUQUESNE TOWN SITE

Stop Leaders: James A. Briscoe and Brenda B. Houser

Duquesne was the company headquarters of the Duquesne Mining and Reduction Company (fig. 10). The white frame building off the road on the right was built for George Westinghouse. There is still a little bit of periwinkle (*Vinca minor*) growing along the foundation on the north side of the house. Some or all of the buildings at Duquesne were reported to have had electricity and indoor plumbing. Some of the adobe buildings on the left may have been used as offices during exploration drilling in the 1960's and 1970's. The green frame building on the right was a boarding house (fig. 11).

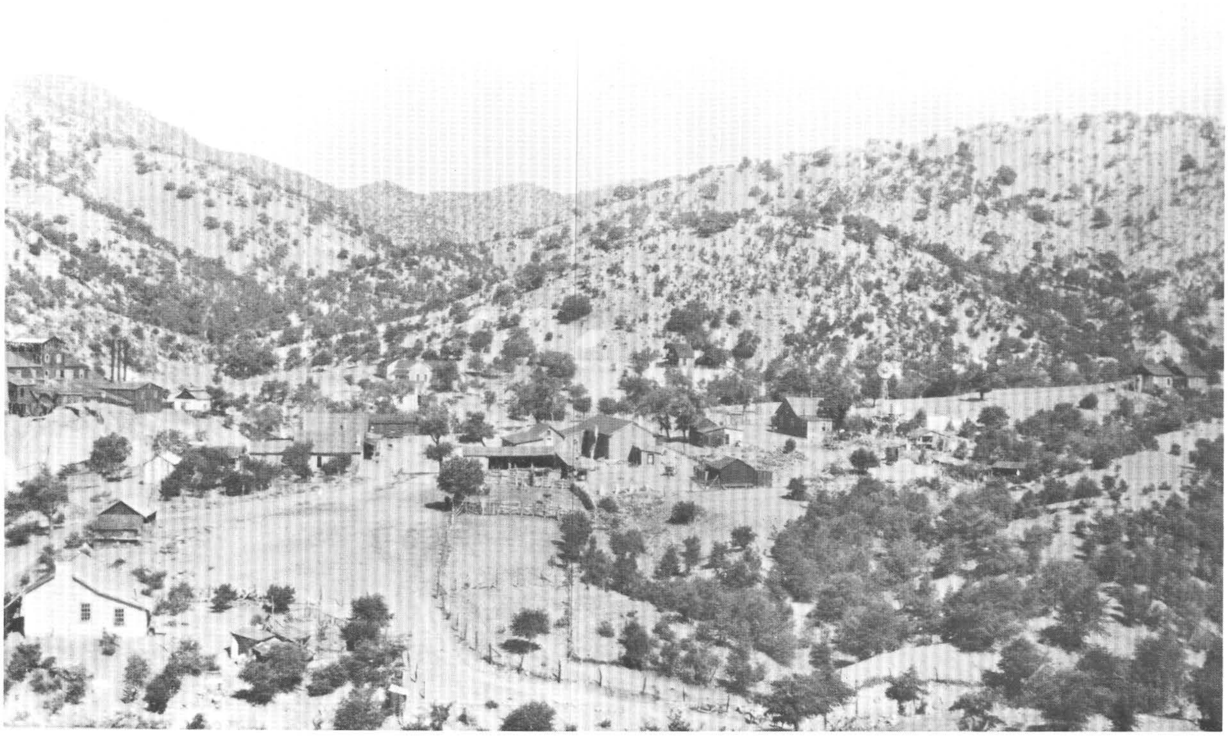


Figure 8. Washington Camp and the Duquesne reduction plant on Washington Gulch, looking west. Pride of the West Mine is to the left, outside the view of the photograph. Photograph from Schrader (1915, pl. 20).

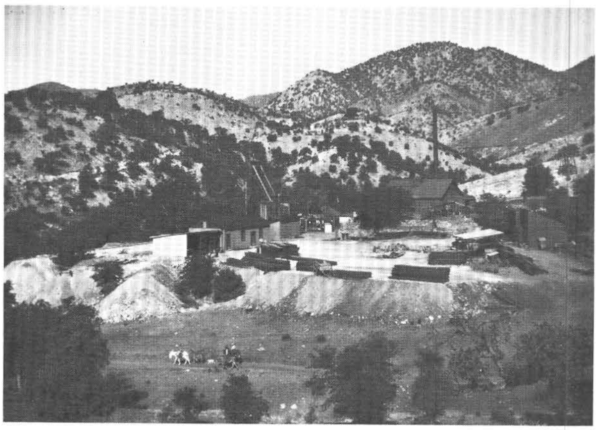


Figure 9. The Bonanza Mine, looking southwest. Photograph from Schrader (1915, pl. 25).

Lehman (1978) did a detailed study of the ore deposits of the Washington Camp–Duquesne area. The following brief description of the geology and mineralization of the area is modified from Simons (1974). An elongate northwest-trending body of biotite-hornblende granodiorite (fig. 4) was emplaced in early Tertiary time in the southern Patagonia Mountains. The southernmost 7 mi or so of the northeast contact is believed to mark the approximate former trace of the Guajolote fault. A related small stock of porphyritic biotite granodiorite (fig. 4) was emplaced in the Washington Camp area. Along the northeast contact of the biotite-hornblende granodiorite, Mesozoic volcanic and sedimentary rocks were hornfelsed and Paleozoic carbonate rocks converted to garnetite, tactite, and marble. Mineralization at Washington Camp and Duquesne is spatially and probably genetically related to the granodiorite bodies.

The Spanish had worked the mineralized deposits of this area for silver prior to the Mexican War of Independence in 1828, but there was virtually no more activity until after 1872, when the first peace was made with the Apaches. Between 1872 and 1879 about five mines were located and worked in what was to become Washington Camp–Duquesne. In 1881 just east of Washington Camp, James Finley (of the Finley House in Harshaw) built a small furnace to process lead-silver ore from a mine that had been developed by W.C. Davis during this period. The furnace was operated intermittently for a year (Tenney, 1929); a small amount of slag on a hilltop in the Pocahontas claim probably marks the site of the furnace.

The first mining camp in the area was named "Luttrell" after a promoter who styled himself the Hon.

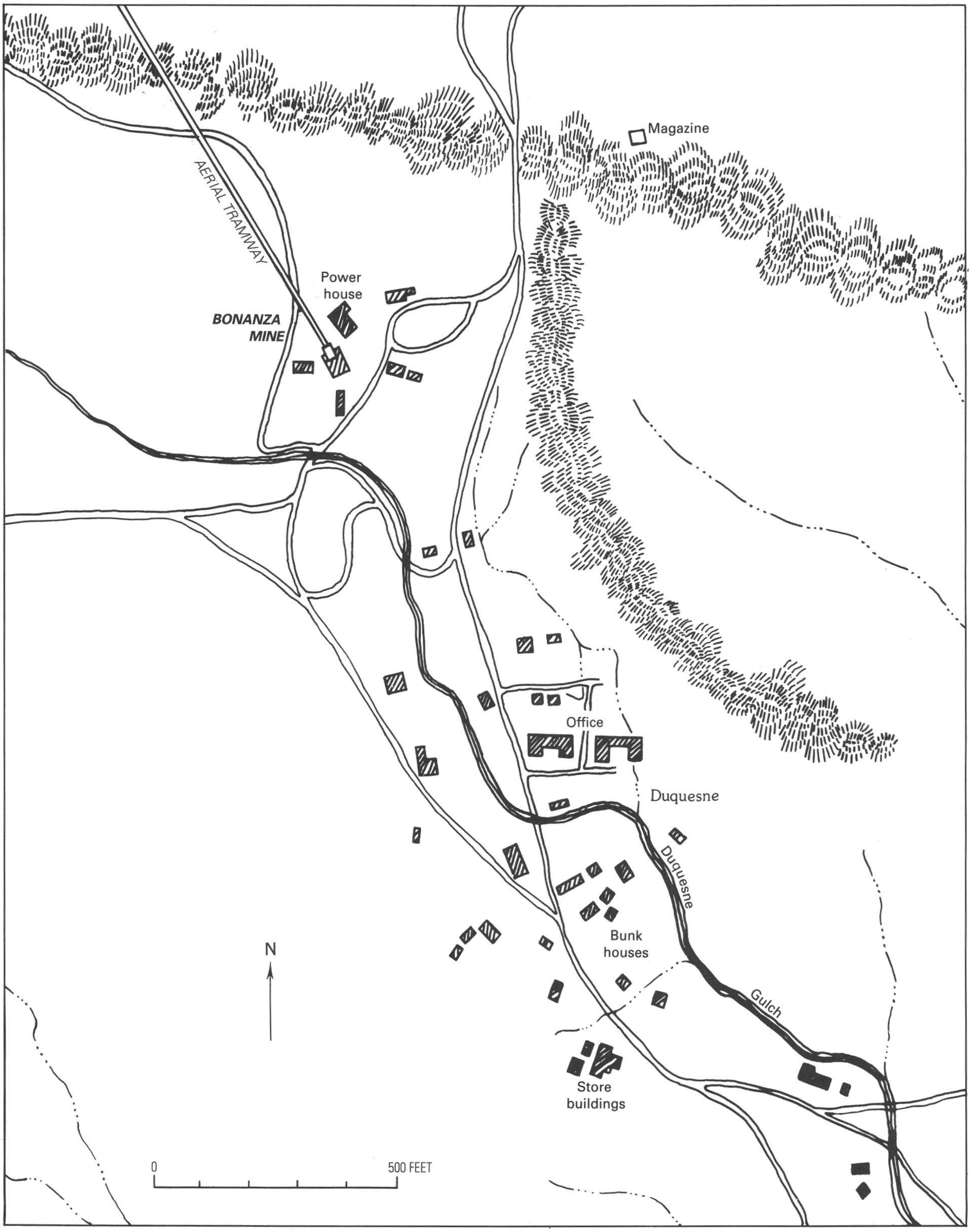


Figure 10. Map showing the location of the office, bunk houses, and stores at Duquesne around 1910 (modified from a claim map of the Duquesne Mining and Reduction Company).

Figure 11. The boarding house at Duquesne. Photograph by B.B. Houser, 1993.

H.J. Luttrell. In 1879 Luttrell organized the Holland Smelting and Mining Company, bought the Holland Mine, and built a smelter south of the mine. Luttrell had a population of 180 by the 1880 census (Granger, 1960), but by 1881 the venture had collapsed financially (Tenney, 1929).

The mines in the area continued to be worked throughout the decade of the eighties, and the Holland smelter was reconditioned and run for a short time. There were two problems, however: (1) the district was 17 mi from the rail head at Crittenden, and (2) in most of the deposits the rich oxide ore changed at shallow depths to massive copper-lead-zinc sulfides associated with garnet and silica.

George Westinghouse recognized the potential of the deposits for copper and in 1889 began acquiring mines in the district, although little was done in the district until the price of copper went up in the late 1890's. In 1899 C.R. Wilfley organized the Pride of the West Mining and Smelting Company and, at the present site of Washington Camp, installed an array of mechanical and magnetic concentrators, a roaster, Wilfley separators, and a reverberatory furnace to deal with the complex sulfide ore. The Pride of the West Mine was closed at the end of 1902 because the ore changed from a high copper to a high zinc content (Tenney, 1929).

Westinghouse bought the Pride of the West Mine in 1906 (along with the Holland, Belmont, and Washington Pool claims) and used the Pride mill and plant to experiment with the ore from the Bonanza Mine. Following 4 years of experimentation, Westinghouse reorganized as the Duquesne Mining and Reduction Company and got ready to go into production. The Bonanza Mine was developed to a depth of 650 ft and connected to the mill at Washington Camp by a 3,000-ft aerial tramway. Housing for workers and a diesel power plant were built at Washington Camp (the pink stucco building on the west side of the road). Production of copper, lead, and zinc concentrates started in August 1912 and continued until early in 1919, when the plant was closed and the mines turned over to lessees. The total gross production of the Duquesne Mining and Reduction Company from August 1912 to the end of 1920 was approximately $6.5 million worth of copper, lead, zinc, silver, and gold (Tenney, 1929).

The plant was dismantled and sold, and in 1926 the property was sold to Bracy Curtis and Associates of Nogales. Little was done during the Depression years. In 1940 Callahan Zinc-Lead Company consolidated a group of mines and constructed a 150-ton/day flotation mill. Over a period of 4 years, they mined and milled more than 100,000 tons of ore.

In the early 1960's two real estate brokers, Fred Williams and Carl Sandberg, acquired the nearly 1,000 acres of patented mining claims of the Washington Camp–Duquesne area. They leased part or all of the property to the J.R. Simplot and Rosario Companies for exploration from about 1968 to 1975. In April 1973 Rosario Exploration employed 18 men on two 8-hour shifts, 5 days/week. Exploration, which centered on the area of the Indiana Mine at the northern end of the district (Lehman, 1978), was suspended after the Simplot exploration shaft caved on July 23, 1975. Fortunately, this was a Sunday and no one was working in the mine. The shaft was not reopened, because the exploration program was nearly completed and the hoist was unsafe.

Table 2, from Lehman (1978), is a summary of the production from the Washington Camp–Duquesne area for the period 1872 to 1959. Except for mineral collecting, there has been no mining activity since the late 1970's. The area is a well-known locality for garnet and Japanese-twin quartz crystals. Persons who wish to collect minerals from the property must obtain permission from the owner of the property. The current owner (1993) is Robert Cote, owner of the Tanque Verde Guest Ranch in Tucson; he should be contacted for permission to visit the site.

Return to vehicles and drive back north on the Harshaw Road to the Mowry Road.

94.4 Junction of Harshaw Road and Mowry Road. Turn right on Mowry Road.

94.6 Mowry town site and junction with the road to the Mowry Mine (fig. 1).

MOWRY TOWN SITE AND MOWRY MINE

The superintendent's house and the store were on the low ridge southwest of the junction; the school, rooming house, office, and caretaker's house were northeast of the

Table 2. Mining production and assays for mines in the area of Washington Camp–Duquesne, Patagonia mining district, 1872–1959[a] (Lehman, 1978, p. 127).

[--, no data]

Mine	Year	Tons	Ag[b] (oz)	Pb[b] (pct.)	Cu[b] (pct.)	Zn[b] (pct.)
Production 1940-59:						
Annie	1951-1952	240	4.59	2.57	0.52	8.36
Belmont	1955	30	3.72	1.87	1.39	12.10
Bonanza	1945-1957	9,580	4.40	0.80	6.60	6.10
California	1949-1950	100	7.60	4.82	0.65	8.30
David Allen	1952	70	9.05	7.03	0.69	12.18
Dudley Standard	1951-1952	220	5.08	2.93	2.84	8.49
Duquesne	1952	440	6.73	3.75	1.63	6.18
Empire	1945-1957	6,020	7.24	4.21	0.79	6.51
Estelle-Louise	1945-1959	3,510	4.72	2.94	1.58	19.93
Holland	1945-1957	24,180	7.77	4.98	1.32	10.49
Illinois	1945-1957	2,000	4.00	2.00	4.00	9.00
Indianapolis	1945-1957	100	6.00	11.00	2.00	--
Indiana	1956-1957	850	5.21	3.21	4.63	16.92
Kansas	1945-1957	20,120	2.66	3.52	2.55	9.28
Maine	1945-1957	3,280	3.57	2.66	2.65	12.48
Manzanita	1945-1957	500	9.00	4.00	1.00	7.00
Mary Jane	1955-1957	630	6.81	6.57	1.33	7.24
North Belmont	1945-1957	2,500	6.00	3.00	3.00	9.00
New York	1945	1,570	2.34	1.23	2.62	7.76
Pride-of-the-West	1944-1945	4,000	5.20	3.21	2.51	10.99
San Antonio	1947-1957	320	7.56	5.69	2.05	7.85
San Ramon	1951	50	6.16	3.00	0.86	4.20
Silver Bill	1953-1954	170	3.30	4.77	1.23	5.20
Texas-Smuggler	1947-1957	580	3.73	2.64	2.85	12.79
Duquesne Mines	1940-1944	116,050	3.77	2.39	1.44	7.75
TOTAL 1940-59		197,110	4.40[c]	2.90[c]	1.90[c]	8.60[c]
Estimate of production prior to 1940:						
Duquesne Mines	1872-1899	25,000	--	--	--	--
Pride-of-the-West	1899-1907	70,000[d]	--	--	--	--
Duquesne Mines	1899-1925	170,000[e]	--	--	--	--
Duquesne Mines	1925-1929	1,500	--	--	--	--
TOTAL 1872-1929		266,500				
TOTAL 1872-1959		463,610				

[a]Sources of information: Mine files, U.S. Bureau of Mines; Mill records, ASARCO, Inc.
[b]Grade per ton.
[c]Average grade per ton.
[d]Values = $1,400,000.
[e]Values = $4,000,000.

junction. Figure 12 is a photograph of Mowry, taken about 1910. Way (1966) reported that there were half a dozen standing buildings of frame and adobe. In 1992 there were only a few adobe walls, some foundations, and a concrete slab surrounded by brick work. According to Spencer R. Titley (University of Arizona, oral commun., 1992), he led a group of Chinese scientists on a field trip to Mowry several years ago, and one of them became very excited when

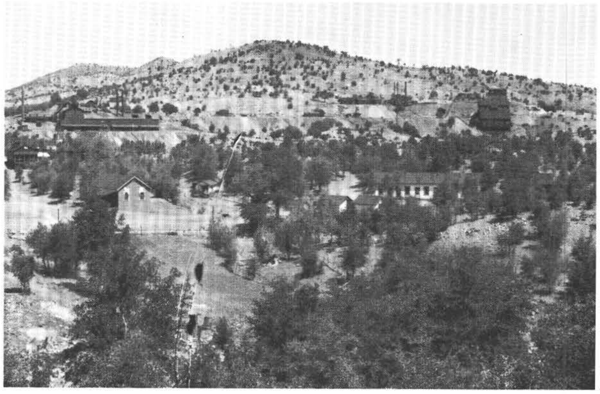


Figure 12. The Mowry mine and part of the Mowry Camp. Mill at right and smelter at left; looking north-northeast (from Schrader, 1915, pl. 22).

he saw the brick work. Apparently the bricks are laid in a unique Chinese style, suggesting that the brick layer was a Chinese immigrant.

The location of the cemetery is not known at present. Way (1966) apparently knew its whereabouts because he stated, ". . . should you discover the hard-to-find cemetery, it is interesting to note that of the seventeen men buried there, fifteen died violently." Robert Lenon has searched for the cemetery, but has been unable to find it (oral commun., 1992). He thought it may have been on a low hill to the south about halfway (0.3 mi) between the mine and the old smelter site at Commission.

Notice that most of the oak trees are fairly small and all are about the same size. The original oaks were probably cut down to make charcoal for the smelter, and thus most of the present trees are second growth. This is also true for Harshaw and Washington Camp–Duquesne.

The Mowry Mine, first called the Corral Viejo Mine, was known to the Jesuits and was worked by Mexicans in the early 1850's. It was relocated in 1858 by a Mexican herder and prospector who sold it to some officers at Fort Buchanan for a pony and other miscellaneous items. The officers named the property the "Patagonia Mine" for reasons that are not known. The mine was bought by Sylvester Mowry in 1859 after he resigned his commission as a first lieutenant in the 3rd Artillery. Mowry is reported to have purchased the mine for $25,000 and to have put about $175,000 into subsequent improvements and equipment. Mowry operated the mine for about 3 years, employed 120 men, and shipped about $1,500,000 worth of ore to San Francisco, London, Europe, and Swansea, Wales, for smelting through the port of Guaymas, Sonora, Mexico (Schrader, 1915; Greeley, 1987).

On the orders of Colonel James H. Carleton, Mowry was arrested and his mine confiscated in June 1862 on the basis of a charge of being a Confederate sympathizer and having sold percussion caps to the Confederate Army. He was found guilty of aiding and abetting the enemy by a military board of inquiry and was ordered to be confined at Fort Yuma. Mowry was acquitted of the charges against him and released from Fort Yuma in November 1862, but, in the meantime, the government receiver for the mines had made the property unworkable by extensive and deliberate damage to the equipment and workings (Granger, 1960). In December 1862 Mowry filed damage claims of more than $1 million against Carleton and others and tried to get the Federal Government to relinquish his property. His mine was sold at public auction in July 1864 for only $2,000. Although Mowry was eventually awarded $40,000 in 1868, it was inadequate to reopen the mine. Mowry died in 1871 while in London, where he had gone for treatment of Bright's disease and to try to raise capital (Wagoner, 1975; Robert Lenon, written commun., 1992).

Because of Apache raids prior to 1872 and the inaccessibility of the area until the railroad to Patagonia was completed in 1883, there was little production from any of the mines in the Patagonia Mountains between 1864 and 1883. The coming of the railroad to Patagonia was not a great stimulus for the Mowry Mine, however, because it was still 14 mi from the railhead at Crittenden. The Mowry passed through a number of hands and was intermittently worked between 1890 and 1907. In 1918 the workings above the water level were reopened and developed. Small shipments of both new ore and ore from old stope fills were made until the working shaft caved in 1928 (Tenney, 1929). Keith (1975) reported that production continued through 1952. He gave the total estimated and reported production of lead-silver ore as 200,000 tons averaging about 4 percent lead, 3 oz silver/ton and minor copper, zinc, and gold. During World Wars I and II, 7,500 long tons of ore containing 25 percent manganese was shipped.

The patented land associated with the Mowry mine is currently in the U.S. Forest Service land exchange program. Approximately 330 acres at Mowry is being exchanged for 15 acres near Sedona, Ariz., a retirement and resort community.

99.0 Junction of Mowry Road and Canelo Road. Turn right on Canelo Road.

102.9 Cross Santa Cruz River.

107.1 The Canelo Hills (fig. 1) are composed chiefly of two Jurassic rhyolite tuff units, as much as 1,000 and 6,000 ft thick, that are partly welded to densely welded to fluidal (Hayes and Raup, 1968; Simons, 1974; Lipman and Hagstrum, 1992). The tuffs enclose large blocks of Paleozoic sedimentary rocks that have been interpreted by Lipman and Hagstrum (1992) to be intracaldera megabreccia lenses.

Between here and Canelo Pass the exposures along the road are of densely welded quartz rhyolite tuff. On the left side of the road 0.7 mi east of the pass, there is a large exposure of a block of Paleozoic limestone and quartzite that both overlies and is surrounded by welded tuff. These rocks are part of the intracaldera fill of the Parker Canyon caldera (fig. 1) of Lipman and Hagstrum (1992).

107.6 Canelo Pass, elevation 5,246 ft (fig. 1).

The Canelo Hills were first shown on an 1896 map as the Canille Mountains (Granger, 1960), and the school at Canelo (now abandoned) is shown as Canille School on the O'Donnell Canyon 7-minute quadrangle. Canelo means cinnamon tree in Spanish and is perhaps descriptive of the color of the hills (Granger, 1960). On the other hand, canille, which means long bone, faucet, spool, or rib (as in a fabric) could also have been descriptive.

111.5 Junction of Canelo Road with SH 83. Turn right (east) on SH 83.

112.5 Canelo, Ariz., elevation 4,975 ft (fig. 1).

W.A. Parker, Sr., settled in the canyon that drains the southern half of the Canelo Hills (now called Parker Canyon) in about 1868. Parker had traveled through the San Rafael Valley on his way to California at the time of the gold rush because it was one of the more Apache-free routes. He left California after a short time, took a boat to Panama, walked across the isthmus, caught a boat on the other side, and returned to his farm in Missouri. He later sold the farm and moved with his family, first to California and then to the San Rafael Valley (Byrd Lindsey, great-grandson of W.A. Parker, Sr., oral commun., 1993). Granger (1960) gave a slightly different version of the story, obtained from a great-granddaughter of W.A. Parker, Sr. In that version, the family moved from Missouri to Phoenix in about 1870, and then moved to Parker Canyon in 1881 when Phoenix became too crowded. W.A. Parker, Jr., homesteaded 160 acres at Canelo in 1910. The house burned in 1923.

112.5 Canille (Canelo) School.

According to Byrd Lindsey, who was making repairs on the school in June 1993, this school was built in 1913 by Robert McGregor as a replacement for the Evans Camp school (location not known). It was closed in 1946 because of the consolidation of various schools in the district that resulted from improved transportation. Lindsey's mother attended eighth grade at the school in 1913; the family recently purchased the school and the surrounding 2 acres from the school district.

112.8 Turn left onto West Gate Road to Fort Huachuca.

117.5 West gate of Fort Huachuca. The road goes through the military base and is not marked. Stay on what appears to be the main road, do not make any sharp turns, and exit the traffic circle by the first road on the right.

126.8 East gate of Fort Huachuca. Go east on the main street through Sierra Vista.

129.9 Turn left (north) on SH 90.

130.2 Turn right on Charleston Road.

137.6 Cross San Pedro River (fig. 1).

CHARLESTON MILL SITE

The Charleston mill site is about 0.3 mi north of here. The following history is taken from Tenney (1929). Charleston was the site of the 10-stamp mill of the Tombstone Mill and Mining Company and the 20-stamp mill of the Corbin Mill and Mining Company, both built in 1879. The mills were built here, 5–10 mi from the mines, because there was no water in Tombstone. Until a steam plant was built in 1882, the mills were run by water power from a dam several miles upstream on the San Pedro River.

The 10-stamp mill was financed in part by Arizona Territorial Governor A.P.K. Safford for a quarter interest in the Toughnut claim, owned by Ed and Albert Schieffelin and Richard Gird, locators of the rich silver ore at Tombstone. Frank Corbin (also an investor in the 10-stamp mill), from New Britton, Conn., built the 20-stamp mill for an interest in the Lucky Cuss claim of the Schieffelins and Gird. In March 1880 a syndicate of eastern investors, including Corbin, bought the interest of the Schieffelin brothers in the Tombstone Mill and Mining Company for $600,000. Gird accepted shares and stayed on for a year as manager of the company, which was merged with the Corbin Mill and Mining Company.

By 1882, there were two other stamp mills at Charleston, in addition to concentrating machinery and a patent roasting furnace. Other mills were built several miles downstream on the San Pedro. According to the *Arizona Weekly Star* of November 2, 1879, the population of Charleston was between 600 and 800. By the beginning of 1881 there were 150 men working in the mills along the river. Charleston had a post office from 1879 to 1888 (Granger, 1960).

The water in the mines at Tombstone, which was first encountered in the summer of 1881 at a depth of 560 ft, spelled the end of the mill town of Charleston. Obviously, if several million gallons of water had to be pumped from the mines each day, it made sense to use this water to operate mills and reduction plants at the mines rather than transporting the ore to the river.

The structures at Charleston suffered considerable damage during the 1887 earthquake on the Pitaycachi fault in northeastern Sonora (estimated magnitude 7.2, Dubois and Smith, 1980. p. 35). Though most buildings remained standing, none was safe to live in. A colorful contemporary description of the effects of the shaking on the Charleston saloon was given in DuBois and Smith (1980, p. 35): "The walls of the saloon did a two-step and the floor did a shimmey." Based on reports of the time, DuBois and Smith (1980) estimated the Modified Mercalli intensity of the earthquake at Charleston to be IX to XI. A few miles to the east at Tombstone, the intensity was calculated to be only VII to VIII, and at Harshaw and Washington Camp the intensity was still lower, only VI to VII. There was virtually no damage to the mines in Tombstone. The lower intensities felt at Tombstone, Harshaw, and Washington Camp were probably a result of the fact that these towns were built on bedrock, whereas many of the structures at Charleston may have been built on unconsolidated Quaternary alluvium or semiconsolidated Tertiary basin fill.

141.4 **STOP 4, ROBBERS' ROOST.** Park in turn-out area on the right side of the road and walk to the sandy wash on the northwest side of the road. Stop leaders are James A. Briscoe and Eric R. Force.

Robbers' Roost (fig. 1) got its name from the habit bandits had in the 1880's of using the breccia pipe here as a hiding place from which to waylay bullion shipments. These shipments were by stagecoach on the Charleston Road, which had the same alignment then as now. The breccia pipe, of probable Laramide age, cuts the 73.5-Ma Uncle Sam Tuff (Marvin and others, 1978).

Return to vehicles and proceed northeast toward Tombstone.

142.8 Armco Milling Facility on the right.

146.5 Junction with West Allen Street. Turn right on West Allen Street.

146.9 Junction with Sixth Street. Turn left on Sixth Street, go one block and turn right on Fremont Street.

147.4 Junction of Fremont Street with old highway. Turn right on old highway.

147.7 **STOP 5.** Turn right on road to the Contention open pit (fig. 1). Drive to north edge of pit and park.

CONTENTION OPEN PIT MINE

Stop Leaders: Eric R. Force and James A. Briscoe

Silver mining at Tombstone caused the site to progress from an occasional Apache campsite before 1878 to a town reportedly of 15,000 (the largest between St. Louis and the west coast at that time) in 1882. This phenomenal growth, coupled with some well-documented violence, made Tombstone famous. Mining activity had peaked by 1886, but showed subsequent bursts of activity in 1903–09 and 1917–22 (Butler and others, 1938). Production was interrupted by flooding of the mines, low silver prices, strikes, and (or) underground fires. The open pit at this stop was developed in 1980–85.

Silver deposits were discovered in the district by Ed Schieffelin in 1877–78, and developed by Schieffelin and Dick Gird. Schieffelin had a way with names—Tombstone was derived from the discouraging words of Fort Huachuca soldiers about prospecting the area ("Son, the only thing you'll find out there is your tombstone . . ."). Schieffelin named his first big discoveries in the district the Tough Nut and the Lucky Cuss Mines, found on consecutive days. The Contention and Tranquility Mines record the progress of a claim dispute. We are told by a notoriously unreliable source that Schieffelin named the town newspaper the *"Epitaph."* In any case, arriving miners loved the image that went with these names, although there have been attempts to change the name of the town.

Schieffelin left Arizona Territory in 1882 and used his earnings from the Tombstone district to fund further prospecting expeditions, with a nice house in Alameda, Calif., to serve as a base. What more could a man of simple tastes want? When he died in 1897 his remains were sent to Tombstone as he had requested. An impressive granite-boulder monument about 2 mi northwest of town was erected near a spring where he and his mule had camped on his first expeditions.

Gird stayed on as manager of the Tombstone Mill and Mining Company for a year after Schieffelin left. He then bought a large ranch in southern California, started growing sugar beets, and eventually established a very profitable sugar refinery business (Tenney, 1929).

Meanwhile, back in town, new arrivals were glorying in a last chapter of the Wild West story. Look around town for the O.K. Corral, Boot Hill, and the Bird Cage Theater ("I'm only a bird in a gilded cage . . ."). The most common date of violent death recorded on tombstones at Boot Hill is 1882. Examining mines in these hills as gunfights are being re-enacted in the town below really takes you back.

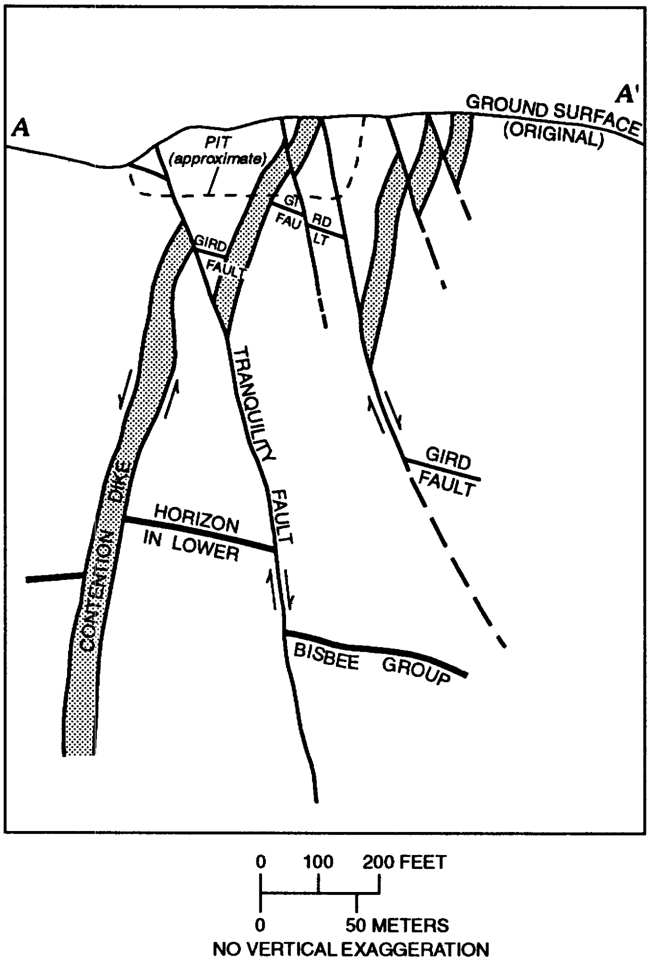


Figure 13. Cross section of the Tranquility-Contention trend of mineralization. Location of cross section shown in figure 14. Modified from F.L. Ransome (*in* Butler and others, 1938, pl. 13).

Some of the old mines are easily visible from the town (Toughnut, Westside). Currently, the greatest impacts of mining on the town are the nearby 1980–85 open pit and the periodic subsidence at the corner of Fifth and Toughnut Streets into shallow workings of the Goodenough mine.

The total value of ores of the Tombstone district was about $463 million in today's dollars (about $50 million at the time of the mining) (Briscoe and Waldrip, 1988). About 1.5 million tons of underground ore and slightly more open-pit ore were exploited. In addition to silver, the mines produced gold, lead, zinc, copper, and manganese.

Most production was from oxidized ores that contained horn silver, relict galena, manganese oxide, argentite, chalcocite, chrysocolla, malachite, cerrussite, wulfenite, and plumbojarosite. Hypogene ore contained tetrahedrite, sphalerite, galena, chalcopyrite, and pyrite. Native gold occurred in both zones.

GEOLOGIC CONTEXT OF MINING

The host rocks of the ores were primarily the Upper Jurassic to Lower Cretaceous Bisbee Group in the Tombstone Basin, variably contact-metamorphosed to spotted hornfelses of wollastonite to epidote grade, as at this stop (Force, unpub. mapping, 1988–90). At depth and in the southern part of the district, Paleozoic rocks were also hosts of ore. The 72-Ma Schieffelin Granodiorite, adjacent to the district and underlying parts of it, intrudes these rocks and produced the contact metamorphism. The Tombstone Basin is a structural feature predating the granodiorite intrusion.

The ores formed primarily along favorable structures of several types and in two stratigraphic horizons in the

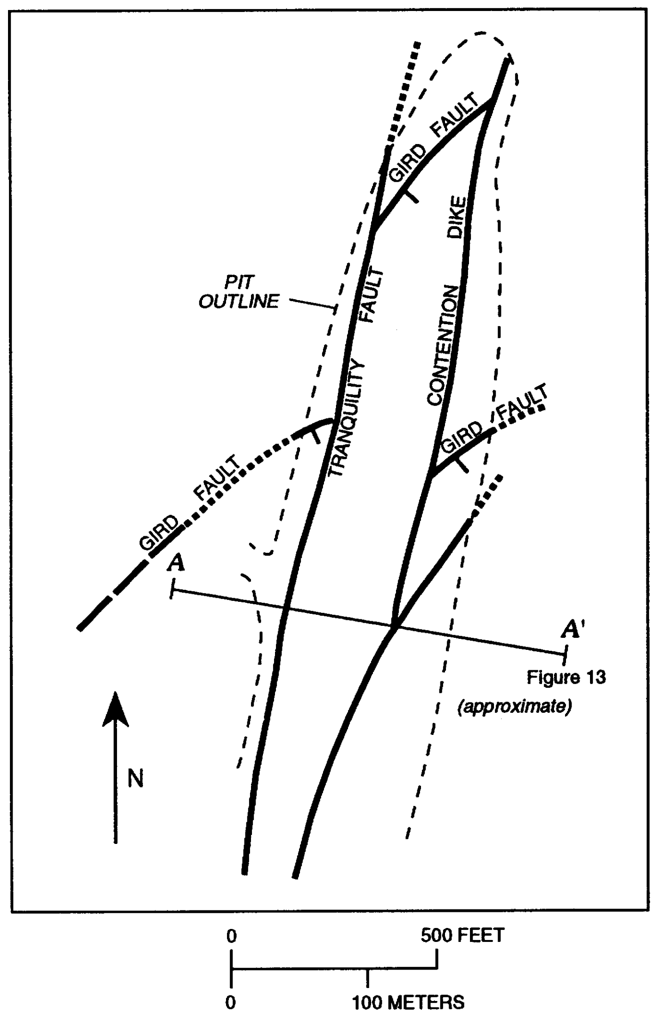


Figure 14. Sketch map of the area of **STOP 5** near Tombstone, Ariz., showing offset of the Contention dike and Gird decollement fault by the Tranquility and related faults, enlarged from Force (unpub. mapping, 1988–90).

lower part of the Bisbee Group: silicified fine limestone-pebble conglomerate ("novaculite"), and coquinoid limestone ("blue limestone"). The favorable structures included porphyry dikes and related faults, decollements, small anticlines ("rolls"), and younger fractures ("fissures").

GEOLOGY

A good share of Tombstone wealth was produced from mines along a single trend, now traversed by the open pit of this stop. The trend included the Grand Central, Contention, and Tranquility deposits. The deposits were along the sheared and altered Contention porphyry dike, which was sliced into several segments by the younger (but apparently mineralized) Tranquility fault set. Also offset by the Tranquility fault set is the Gird fault, a roughly bedding-parallel decollement that divides the stratigraphic pile into two structural packages, with "rolls" below and open folds above (figs. 13, 14) (Force, unpub. mapping, 1988–90).

End of trip. Return to Tucson by way of Benson and I–10.

ACKNOWLEDGMENTS

Many people provided invaluable assistance in all stages of the planning and organization of this field trip. The trip was much improved by the leaders not affiliated with the U.S. Geological Survey who volunteered their time and knowledge: Mary M. Farrell, John Wiens, and James A. Briscoe. F.N. Houser provided help with many aspects of the project. Robert Lenon (retired mining engineer, Patagonia) generously shared his 60 years of knowledge of the Harshaw and Patagonia mining districts. The Hale family kindly gave us access to their property at Harshaw and supplied much interesting information about the people, buildings, and plants of Harshaw. The road log was improved by reviews by T.F. Harms, F.N. Houser, R.J. Kamilli, and A.L. Bush.

REFERENCES CITED

Briscoe, J.A., and Waldrip, T.E., 1988, The Tombstone mining district—Part of the Tombstone caldera complex, Cochise County, Arizona, *in* Dummett, Hugo, and Colburn, Nora, eds., Visit to the Tombstone, Bisbee, and Commonwealth districts, Arizona: Tucson, Arizona Geological Society Fall 1988 Field Trip Guidebook, Field guide notes section, 34 p.

Brown, D.E., ed., 1982, Desert plants—Biotic communities of the American southwest, United States and Mexico: Tucson, University of Arizona Press, 131 p.

Butler, B.S., Wilson, E.D., and Rasor, C.A., 1938, Geology and ore deposits of the Tombstone district, Arizona: Tucson, Arizona Geological Survey, Arizona Bureau of Mines Bulletin 143, 114 p.

Butler, G.M., 1937, Arizona gold placers and placering: Tucson, Arizona Geological Survey, Arizona Bureau of Mines Bulletin 142, 148 p.

Corn, R.M., 1975, Alteration-mineralization zoning, Red Mountain, Arizona: Economic Geology, v. 70, p. 1437–1447.

Drewes, Harald, 1980, Tectonic map of southeast Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–1109, scale 1:125,000.

DuBois, S.M., and Smith, A.W., 1980, The 1887 earthquake in San Bernardino Valley, Sonora—Historic accounts and intensity patterns in Arizona: Tucson, Arizona Bureau of Geology and Mineral Technology [now Arizona Geological Survey], Special Paper No. 3, 112 p.

Finnell, T.L., 1974, Preliminary geologic map of the Empire Mountains quadrangle, Pima County, Arizona: U.S. Geological Survey Open-File Report 1971, scale 1:48,000.

Granger, B.H., 1960, Will C. Barnes' Arizona place names: Tucson, University of Arizona Press, 519 p.

Greeley, M.N., 1987, The early influence of mining in Arizona, *in* Canty, J.M., and Greeley, M.N., eds., History of mining in Arizona: Tucson, Mining Club of the Southwest Foundation, p. 13–30.

Hayes, P.T., and Raup, R.B., 1968, Geologic map of the Huachuca and Mustang Mountains, southeastern Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–509, scale 1:48,000.

Keith, S.B., 1974, Index of mining properties in Pima County, Arizona: Tucson, Arizona Geological Survey, Arizona Bureau of Mines Bulletin 189, 156 p.

———1975, Index of mining properties in Santa Cruz County, Arizona: Tucson, Arizona Geological Survey, Arizona Bureau of Mines Bulletin 191, 94 p.

Lehman, N.E., 1978, The geology and pyrometasomatic ore deposits of the Washington Camp–Duquesne district, Santa Cruz County, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 285 p.

Lipman, P.W., and Hagstrum, J.T., 1992, Jurassic ash-flow sheets, calderas, and related intrusions of the Cordilleran volcanic arc in southeastern Arizona—Implications for regional tectonics and ore deposits: Geological Society of America Bulletin, v. 104, p. 32–39.

Marvin, R.F., Naeser, C.W., and Mehnert, H.H., 1978, Tabulation of radiometric ages—Including unpublished K-AR and fission track ages for rocks in southeastern Arizona and southwestern New Mexico, *in* Callender, J.F., Wilt, J.C., and Clemons, R.E., eds., Land of Cochise, 29th Field Conference, New Mexico Geological Society, p. 243–252.

Quinlan, J.L., 1986, Geology and silicate-alteration zoning at the Red Mountain porphyry copper deposit, Santa Cruz County, Arizona, *in* Beatty, Barbara, and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the southwest: Tucson, Arizona Geological Society Digest Volume 16, p. 294–304.

Schrader, F.C., 1915, Mineral deposits of the Santa Rita and Patagonia Mountains, Arizona: U.S. Geological Survey Bulletin 582, 373 p.

Sellers, W.D., and Hill, R.H., eds., 1974, Arizona climate: Tucson, University of Arizona Press, 360 p.

Sherman, J.E., and Sherman, B.H., 1969, Ghost towns of Arizona: Norman, University of Oklahoma Press, 208 p.

Simons, F.S., 1972, Mesozoic stratigraphy of the Patagonia Mountains and adjoining areas, Santa Cruz County, Arizona: U.S. Geological Survey Professional Paper 658–E, 23 p.

———1974, Geologic map and sections of the Nogales and Lochiel quadrangles, Santa Cruz County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–762, scale 1:48,000.

Tenney, J.B., 1929, History of mining in Arizona: Tucson, University of Arizona Library, Special Collections, unpublished manuscript, 401 p.

Varney, Phillip, 1980, Arizona's best ghost towns: Flagstaff, Northland Press, 142 p.

Wagoner, J.J., 1975, Early Arizona—Prehistory to Civil War: Tucson, University of Arizona Press, 547 p.

Wallace, Andrew, ed., 1965, Pumpelly's Arizona: Tucson, Palo Verde Press, 141 p.

Way, W.J., 1966, Ghosts and ghost towns: Tucson, The Livingston Press, 56 p.

Wiens, J.F., 1991, Vascular plants of the Silver Bell Mountains: Arizona Native Plant Society, The Plant Press, v. 15, no. 2, p. 1 and 6-10.

Wilson, J.P., 1988, Islands in the desert—A history of the upland areas in southeastern Arizona: U.S. Forest Service, Coronado National Forest, unpublished report on file at 300 West Congress Street, Tucson, AZ 85701.

GEOLOGY OF THE GOLD PLACERS IN THE GREATERVILLE DISTRICT, ARIZONA

By Leslie J. Cox[1]

INTRODUCTION

This paper was originally written for the 1992 Arizona Geological Society Fall Field Trip as a geological complement to the historical presentation given by the U.S. Forest Service at the Kentucky Camp site, in the Greaterville placer district (Houser, 1992, p. 5–6 and appendix 10). It is presented here, with slight modifications, as a supplement to the field trip to historic mining camps by B.B. Houser and others (this volume).

A synopsis of the literature on the Greaterville district placers was given by Johnson (1972, p. 35–37). She found accounts of the production ranged from $500,000 to $7 million for the value of gold recovered before 1900. Lode production of gold and silver was greatly surpassed by the placer activity, which began in 1874 and peaked before 1890. The scarcity of water in the district made placer mining uneconomical once the easily obtained gold was recovered. Interest in the placers was revived in 1904 with an ambitious scheme to channel runoff from the Santa Rita Mountains' snowmelt (Hill, 1910; Schrader, 1915, p. 159; Tenney, 1929; Houser, 1992, appendix 10). The most recent activity was in 1948, when 535 oz of gold (averaging 0.006 oz per cubic yard) was mined in Louisiana Gulch (fig. 1) (Johnson, 1972).

In order to describe the gold placer deposits of the Greaterville district in a modern context, I transferred the placer locations shown by Hill (1910) to a modern topographic base (fig. 1). I compiled a map of the most recent geology of the area from the geologic maps of Drewes (1970, 1971a,b, and 1980) and Reynolds (1988) and superposed the placer gravel outlines on the geology (fig. 2). I then drew a schematic cross section (*A–A'*, fig. 4) and used post-Eocene stratigraphy established by Menges (1981) to arrive at an interpretation of the timing of exposure of lode gold to erosion. An analysis of these data suggests that Oligocene to Pliocene gravels may have potential for placer deposits, whereas only Quaternary gravels have been exploited to date. Also, there may be additional potential for vein, fracture-filling, and replacement deposits similar to those that have been exploited in Cretaceous and older strata.

Whereas the Greaterville district of Arizona has been the source of gold from lode and placer deposits, the source of base metals and silver from vein and replacement deposits, and the site of exploration for porphyry copper deposits, this paper focuses its review on aspects important to the gold placer deposits. Lode deposits are reviewed first to identify the local sources of bedrock gold. The descriptions of the lode deposits and the placer gravels emphasize their relationships to quartz latite porphyry of Paleocene age. The section on geology and physiography emphasizes the description of hosts to the Paleocene intrusions and the events that would bring mineralized ground to surface exposure. The relationship of the bedrock to the basin-fill is discussed, and the locations of undiscovered gold resources are speculated upon.

DESCRIPTION OF THE LODE DEPOSITS

Early accounts of the Greaterville district attribute the source of the lode gold to the intrusion of light-colored, chalky-appearing, pyritiferous quartz latite porphyry (Hill, 1910, p. 20–21). A Paleocene age (55.7±1.9 Ma) for the quartz latite porphyry (K-Ar from biotite) (unit Tp, fig. 2) was established by Drewes (1970, p. A8). Thus, the porphyry was emplaced at the end of the Laramide orogeny (see below). The porphyry intrusions are within or near the head of several of the productive gulches (fig. 2).

Prior to the 1874 discovery of the placers, early miners of the St. Louis Mine (fig. 2; the Morning Star Mine site in fig. 1) and nearby workings recovered native gold and silver- and gold-bearing cerussite, as well as argentiferous galena and sphalerite, pyrite, chalcopyrite, and barite, from quartz-calcite veins in the quartz latite porphyry and

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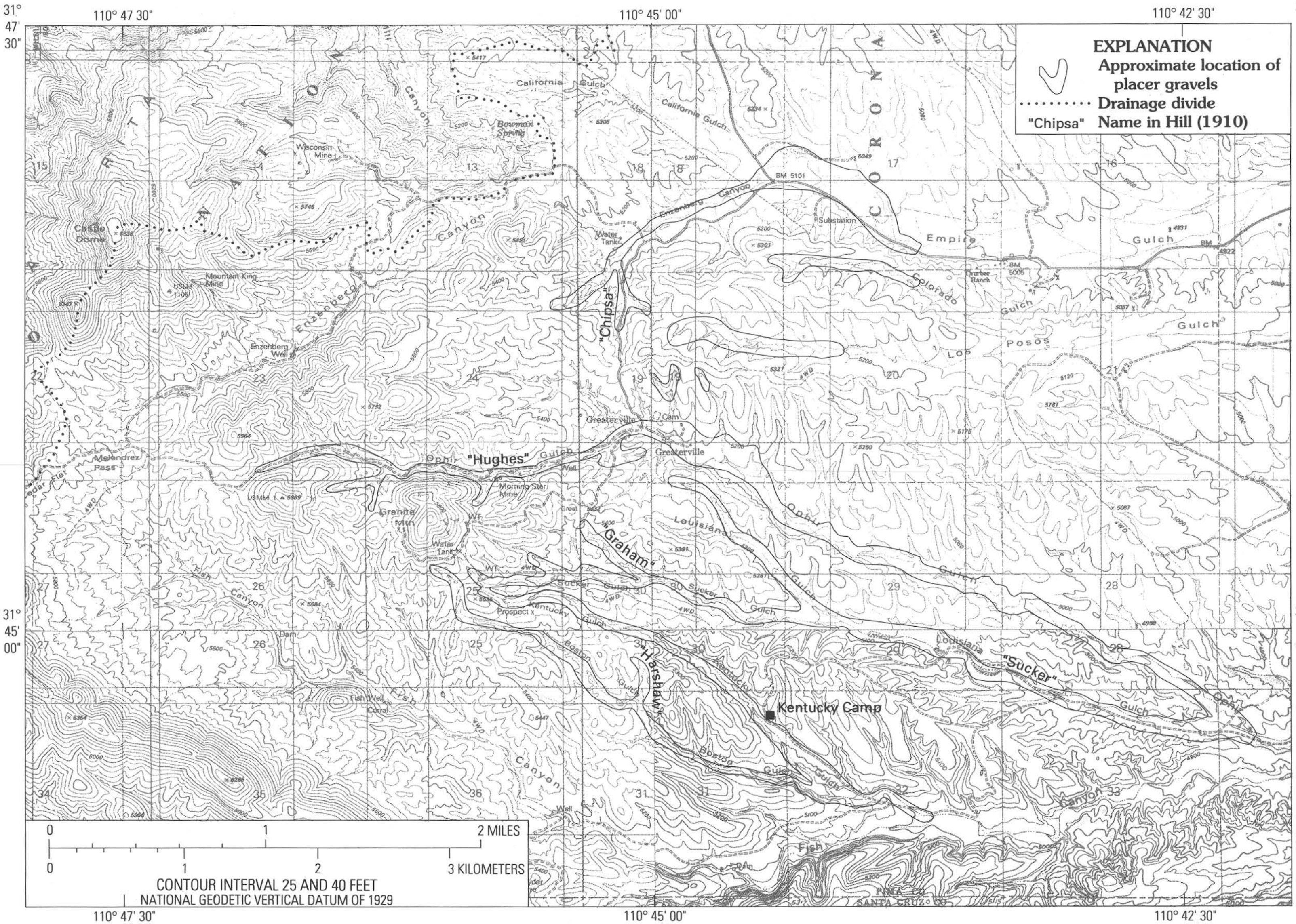

Figure 1. Map showing location of placer gravels in the Greaterville district. Approximate locations of the placer gravels are adapted from Hill (1910, fig. 1). Differences between depictions of 1910 and modern topography make exact correlation difficult and result in uncertain placement of some of the gravels, particularly those of upper Louisiana Gulch and the small areas north of Greaterville. Base from U.S. Geological Survey, 1:24,000 (Empire Ranch, Helvetia, and Mount Wrightson, 1981; Sonoita, 1958, photo revision as of 1983).

adjacent sedimentary rocks at Granite Mountain (Hill, 1910; Schrader, 1915; and Tenney, 1929). According to Tenney (1929, p. 276–278), after the discovery of placers the search for lodes was renewed. Work began at several locations (see Schrader, 1915, p.153–158) including the Snyder (also known as the Anderson or Conglomerate) Mine and the Mountain King (or Enzenberg) Mine (figs. 1 and 2). The ore mined at the Snyder Mine included galena, cerussite, chalcopyrite, and "horn silver" (cerargyrite). Schrader (1915, p.154) described the ore as scattered through the brecciated and silicified contact zone between Precambrian granodiorite and Paleozoic limestone. Drewes (1971a), however, showed the Snyder mine on a fault contact between Precambrian granodiorite and Glance Conglomerate, consisting of limestone cobble conglomerate. At the Mountain King Mine, small tonnages of high-grade lead-silver ore, as well as gold, copper, and zinc, were recovered from faults and permeable fracture zones in the Willow Canyon Formation (Lower Cretaceous) (as reported in the U.S. Geological Survey Mineral Resource Data System).

DESCRIPTION OF THE GOLD AND PLACER GRAVELS

In the early days of the camp, gold from the placer gravels was said to have been very coarse: one nugget weighing 37 oz was found in the period 1874–84. In later days, the coarsest gold found was as small flakes as much as 0.1 in. long. Common associations were quartz and gold, and galena and gold (Hill, after Mr. Coyne, 1910).

The placer gravels in the Greaterville district were assigned to the Pleistocene on the basis of the discovery of vertebrate fossils in one of the placer diggings (Blake, 1898). These gravels were almost at the surface in the heads of the gulches and buried to depths of 10–20 ft in the lower eastern ends of the diggings (Hill, 1910). Although the gold placers in the upper reaches of the gulches were mostly found in channels on Cretaceous bedrock, gold was also found in older, higher terraces preserved in Kentucky (Maynard, 1907), Hughes, Graham, and Sucker Gulches (Hill, 1910). The gold placers in the gulches that dissect basin-fill were found on "cement rock" (Hill, 1910). The "cement rock" occurs along many of the multiple, diastem-like minor disconformities characteristic of the upper basin-fill described by Menges (1981, p. 59–60). Gold was concentrated on the riffled surface of the diastemlike horizon that texturally resembles the surface of the weathered Cretaceous beds.

Hill (1910, p. 19) best described the placer gravels,

> The pay dirt is found on bed rock distributed rather evenly through a 2-foot bed of angular gravels in a fine red-brown, somewhat clayey matrix. Some of the gravels are yellow to gray-brown, but these as a rule were not so rich as the heavily iron-stained beds. The conditions were essentially the same in all the gulches, and the thickness of the pay varied little from place to place.
>
> The constituents of this bed are rather fine, usually less than 1 inch in greatest dimension, . . . In a few places the materials of this bed are roughly stratified and somewhat cemented, usually by lime.
>
> . . . The coarse material is red and yellow sandstone, shales of various colors, pebbles of arkose, a few fragments of dense white rhyolite, and a very minor amount of granite porphyry.

GEOLOGY AND PHYSIOGRAPHY

This part of southeastern Arizona is underlain by Proterozoic to Quaternary rock units, many of which have been deformed and (or) mineralized during several major orogenic events. Most of the important mineralization in this region occurred during the Mesozoic to early Cenozoic Laramide orogeny.

The Laramide orogeny in southeastern Arizona is Late Cretaceous (about 90 Ma) to Paleocene (about 52 Ma) in age (Drewes, 1969). Two phases of the Laramide orogeny are identified in the Santa Rita Mountains; the earlier phase is associated with regional northeast-directed compression (Drewes, 1970, p. A11). In the Greaterville district, the deformation is evident in the strongly folded Bisbee Group of Early Cretaceous age. The later phase is associated with northwest-oriented compression (Drewes, 1970, p. A11). Paleocene quartz latite porphyry associated with the gold mineralization was intruded in the later Laramide phase.

The Continental Granodiorite, of Middle Proterozoic age, and the Bisbee Group, of Lower Cretaceous age, are hosts to the Paleocene intrusions. Bisbee Group strata unconformably overlie, and are in fault contact with, the granodiorite (fig. 2). The intruded Bisbee rocks consist of arkosic conglomerate, arkose, siltstone, and limy siltstone of the Willow Canyon Formation and siltstone, silty shale, and laminated limestone of the Apache Canyon Formation (the uppermost unit of the Bisbee Group exposed in this area) (Drewes, 1970, p. A6). Although the basal Bisbee Group unit, the Glance Conglomerate, is exposed in the area, it is not intruded at the surface. Whether the Glance and additional units, such as Paleozoic limestone, intervene between the granodiorite and Bisbee Group at depth, has been speculated upon (Drewes, 1970) but is not known. If they do, they would host the Paleocene intrusions at depth. This relation might be significant to mineral exploration because lowermost Bisbee units (presumably equivalent to the Glance) are important hosts for replacement mineralization in the Tombstone district (Force, unpub. mapping, 1988–90) to the east and the Paleozoic rocks are important hosts to mineralization in the nearby Helvetia and Rosemont mining districts (Drewes, 1970, p. A5).

Fold and fault structures imposed by the early Laramide events served as conduits for the Paleocene stocks and

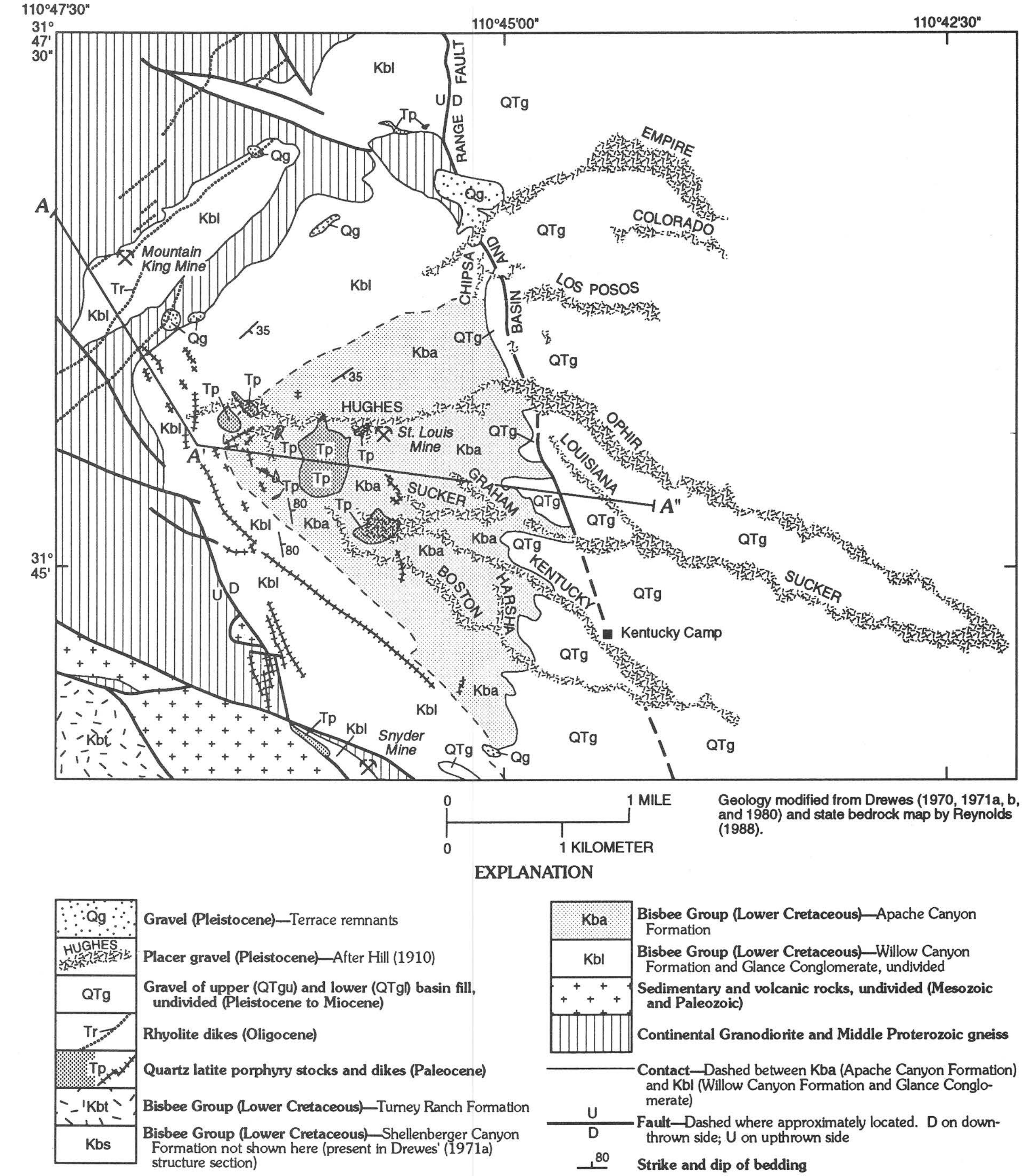

Figure 2. Map showing geology and location of placer gravels in the Greaterville district. Section *A–A'* shown in figure 4. Geology modified from Drewes (1970, 1971a,b, and 1980) and "Geologic Map of Arizona" by Reynolds (1988).

the mineralizing fluids (Drewes, 1970). Paleocene stocks and dikes were intruded along the southeast-trending fold axes of the asymmetrically folded Cretaceous rocks (fig. 2) (Drewes, 1970, 1971a,b).

Upper Cretaceous sedimentary and volcanic rocks are absent in the Greaterville district but are preserved in the northern and southern Santa Rita Mountains. If the andesite that overlies the tilted Glance Conglomerate (just 1,000 ft

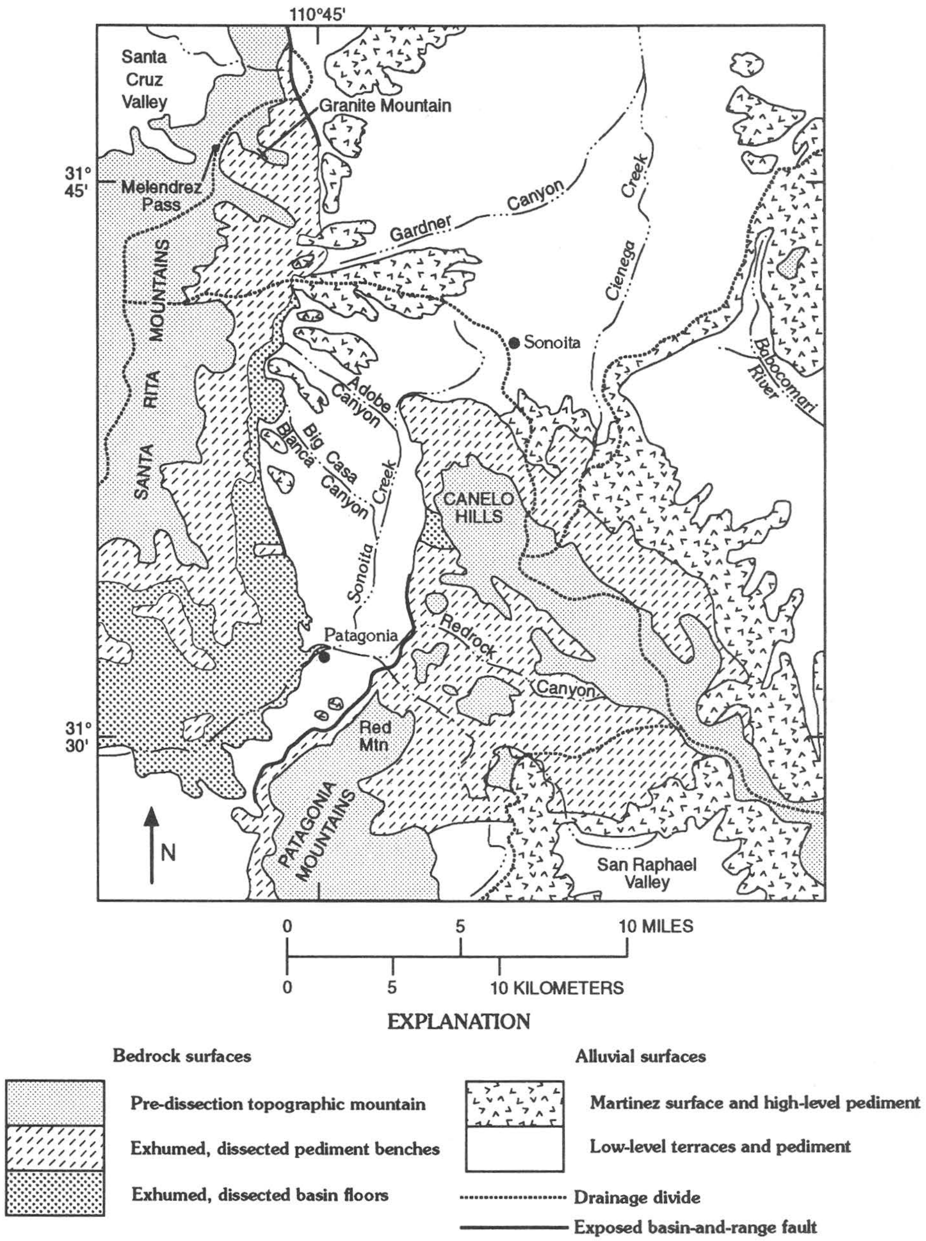

Figure 3. Generalized map of the geomorphology of the Sonoita-Patagonia area (from Menges and Pearthree, 1989). The predissection landscape represented by preserved remnants of the Martinez pediment and surface was partially reconstructed by Menges (1981).

north of the area shown in fig. 1) is coeval with the Paleocene intrusions, it is likely that most of the Upper Cretaceous rocks were removed before the emplacement of the Paleocene intrusions. The thickness to which volcanic rocks accumulated during the last stages of the Laramide is also not known. This is of interest because one wonders how close to exposure the pronounced regional erosion that occurred in the Eocene (Menges, 1981, p. 17) is likely to have brought the gold-bearing rocks (the subvolcanic Paleocene stocks and adjacent Lower Cretaceous rocks).

In any case, the postulated gold-bearing Paleocene source rocks could not have been exposed before the middle Tertiary tectonic event (between 40 and 24 Ma), which is represented in the area by the rhyolite dikes (26.1±0.8 Ma, K-Ar from sanidine; Drewes and Finnell, 1968, p. 521). The absence of placer deposits downstream of the widespread Tertiary rhyolite dikes and their unaltered appearance (Drewes, 1970, p. 8A) also support the idea that the mineralization is genetically associated with the Paleocene stocks. The middle Tertiary event brought an additional layer of cover to the region and probably to the Greaterville area. The thickness of the Tertiary volcanics is not known, nor whether they were deposited on top of Laramide volcanics, Upper Cretaceous rocks, or Lower Cretaceous rocks.

Menges (1981) established a post-Eocene stratigraphy for the area that encompasses the Greaterville district. This stratigraphy is described in items 1–4 below, interspersed with some discussion (units in parenthesis correspond to those in figs. 2 and 4):

1. Lower- to-middle Tertiary (25–20 Ma) fanglomerates (unit Ts) that predate all Miocene (basin and range) graben formation: not exposed in the Greaterville area but may be preserved at depth east of the Basin and Range fault. In the Sonoita Creek Basin south of Greaterville, clasts in deformed Tertiary (Oligocene to middle Miocene) sediments record a topographic highland that preceded, and is quite different from, the post-middle Miocene highland that dominated the subsequent basin-and-range faulting and basin-filling episode (Menges, 1981). One thus surmises that if the locally derived Oligocene to mid-Miocene Tertiary sediments were available for examination, the clast compositions would reveal the presence and proportions of Cretaceous and Tertiary rocks in the early Tertiary highlands of the Greaterville area. This would help establish the earliest possible exposure of the gold bearing lodes.
2. Middle and upper Miocene syntectonic basin-and-range fill units (unit Tgl), which are the main units deposited during the basin-and-range event; in places uppermost fill accumulated after tectonism ended and overrides basin-boundary faults.
3. Undeformed post-tectonic upper basin-and-range fill (unit QTgu; 5.8–3.3 Ma with a minimum age of 2.5–2.0 Ma for the Martinez surface) that overrides basin-boundary faults. Melendrez Pass (5,860 ft in elevation) and drainage divide (fig. 1) mark the approximate western extent of what Menges (1981, p. 70 and 75) called the Martinez surface, or "high basin stand" of the general Sonoita-Patagonia area (fig. 3). A projection of the Martinez surface, the highest and oldest geomorphic surface in the basin (Menges, 1981), up to Melendrez Pass is interrupted by the topographically higher Granite Mountain (fig. 4). The underlying bedrock terrane is an exhumed, dissected, bedrock (or pediment) surface. This pediment surface has the same altitude and stratigraphic-structural position within the basin as upper basin-and-range fill (Menges, 1981). The maximum development and extent of the pediment ends with the Martinez "high basin stand" after which basin dissection began (Menges, 1981).
4. Undeformed Quaternary climatic terraces that developed during basin dissection (unit Qg).

DISCUSSION

PLACER GRAVELS

The stratigraphy established by Menges (1981) allows reconstruction of, and speculation about, the timing of exposure and erosion of gold-mineralized bedrock and the destinations of the erosion products.

Boston, Kentucky, Sucker, and Hughes Gulches, as well as two short branches to Hughes Gulch, head in the area that is topographically above the Martinez surface and are the only gulches that presently head in altered Laramide intrusions (figs. 1 and 2). This indicates that placers began to accumulate prior to the end of basin aggradation (prior to the Martinez surface).

Using Menges' (1981) ages for undeformed, post-tectonic, upper basin-and-range fill and his estimate for the slow aggradation of the upper basin-and-range fill (100–60 m/m.y.), one calculates a thickness of 200–330 ft for the upper basin-and-range fill (fig. 4, unit QTgu). One might assume that most of the rock that was once between the projected Martinez surface and the top of Granite Mountain was eroded prior to the Martinez and constitutes a large part of the upper basin-and-range fill (fig. 4, unit QTgu). Rock that was once above the present Granite Mountain exposure probably constitutes a large part of the lower basin fill (fig. 4, unit Tgl), and rock that was once between the projected Martinez surface and the present-day (exhumed pediment) surface probably constitutes the Quaternary terraces (fig. 4, unit Qg).

If most of the lode gold had been hosted by the interval of rock between the present-day pediment and the top of Granite Mountain, it would now be dispersed, according to hydraulic conditions of the time, in the basin-and-range fill (fig. 4, units QTgu and Tgl) in addition to the already-exploited Quaternary (Pleistocene) gravels.

If some of the lode gold were hosted by rocks above the top of Granite Mountain, there is a chance that the Oligocene to middle Miocene sedimentary rocks may contain some gold-bearing gravels (fig. 4, unit Ts).

LODE SOURCE FOR PLACER GRAVELS

Paleocene intrusions are the most logical sources for the gold-bearing quartz-calcite veins. Yet, it is possible that epithermal replacement of favorable Cretaceous beds deserves more attention as an additional source for gold in the placers. Tunnels into the north side of Granite Mountain revealed several feet of altered mineralized sedimentary

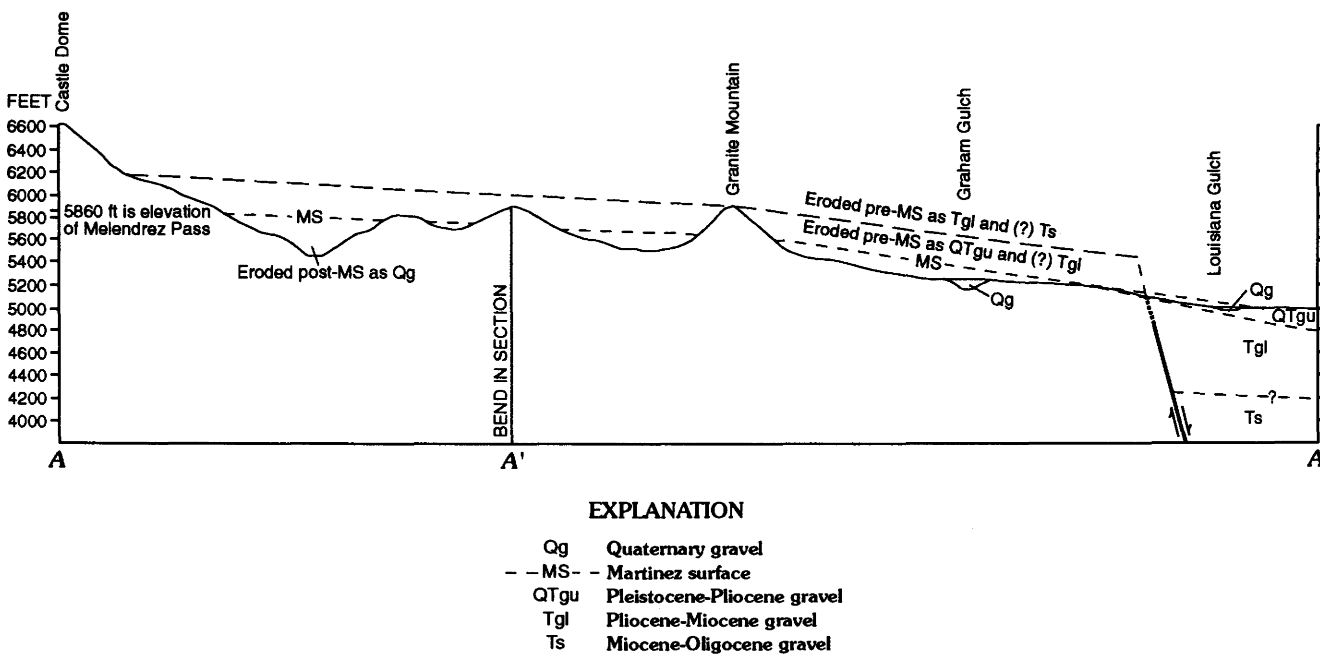

Figure 4. Schematic cross section showing the projected Martinez surface. Line of section shown on figure 2, same scale; vertical exaggeration ×2.

rocks in sharp contact with the intrusion (Hill, 1910, p. 16). Strongly mineralized limestone at the head of Harshaw Canyon reportedly contained good concentrations of gold (Maynard, 1907).

All of the gulches having gold-bearing gravels are east of the drainage divide and, except for Colorado and Los Posos Gulches, head in folded Cretaceous rocks (figs. 1 and 2). The heads of Colorado and Los Posos Gulches probably terminated in Cretaceous pediment after cessation of basin-and-range faulting and prior to the dissection of the Martinez surface and its pediment equivalent. Graham Gulch, one of the most productive areas in the district, is cut entirely in Cretaceous rock.

The lack of gold gravel in the branch of Ophir Gulch northwest of Greaterville (fig. 1) probably turned the attention of the prospectors away from the Cretaceous beds and toward the more obviously mineralized Paleocene intrusions. However, the lack of gold gravel could be a function of inopportune preservation rather than the absence of mineralized rock. Reports of chemical analyses of Cretaceous rocks farther than 1,000 ft from an intrusive body are scarse.

REFERENCES CITED

Blake, W.P., 1898, Remains of a species of *Bos* in the Quaternary of Arizona: American Geologist, v. 22, p. 65–72.

Drewes, Harald, 1969, The Laramide orogeny of Arizona southeast of Tucson, *in* Abstracts for 1968: Geological Society of America Special Paper 121, 501–502 p.

———1970, Structural control of geochemical anomalies in the Greaterville mining district southeast of Tucson, Arizona: U.S. Geological Survey Bulletin 1312–A, 49 p., 1 pl., scale 1:24,000.

———1971a, Geologic map of the Mount Wrightson quadrangle, southeast of Tucson, Santa Cruz and Pima Counties, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map 1–614, scale 1:48,000.

———1971b, Geologic map of the Sahuarita quadrangle, southeast of Tucson, Pima County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map 1–613, scale 1:48,000.

———1980, Tectonic map of southeast Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map 1–1109, scale 1:125,000.

Drewes, Harald, and Finnell, T.L., 1968, Mesozoic stratigraphy and Laramide tectonics of part of the Santa Rita and Empire Mountains southeast of Tucson, Arizona—Field trip II, *in* Titley, S.R., ed., Tucson, Arizona Geological Society, Guidebook 3, Southern Arizona: p. 315–324.

Hill, J.M, 1910, Notes on the placer deposits of Greaterville, Arizona, *in* Contributions to economic geology: U.S. Geological Survey Bulletin 430, p.11–22.

Houser, B.B., ed., 1992, Historic mining camps and Jurassic calderas: Arizona Geological Society Fall Field Trip, 1992, Guidebook, 46 p., 10 appendixes.

Johnson, M.G., 1972, Placer gold deposits of Arizona: U.S. Geological Survey Bulletin 1355, 103 p.

Maynard, G.W., 1907, Examining a placer property: The Mining World, July 6, 1907, p. 7–8.

Menges, C.M., 1981, The Sonoita Creek Basin—Implications for late Cenozoic tectonic evolution of basins and ranges in southeastern Arizona: Tucson, University of Arizona, M.S. thesis, 239 p.

Menges, C.M., and Pearthree, P.A., 1989, Late Cenozoic tectonism in Arizona and its impact on regional landscape evolution, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 649–680.

Reynolds, S.J., 1988, Geologic map of Arizona: Arizona Geological Survey Map 26, scale 1:1,000,000.

Schrader, F.C., 1915, Mineral deposits of the Santa Rita and Patagonia Mountains, Arizona: U.S. Geological Survey Bulletin 582, 373 p.

Tenney, J.B., 1929, History of mining in Arizona: Tucson, University of Arizona Library, Special Collections, unpublished manuscript, 401 p.

RELATIONSHIP OF MINERALIZATION TO KEY ROCK TYPES AND STRUCTURAL FEATURES OF SOUTHEASTERN ARIZONA

By Harald Drewes[1]

Field trip co-leader: S. J. Reynolds[2]

INTRODUCTION

Southeastern Arizona is renowned for its many large mineral deposits and famous mining districts. The region of the Coronado National Forest, located mainly in southeastern Arizona and the surrounding 50 mi of Arizona, New Mexico, Sonora, and Chihuahua, has produced about $20 billion in copper, lead, silver, and gold, primarily (Mardirosian, 1977). This extraordinary production, however, was not from deposits uniformly distributed throughout this region; most production has been from a northwest-trending metallogenic belt that crosses through the region west of a line extending from near Douglas to Hayden, Ariz. Southwest of this line many deposits are so large that relatively low grade ore lacking significant amounts of precious metals can be mined profitably. Most deposits northeast of this line are smaller, so that, under present conditions, gold or silver must be the main product or at least a substantial byproduct for them to remain economically viable.

Each of these two metallogenic terranes coincides with a distinct tectonic zone; both tectonic zones developed during the orogenic period in which most of the deposits formed. The southwestern metallogenic terrane, known as the porphyry copper belt because of the abundant porphyry copper deposits contained therein, is coincident with a more intensely deformed tectonic zone, referred to as the Western Intermediate tectonic zone (Drewes, 1981), and with large differentiated plutons associated with the Cordilleran (Laramide?) orogeny. By way of contrast, the northeastern metallogenic terrane is coincident with less deformed tectonic zones and with fewer, smaller, and less evolved plutons also associated with this orogeny.

While the main period of deformation and mineralization occurred during the Late Cretaceous and early Tertiary (near the area of present-day Tucson about 75–50 Ma), earlier and later events also occurred to contribute to the particular complexities of the region. Some structural features have been reactivated, in places having diverse directions of movement. Likewise, some mineral deposits appear to reflect hydrothermal overprinting, and geochemical remobilization may have occurred in some areas. The net result is a geologic legacy that is both bountiful and challenging. It is therefore no wonder that the geologic community working in this area has generated so many new concepts in economic and structural geology, while also producing a few conceptual conflicts.

TRIP OBJECTIVES

Through this field trip, Steve Reynolds and I intend to illustrate some of the key geologic associations of southeastern Arizona mineral deposits. We will visit the mineralized and much-deformed area at Helvetia and a nearly unmineralized, intensely deformed area at the base of the Rincon Mountains (fig. 1).

In the Helvetia district, base- and precious-metals deposits occur in a terrane composed of Paleozoic and Mesozoic sedimentary rocks and of Paleocene granite and latite porphyry stocks. Deposits are localized within selected formations, including the Middle and Upper Cambrian Abrigo Formation and Upper Devonian Martin Formation, where they are intersected by selected faults, such as northwest-trending high-angle faults (an area-wide association) and thrust faults (local association), and where there are bodies of a Paleocene quartz-latite porphyry

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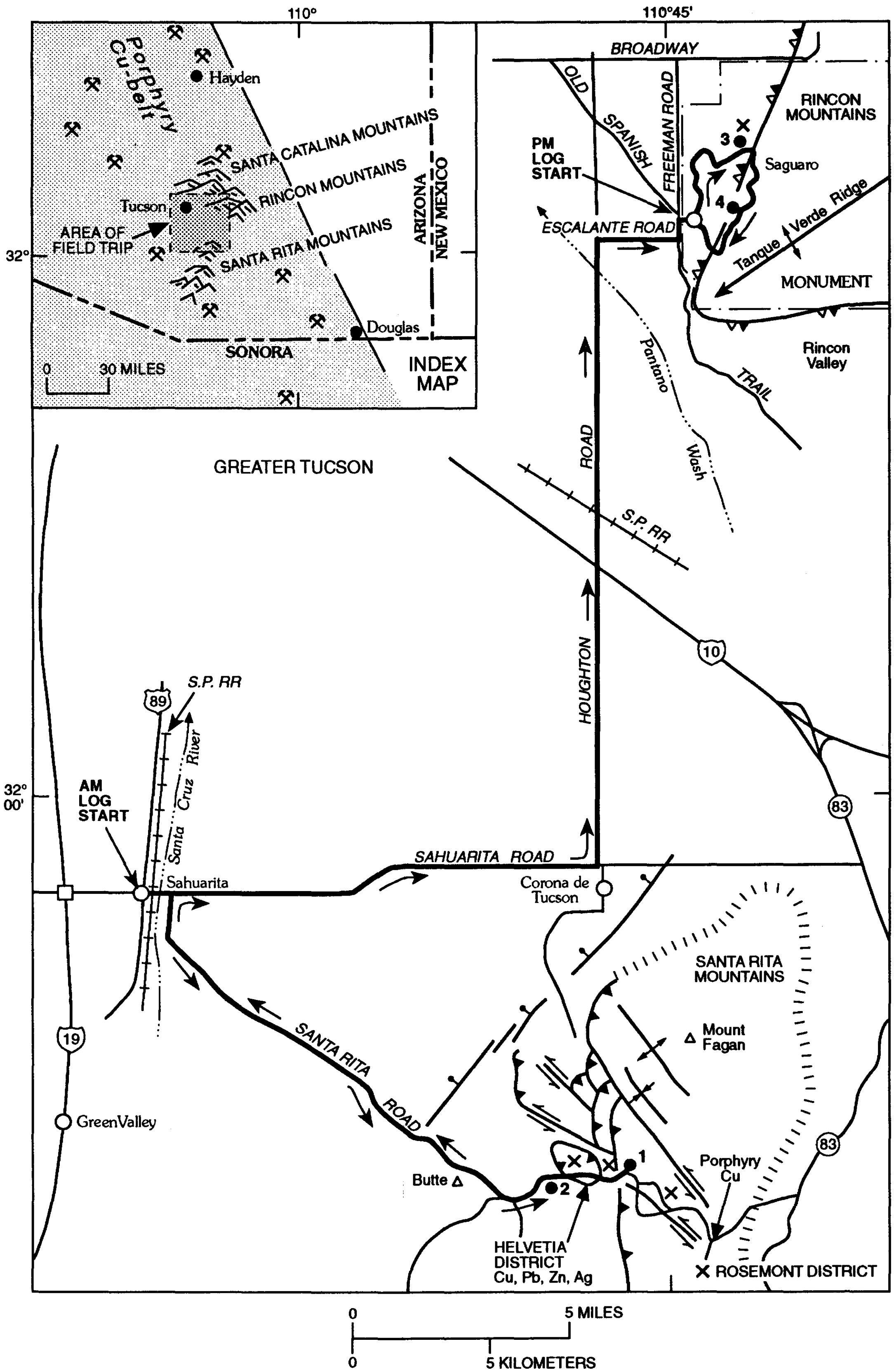


Figure 1 (above and facing page). Location of areas near Tucson to be visited on field trip (numbers 1–4 keyed to stops), and likely route to be used between them. Key geologic features shown are adapted from Drewes (1971a, 1977).

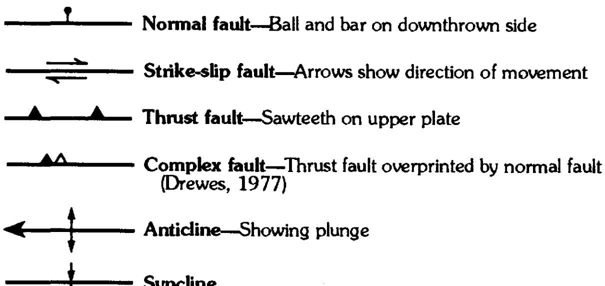
known as the ore porphyry. The Helvetia district has replacement, vein, and porphyry types of deposits. Similar geologic associations are common throughout southeastern Arizona. Many major porphyry deposits also contain replacement, vein, and porphyry deposit types and some additional deposit types. Indeed, porphyry copper deposits occur in the adjacent Rosemont district; the mineralizing systems of the Helvetia and Rosemont districts may be genetically related.

In the Rincon Mountains minor mineralized rock is present in rocks having a geologic setting similar to that at Helvetia, but occurring on the flank of a gneiss-cored dome (core complex). Such domes occur in a few southeastern Arizona ranges and in more ranges to the west and south. Probably all of these terranes have had a complex history of compression followed by extensional deformation. Low-angle faults typically flank such domes, and in many places to the west mineral deposits are linked to these structures. However, in southeastern Arizona base- and precious-metals mineralization along, and a short distance above, such faults is minor; yet mineralized rock of the types common in southeastern Arizona is encountered away from the gneiss-cored domes.

The two areas to be visited are characterized by at least two major geologic differences that might account for the contrast in amount of associated mineralized rock. First, the intrusive rocks present differ as to the type of magma. The gneiss-cored domes were intruded by a two-mica- and garnet-bearing peraluminous granite, whereas the intrusive rocks at Helvetia are quartz latite porphyry derived from a differentiated granitic suite. Second, outward-moving hydrothermal systems would have developed as a result of the Paleocene-Miocene(?) heating of rocks of the dome and the rising of the Oligocene-Holocene topographic dome, possibly well after the structural dome formed. Together, these conditions would not have favored initial accumulation of ore minerals and could even have resulted in unfavorable redistribution of ore minerals.

The observations and ideas offered on this trip thus serve to flag some helpful geologic characteristics (host rocks, faults, intrusive rocks) and some detrimental characteristics (later heating and doming) associated with southeastern Arizona ore deposits. In order to make practical decisions, a mineral explorationist must cope with a wide range of geologic features and an involved geologic history, which are summarized in the next section.

EXPLANATION



GEOLOGIC BACKGROUND

The general features of southeastern Arizona geology are well known through mapping, topical studies, field trips, and regional summaries (Drewes, 1981, 1991; Kranz, 1989). As a consequence of the sustained research efforts of the geologic community, controversies have arisen, been resolved or tabled, and new ones developed. The following understanding of the geologic development of the region, with possible minor variations, is accepted by most workers.

The oldest rocks show that during the Proterozoic Eon the region was covered by sedimentary and volcanic deposits (fig. 2). Upon deep burial, these rocks were intruded by large bodies of granite and granodiorite and were metamorphosed, or later retrograded, to the greenschist facies. The resultant schist, phyllite, metarhyolite, and metaquartzite, and the plutons intruding these rocks were strongly uplifted and deeply eroded before the end of the Proterozoic. They were also cut by major northwest-trending faults that may have been a part of the terrane marginal to the North American craton.

Following these events, the region was successively covered by Late Proterozoic, Paleozoic, Mesozoic, and Cenozoic sedimentary and volcanic rocks. Numerous gaps in the continuity of these sequences indicate periods of uplift and nondeposition or erosion. Some of the results of these times of uplift are accentuated by gentle tilting and, in one case, by strong deformation, known as the Cordilleran orogeny (the term "Laramide" is widely used but is preferred as the label for an orogenic phase (Drewes, 1988, 1991). Marine sedimentation predominated during the Paleozoic Era and occurred again briefly during the Early Cretaceous. Continental sedimentation of the Mesozoic Era was accompanied by effusion of andesite and rhyolite lavas and ash. During Jurassic time, granite plutons were emplaced locally. Upsection, the Late Cretaceous deposits became increasingly coarse and laden with andesitic detritus, indicative of both increasing relief and encroachment of the andesite-capped Cordilleran orogenic belt.

Mineralization occurred at a few sites, such as Bisbee, during the Jurassic. It may also have occurred around other Jurassic plutons of southeastern Arizona, but, because the older plutons are also sites of younger plutons, older mineral deposits may have been overprinted and, in any case, would be more difficult to date than the less altered younger plutons.

The long-lived Cordilleran orogenic period was composed of complexly intertwined sedimentation, deformation, magmatism, metamorphism, mineralization, and

AGE		STRATIGRAPHIC UNIT	DESCRIPTION	THICKNESS (m)
QUATERNARY	Holocene	unnamed	Gravel and sand	
	Pleistocene			
TERTIARY	Pliocene			
	Miocene			
	Oligocene	unnamed	Rhyolite dikes	
	Paleocene	unnamed	Quartz latite dikes and plugs of the Greaterville intrusives Quartz monzonite of the Helvetia stocks	
CRETACEOUS	Late Cretaceous	Elephant Head Quartz Monzonite Madera Canyon Granodiorite	Stocks	
		Salero Formation	Rhyolite, andesite, and sedimentary rocks	2000 ±
		Fort Crittenden Formation	Conglomerate, sandstone, and shale; tuff in upper part	3000 ±
	Early Cretaceous	Bisbee Group	Arkose, sandstone, shale, and siltstone	2700 ±
JURASSIC		Canelo Hills Volcanics	Arkose, sandstone, shale, and tuff	180 ±
		Gardner Canyon Formation	Red mudstone, dacite, and conglomerate	600±
TRIASSIC		Mount Wrightson Formation	Rhyolite, andesite, and sandstone	2600 ±
PERMIAN	Early Permian	Rainvalley Formation	Limestone, dolomite, and sandstone	0-90
		Concha Limestone	Cherty limestone	120-175
		Scherrer Formation	Quartzite, dolomite, and sandstone	220 ±
		Epitaph Dolomite	Limestone and dolomite	300 ±
		Colina Limestone	Limestone	110 ±
PENNSYLVANIAN	Late Pennsylvanian	Earp Formation	Siltstone and marlstone	250 ±
	Late and Middle Pennsylvanian	Horquilla Limestone	Fine-grained limestone	300 ±
MISSISSIPPIAN		Escabrosa Limestone	Coarse-grained limestone	170 ±
DEVONIAN	Upper Devonian	Martin Formation	Dolomite, limestone, and siltstone	120 ±
SILURIAN				
ORDOVICIAN				
CAMBRIAN	Late Cambrian	Abrigo Formation	Shale, sandstone, and limestone	225-275
	Middle Cambrian	Bolsa Quartzite	Quartzite	140 ±
	Early Cambrian			
PROTEROZOIC	Middle Proterozoic	Continental Granodiorite	Granodiorite porphyry	
	Early Proterozoic	Pinal Schist	Gneiss and schist	

Figure 2. Stratigraphic section of the Helvetia area and the Sahuarita quadrangle (Drewes, 1971a).

erosion (Drewes, 1981, 1991). Because the few spectacular effects of these processes are far better appreciated than the many less spectacular ones, there is a tendency to view these events as much shorter-lived than they actually were. Compressional deformation peaked twice during this period, first at about 75 Ma and then at 52 Ma, but deformational responses occurred during a span of time lasting tens of millions of years. Regionally, the compressional orientation was east-northeast to west-southwest, but locally the orientation of compression during the second phase was markedly different, probably in response to local controls rather than to a massive reorientation of the regional stress vector. Deformation depth (equals thickness of cover beneath which main thrust faulting occurred) increased during the early (main) phase, perhaps to levels exceeding 6 km (Drewes, 1991). Deformation intensity increased westward and involved crystalline basement in eastern Arizona but not in western New Mexico. Many large and multiphase plutons were emplaced near Tucson, in places accompanied by (capped by?) volcanic effusion and caldera formation (Drewes, 1980, 1991; Lipman and Sawyer, 1985); to the east these activities decreased. The subtler aspects of orogenic processes lasted longer and added a gradational quality to the otherwise distinct episodic aspects of orogenic activity. Some examples are covered by Drewes (1991).

Accompanying or immediately following the magmatic event (or the second of two such events), mineralization was widely active. Fluids migrated along major, steep, commonly northwest-trending faults at depth, and at shallower levels they spread out into available faults of diverse trend and inclination.

While these events were taking place over most of the region, although systematically younger and less intensely in the east than the west (Drewes, 1991), a slightly different development occurred in the terrane of the gneiss-cored domes. Even now their development, especially their early (late orogenic) phase, is poorly understood, and even the existence of an early phase is controversial. The trip leaders are in accord that in the case of the Rincon Mountains, emplacement of the early and main phase of peraluminous granite took place by late Paleocene or early Eocene time, essentially concurrently with the emplacement of the ore porphyry at Helvetia and elsewhere. Discussions concerning the contrast in sources of these magma types, their environments of emplacement, and their association with tectonic events are deferred to informal discussions during the excursion. Less uncertainty exists concerning the Miocene to Holocene development of the structures in the Rincon Mountains.

Post-Cordilleran orogenic development involved many changes, of which the most significant are that results we see mainly are near-surface, rather than deep-seated, phenomena, and that extensional stress replaced compressional stress. Again, questions have been raised about a possible spatial or genetic link between these two tectonic environments, discussions of which also are best deferred to informal communication during the excursion.

Well established is the fact that during late orogenic time and early post-orogenic time uplift was large and erosion deep. By Oligocene time volcanism became widespread and block faulting was initiated. Volcanism was mainly rhyolitic, with the eruption of extensive ash-flow sheets from calderas, only a few of which are as yet identified. Block faulting continued even after volcanism waned toward the end of the Miocene; consequently the present basin-and-range topography developed, and extensive basin sediments conceal much of the volcanic story. Small and generally simple granite plutons were emplaced in the root zones of volcanic systems, and in places are associated with mineral deposits. Probably the chief result of these post-orogenic events was the partial concealment and frequent disruption of older rock sequences and structures.

Once more, the terrane of gneiss-cored domes developed somewhat differently than did the surrounding region. In particular, peraluminous granite was emplaced and a rapid and large amount of uplift of the domes occurred during and after late Oligocene time; extensional tectonism may have occurred at several times and under varied conditions, all intertwined with a protracted(?) cooling history extending well into the Miocene. The low-angle fault flanking the Rincon Mountains and other such gneiss-cored domes is a reactivated structure having a history of diverse movement in several tectonic environments. Rocks along and above this fault have numerous sites of mineral concentration, all of them small, however. Speculations on the significance of these mineral occurrences and description of other features of the domes will be additional topics for informal discussion during the field trip.

FIELD TRIP PLANS

The excursion is designed to be run with vans during a single day. The first area to be visited will be the Helvetia district in the northern Santa Rita Mountains; the afternoon will be spent on the west flank of the Rincon Mountains. Lunch will be taken at the vehicles before leaving Helvetia (fig. 1).

Some walking will be necessary in both areas. Most of the walking will be on tracks or fairly level ground, but in each area there will be some cross-country segments about 1 km long. Boots are recommended footwear.

Because of uncertainty about the route to be used between the areas to be visited, separate roadlog starting points are used for each part of the day. Roadlog distances are given in miles to be most practical with odometers of older cars. General directions are given in compass quadrants; detailed directions while underway are given in terms of the "clock compass," following the convention that the front of the car at the point of comment is 12 o'clock.

ROAD LOG

Miles

0.0 Sahuarita community, at junction of Sahuarita Road and U.S. 89, about 1.9 mi east of I–19; eastbound. Cross S.P. Railroad track and pass through pecan grove (fig. 1).

0.8 Turn right (south) on Santa Rita Road.

10.7 Knoll at 9 o'clock is underlain by Middle Proterozoic Continental Granodiorite.

11.1 Butte at 3 o'clock is also underlain by this granodiorite, except the crest of the hill, which is underlain by an aplite dike.

12.5 Road junction; continue straight ahead another 0.05 mi to another junction, then bear left, to northeast.

Hills at 3 and 9 o'clock between these junctions are also underlain by the Continental Granodiorite, which typically weathers dark brownish gray. The basin at 8 to 10 o'clock, beyond the junctions, is underlain by a Paleocene (54-Ma) granodiorite that weathers light brownish gray. Jagged crest of the Santa Rita Mountains beyond the basin is underlain mainly by lower Paleozoic sedimentary rocks (fig. 2).

13.8 Hill at 10 o'clock marks west end of Helvetia klippe (figs. 3, 4). Bear right in next wash, keeping to main road.

14.2 Helvetia site (fig. 3) nearby at 9 o'clock. Beyond the site are many outcrops along the road that we will visit on our return down the road. Rocks along the road include the Lower Permian Scherrer Formation (quartzite) and Concha Limestone, and the Lower Cretaceous Bisbee Group (shale); these strata are part of a sequence summarized on figure 2. The reported Jurassic age of the Glance Conglomerate (Bilodeau and others, 1987, in turn based on thesis work of the last two authors) is based on dates of an underlying volcanic rock (Hayes and Raup, 1968) and so is not acceptable. Furthermore, some Glance is known to be interbedded in the overlying Morita Formation and even in Mural Limestone, both of the Bisbee Group, and Mural contains Aptian-Albian fossils. Slopes across the canyon from a mine (at 9 to 10 o'clock) along the road are underlain by Paleocene quartz latite porphyry (56 Ma). The hill beyond this porphyry (locally known as the "ore porphyry") stock is underlain by Concha Limestone. These sedimentary rocks, as well as some Cambrian and Devonian formations, are part of the Helvetia klippe, which is faulted over the Proterozoic and Paleocene granodiorites (figs. 4, 5). In turn, the klippe is intruded by the quartz latite porphyry. Features of this klippe will be reviewed at **STOP 1, site 1h**, and **STOP 2**. Petrographic descriptions were given by Drewes (1976).

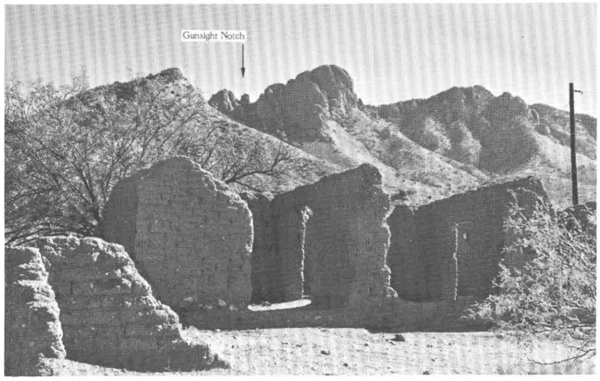


Figure 3. View east of the crest of the northern part of the Santa Rita Mountains and the conspicuous Gunsight Notch above Helvetia ghost town. Much of the crest south of the notch is underlain by Middle Cambrian Bolsa Quartzite, which dips steeply to the east. A major strike-slip fault trends northwest through the notch. Photograph by Jack Rathbone.

15.7 **STOP 1. Flat area below large mine dump at 9 o'clock.** Continue on foot, following traverse **1a–1i** shown in figure 4.

Supplemental map data given by Drewes (1971a; 1972a, pl. 4).

(1a) Drill site at lower member of the Lower Permian Epitaph Dolomite, which is mainly composed of marlstone, dolomitic siltstone, and interbedded argillite and limestone. Note the tectonic pod of gypsum. Slope to east is underlain by the Lower Permian Scherrer Formation (composed mainly of fine-grained, very light pinkish gray quartzite or sandstone), by the overlying Lower Permian Concha Limestone, and by the capping Lower Permian Rainvalley Formation (limestone, dolomite, and sandstone).

(1b) Hilltop, underlain by upended, metamorphosed Middle and Upper Pennsylvanian Horquilla Limestone, provides an overview of the Paleozoic rocks and of the thrust faults and tear faults of Paleocene age (Helvetian phase of the Cordilleran orogeny). Geology reviewed on panorama (fig. 6).

(1c) Thrust-faulted slivers of Upper Devonian Martin Formation (brown dolomite, limestone, and some sandstone), here strongly altered to calc-silicate minerals, and of Middle and Upper Cambrian Abrigo Formation (thin-bedded shale, siltstone, and some limestone), also altered to calc-silicates, and of Middle Cambrian Bolsa Quartzite (coarse-grained, light-gray to brownish- or purplish-gray, arkosic rock). To the west is the northeast corner of the Helvetia klippe (fig. 7); prospect pits are located along its base.

(1d) Continental Granodiorite thrust slice. Rock is coarse grained and very coarsely porphyritic. Elsewhere in the Santa Rita Mountains it is dated at 1,450 Ma (slightly reset?) and in the Rincons it may be as old as 1,650 Ma; locally, however, its radiogenic age is strongly reset, reflecting a 55-Ma thermal event probably related to the emplacement of the late orogenic stocks (Drewes, 1976, p. 9–17).

(1e) Second thrust plate of lower Paleozoic formations.

(1f) Another slice of Continental Granodiorite.

(1g) Recrystallized Bolsa Quartzite along the Gunsight Notch fault zone, a tear fault that bounds the southwest sides of some of the local thrust plates. These thrust and tear faults merge in such a way as to show that they were active concurrently. The largest offset on a tear fault here is about 2 km.

This group of tear faults is believed to have developed near (above?) a major left-lateral fault in the basement rocks. A similar structure, the Sawmill Canyon fault zone, lies 15 km to the south (Drewes, 1971a,b).

Return to road for lunch. After lunch, continue traverse down road while cars are shuttled to flat area near ghost town.

(1h) The Paleocene granodiorite stock of the flats south of Helvetia is cut by the thrust fault beneath the klippe, and that thrust fault is cut by the quartz latite porphyry stock (fig. 7), thereby closely dating this phase of faulting at 54–56 Ma (Drewes, 1971a, 1972a, 1976). (Note that the determined ages of the two stocks are reversed compared to their relative ages as indicated by field relations but are within the margin of analytical error of each other.)

(1i) Road cut of thrust fault at base of klippe located 0.1 mi down the road from a sharp curve. Lower quartzite member of the Scherrer Formation is thrust faulted on the Paleocene granodiorite. Return to vehicles.

16.1 **STOP 2. Southwest side of wash.** Review features of west side of Helvetia klippe. Brown ledge is the Cambrian Bolsa Quartzite, which is overlain by a normal succession of Cambrian Abrigo and Devonian Martin Formations. The Pennsylvanian Horquilla Limestone caps the hills. The Mississippian Escabrosa Limestone, which normally separates the Martin from the Horquilla, is here cut out by a low-angle fault. The thrust fault is well exposed in adits on all sides of the klippe and has been penetrated by many drill holes through the klippe, which establish the fault is saucer shaped. Copper was deposited from hydrothermal solutions related to the "ore porphyry," spread along the faults from the stock, and locally replaced the Abrigo and Martin Formations (Schrader, 1915; Creasey and Quick, 1955; Heyman, 1958; Lutton, 1958; Michel, 1959; Drewes, 1972b).

A knoll 1 km northwest of this stop is underlain by Mississippian Escabrosa Limestone and Pennsylvanian Horquilla Limestone, which are folded about a southwest-inclined axial plane. Similarly oriented folds occur near Mount Fagan (fig. 1) and elsewhere in the region. These folds of the early phase (Piman phase) of the Cordilleran orogeny formed after the deposition of the Fort Crittenden Formation of late Late Cretaceous age and before emplacement of latest Cretaceous stocks that are found in the main part of the Santa Rita Mountains (Drewes, 1971b,c, 1976). Movement on the thrust and tear faults of the Helvetia area was to the northwest and marks the local transport direction during the late (Helvetian) phase of the Cordilleran orogeny, about 55 Ma. Escabrosa Limestone on another higher knoll, 2 km to the northeast, was mined for smelter flux.

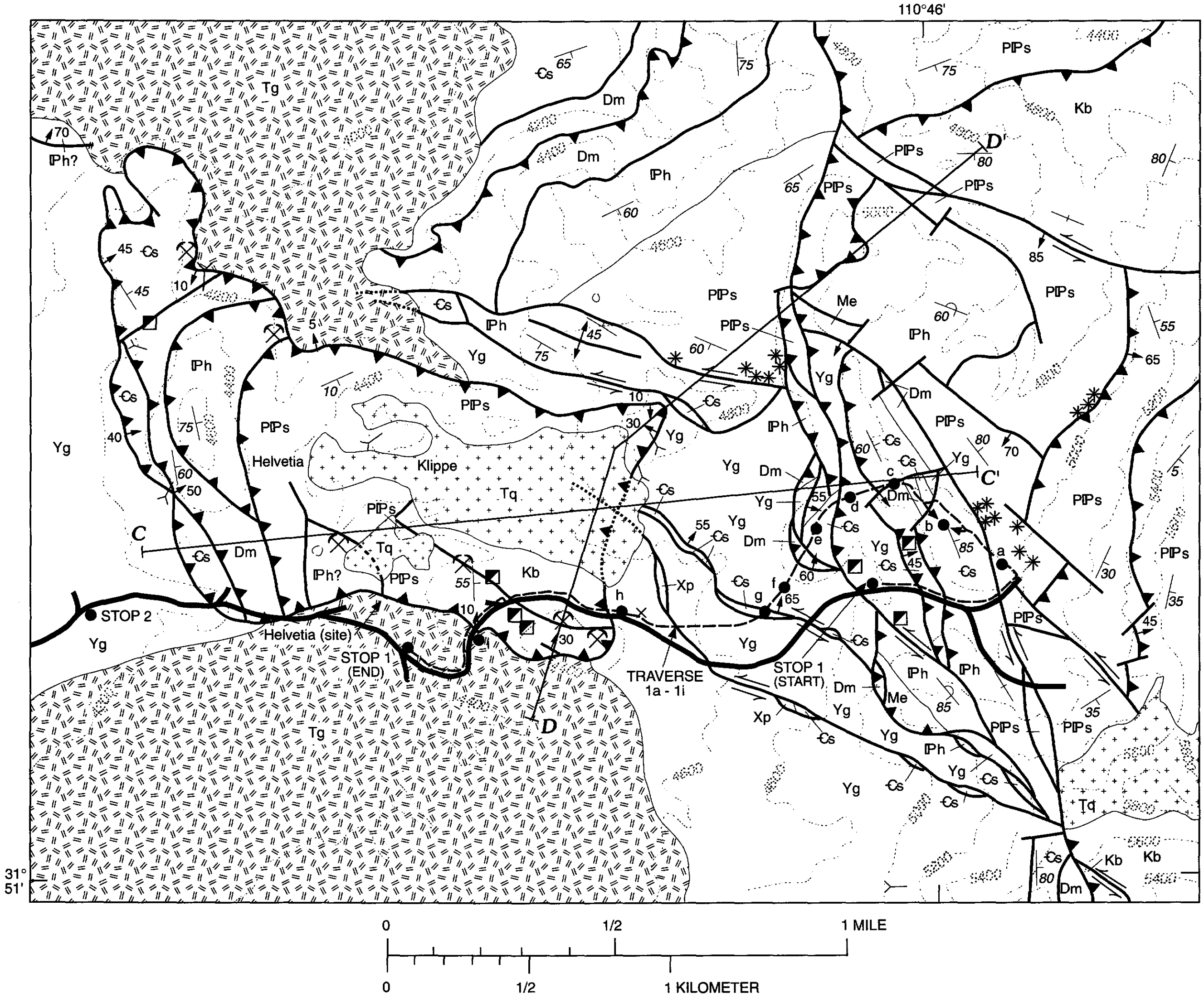
Return to Sahuarita Road.

29.1 Road junction, Sahuarita Road. **End of first part of the road log**. Likely route shown in fig. 1; turn right to Corona de Tucson community, thence turn north on Houghton Road past I–10 and Pantano Wash, east on Escalante Road, and finally north again on Freeman Road for 0.2 mi to the entrance of Saguaro National Monument. **The second part of the road log begins at the Park entrance.**

0.1 Monument Headquarters buildings. Stop for a check-in; then continue on Loop Drive (fig. 8). Hills near Headquarters are underlain by a quartzitic variety of the Early Proterozoic Pinal Schist (actually a quartzose phyllite here) mapped by Pashley (1966), Drewes (1977), and Thorman and Drewes (1981), and adapted in figure 8.

3.6 Small rubble-crop near the road at 3 o'clock is of dark-brownish-black turkey-track andesite porphyry, noted for its large phenocrysts (Cooper, 1961), here in the Oligocene and Miocene Pantano Formation.

OPTIONAL STOP 3. Park and walk trail to the Loma Verde Mine area (fig. 8). Copper oxide minerals coat fractures in Tertiary andesite porphyry and Middle Proterozoic Rincon Valley Granodiorite, dated from nearby at 1,440 Ma and dated from farther away (off area of fig. 8) at



EXPLANATION

CORRELATION OF MAP UNITS

Unit	Age
Tq	TERTIARY
Tg	TERTIARY
Kb	CRETACEOUS
PIPs	PERMIAN AND PENNSYLVANIAN
IPh	PENNSYLVANIAN
Me	MISSISSIPPIAN
Dm	DEVONIAN
Cs	CAMBRIAN
Yg	PRECAMBRIAN
Xp	PRECAMBRIAN

DESCRIPTION OF MAP UNITS

- **Quartz latite porphyry**
- **Granodiorite and quartz monzonite**
- **Bisbee Group**
- **Rainvalley to Earp Formations**
- **Horquilla Limestone**
- **Escabrosa Limestone**
- **Martin Formation**
- **Abrigo Formation and Bolsa Quartzite**
- **Granodiorite porphyry**
- **Pinal Schist**

Contact—Dotted where concealed

75 **Fault**—Showing dip. Dotted where intruded

Thrust fault—Sawteeth on upper plate

Strike-slip fault—Arrow couple shows direction of movement

Strike and dip of beds

15 **Inclined**

Vertical

80 **Overturned**

Gypsum—Includes anhydrite (?); in tectonic pods

Adit

Shaft

Prospect

Quarry

h g **Traverse**—Showing sites described in text

Figure 4. Geology of the central part of the Helvetia area showing route of walking tour of **STOP 1** (Drewes, 1972a, pl. 4). *C–C'* and *D–D'* refer to structure sections shown as figure 5. Other sections are shown with published maps (Drewes, 1971a, 1972a) and with other roadlogs.

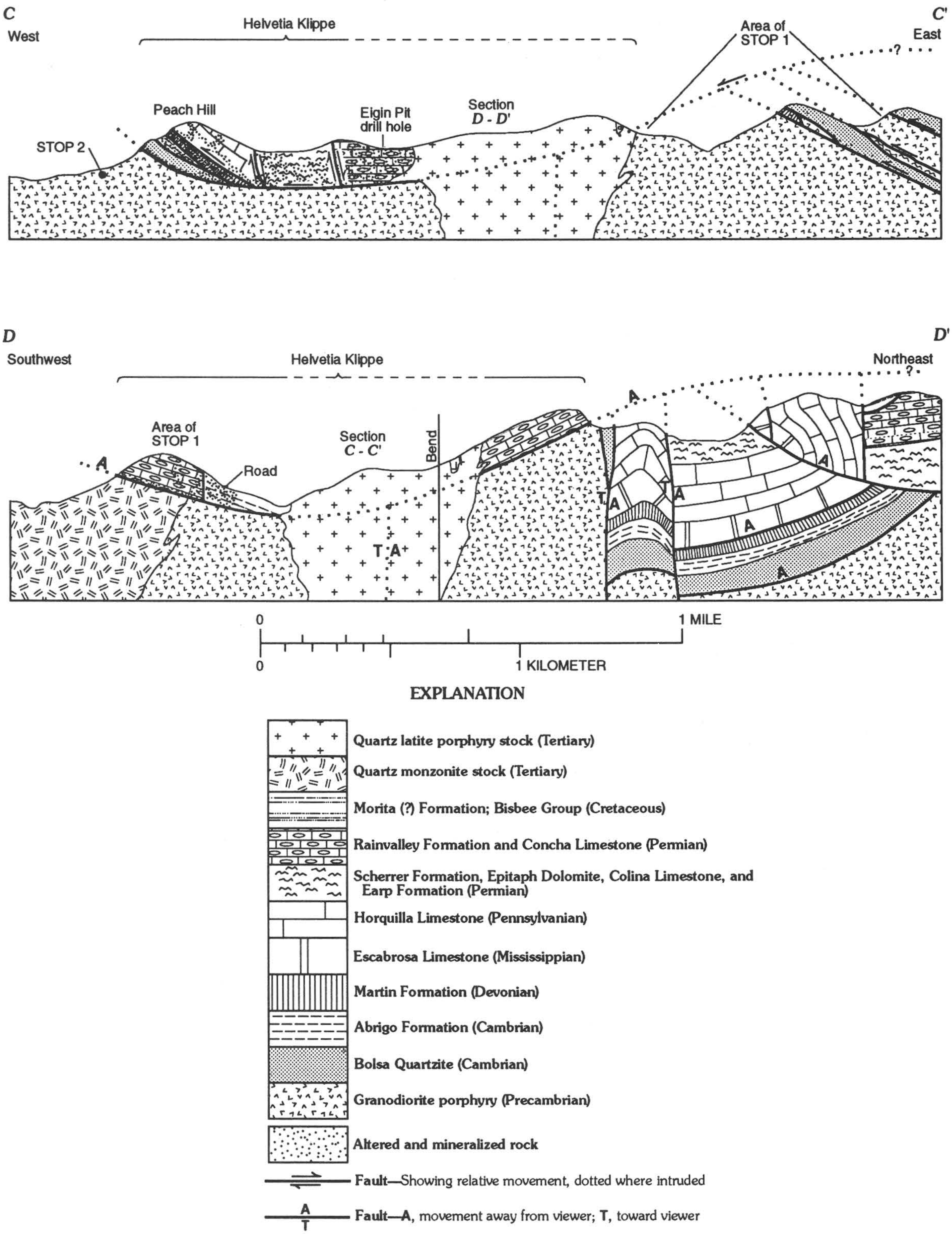


Figure 5. Generalized structure sections of the Helvetia area of the Santa Rita Mountains.

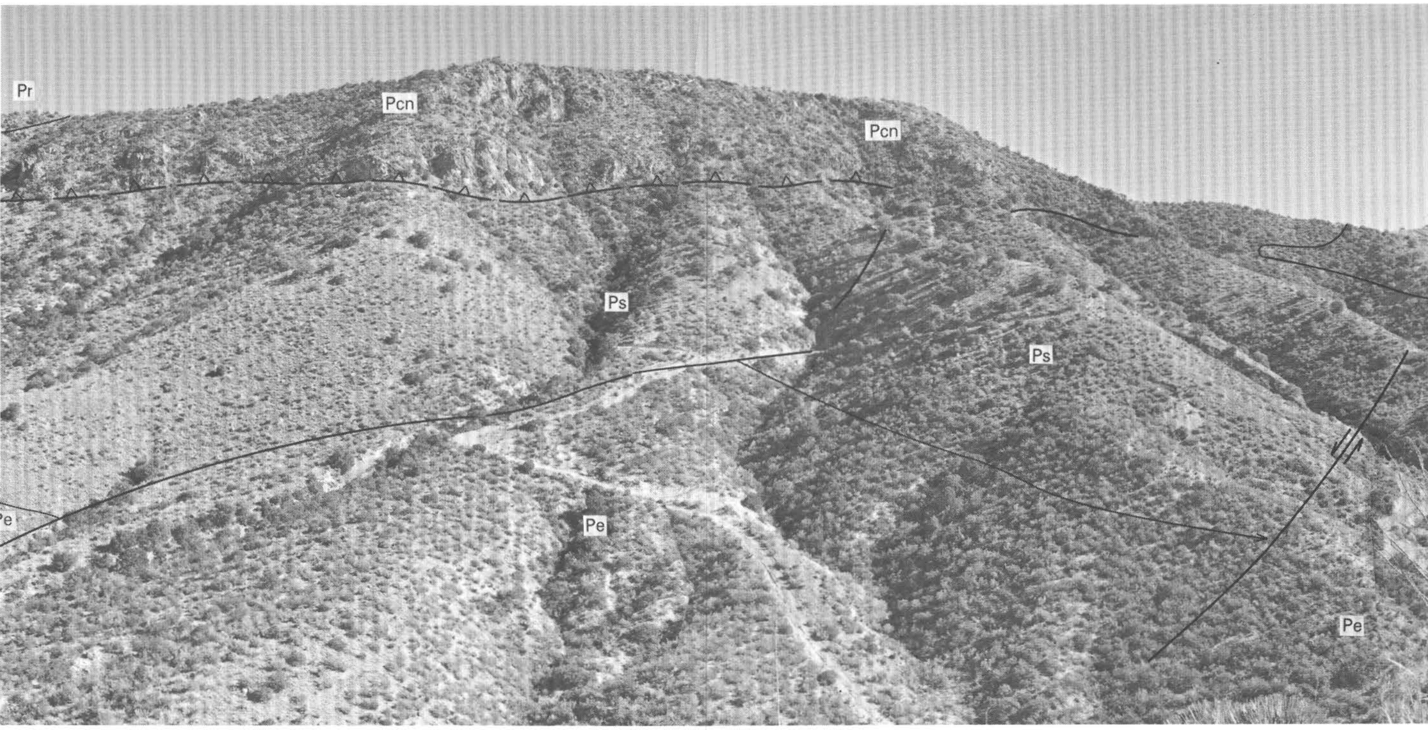


Figure 6 (above and facing page). Panorama to east and southeast from **STOP 1b**. Slope to east is underlain mainly by the Lower Permian Scherrer Formation (Ps) and Lower Permian Concha Limestone (Pcn), which are separated by a bedding-plane thrust fault. The low spur to the southeast is mostly of Middle and Upper Pennsylvanian Horquilla Limestone (IPh), and the high hill beyond and left of the spur has a plug of quartz latite porphyry (Tql). Gunsight notch lies between the plug and the bold knob of Middle Cambrian Bolsa Quartzite (Ꞓb) and Middle Proterozoic Continental Granodiorite (Yg). The thrust faults, which we will cross in the next part of the traverse (d–f), merge with strands of a left-lateral fault that crosses the range at the notch. Units are Pr, Permian Rainvalley Formation; Pe, Epitaph Dolomite; Ꞓa, Upper Cambrian Abrigo Formation. Photographs by Jack Rathbone.

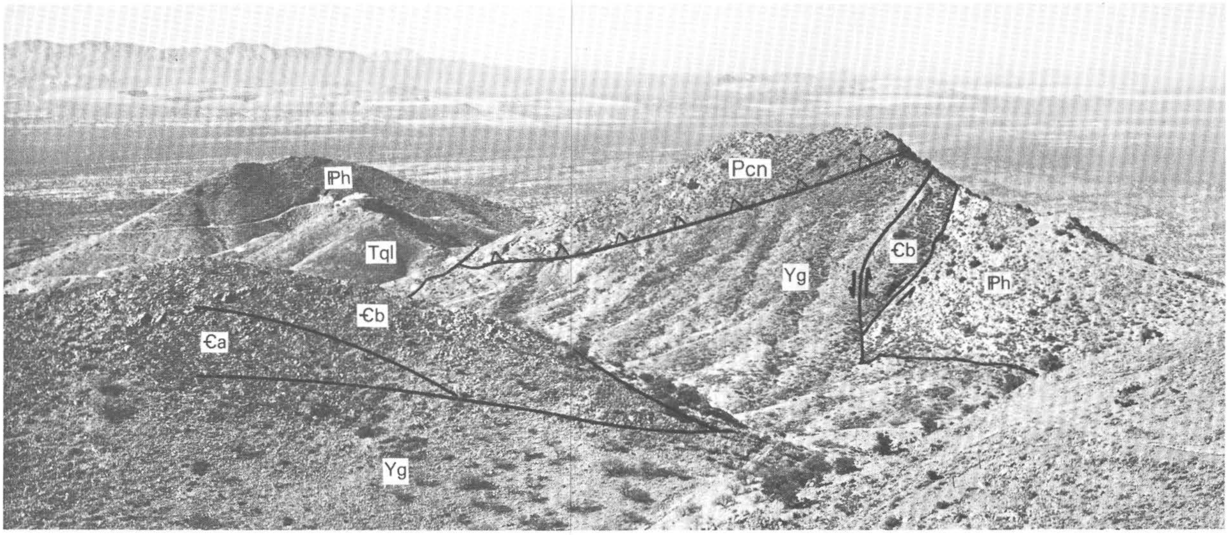
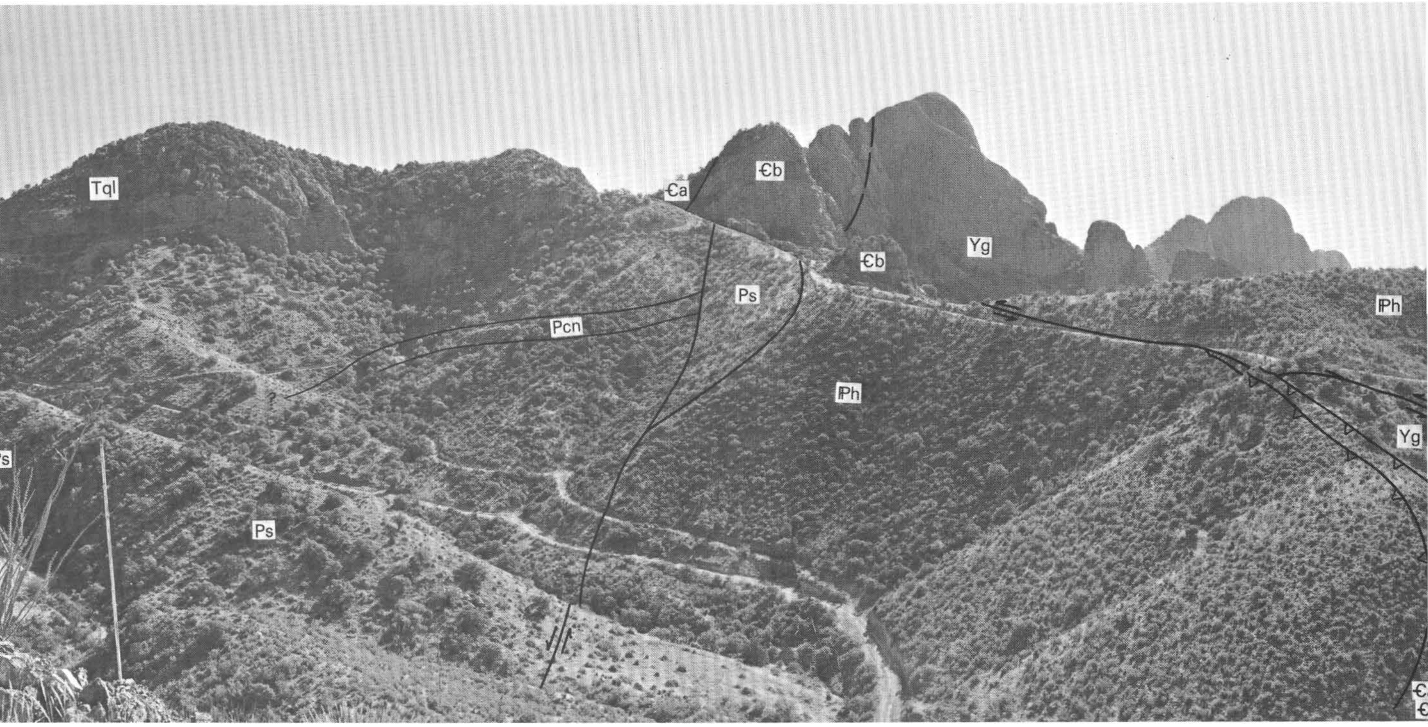


Figure 7. View west of the Helvetia klippe and, beyond the Santa Cruz River valley, the mine dumps on the east flank of the Sierrita Mountains (light areas). To the right a left-lateral fault separates Paleozoic formations (Ꞓb, IPh) from Proterozoic granodiorite (Yg). To the left an "ore porphyry" plug (Tql) cuts the Helvetia klippe. Units are Pcn, Permian Concha Limestone; Ꞓa, Upper Cambrian Abrigo Formation.



1,450–1,560 Ma (Marvin and others, 1978). At other nearby sites, Miocene ages, believed to reflect a late thermal event of the gneiss cored dome, have been obtained.

All the rocks of this stop area are part of the carapace of the gneiss dome, forming the hanging wall of the Santa Catalina complex fault. This fault is concealed nearby but is well exposed at the next stop. It is called a "complex" fault to indicate that it was reactivated and that movement on the fault was in different directions—Late Cretaceous-Paleocene movement was top to the east-northeast, as a thrust fault; Oligocene movement was top to the south-southwest, as a low-angle normal fault. During the interim the tectonic environment changed markedly.

Return to vehicles and resume tour of Loop Drive.

Outcrops along road are of crystalline rocks of the dome core. Santa Catalina complex fault is covered along the drive.

5.2 **STOP 4.** Traverse on foot; head northwest (fig. 8).

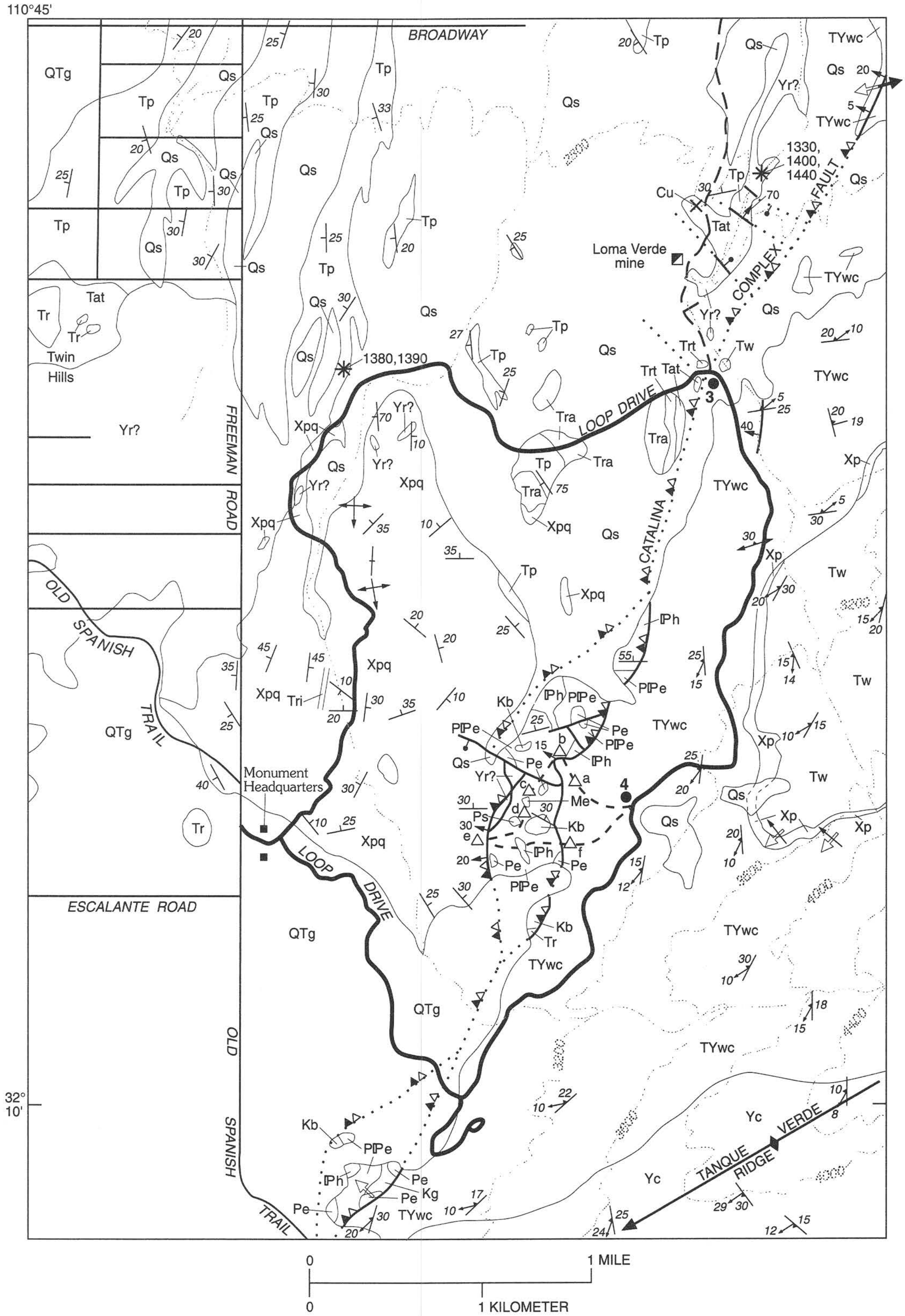
(4a) Overlook into gully. En route to **4a**, note the lit-par-lit gneiss, the foliation and lineation, and the protomylonitic fabric. Both ductile and brittle fabric elements are present. On the opposite canyon wall the ledge, which dips 15° W., is indurated brecciated protomylonite, which separates the underlying crystalline core rocks from an overlying melange sheet. Continue across the canyon to the stripped surface of the Santa Catalina complex fault.

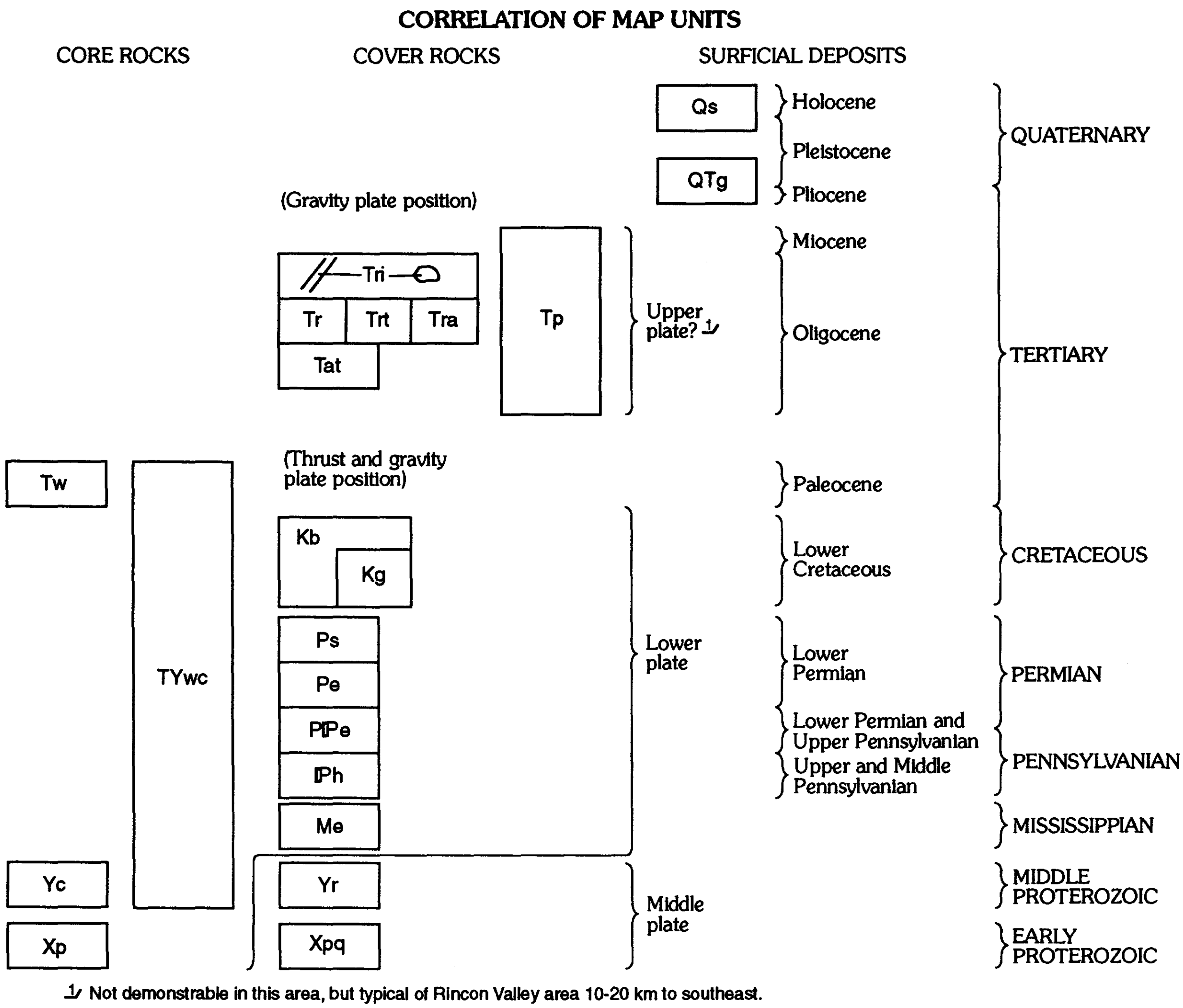
(4b) Fault surface. The ledge is composed of an indurated breccia of the protomylonitized core rock. The overlying rocks form a tectonic melange sheet, in which scattered blocks as much as 100 m across are present. The matrix is a red siltstone or marlstone of the Upper Pennsylvanian and Lower Permian Earp Formation. The blocks are of assorted Paleozoic and Mesozoic formations. Some of the limestone blocks are internally folded, and these were systematically studied by Davis (1975) and his students, who inferred the melange to have moved northwest off the adjacent part of the Tanque Verde Ridge. This movement is different from, and probably later than, that which formed the ductile feature of the lineation in the gneiss below the Santa Catalina fault.

(4c) First knoll on the ridge. Nearby blocks in the melange are of red jasper-pebble conglomerate (Earp) and of dark-gray dolomite (Permian Epitaph Dolomite). Outcrops on the hill below, to the west, are quartzitic Pinal Schist, which overlies the melange sheet.

Continue south along the ridge.

(4d) Second knoll on the ridge. Nearby blocks are brownish-gray to purplish-gray quartzite (Bolsa)


110°45'
BROADWAY
FREEMAN ROAD
OLD SPANISH TRAIL
ESCALANTE ROAD
LOOP DRIVE
Twin Hills
Monument Headquarters
Loma Verde mine
CATALINA
COMPLEX FAULT
TANQUE VERDE RIDGE
1380,1390
1330, 1400, 1440
32° 10'
0 1 MILE
0 1 KILOMETER



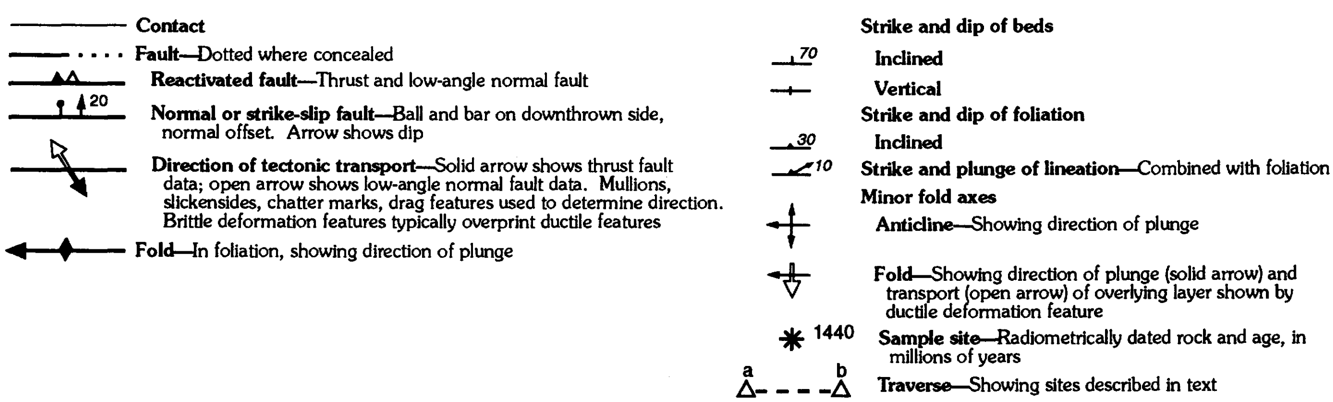


Figure 8 (above, facing, and following page). Geology of Loop Drive area, at the foot of the Rincon Mountains, showing stops at which mineralized rock and structural features will be examined along and near the Santa Catalina complex fault (diversely reactivated fault), adapted from Drewes (1977).

DESCRIPTION OF MAP UNITS FOR FIGURE 8

Qs **Sand, silt, and gravel (Holocene and Pleistocene)**—Stream and terrace deposits

QTg **Sand and gravel (Pleistocene and Pliocene)**—Pediment and basin-fill deposits. Light-gray, coarse, subangular deposits derived from core rocks nearby

Tp **Pantano Formation (Miocene to Oligocene)**—Fluvial deposits. Pinkish-gray, poorly indurated, fine-grained conglomerate, sandstone, and claystone. Pebbles derived from cover rocks at a moderate distance and from volcanic rock nearby

Rhyolitic rock (Oligocene)

Tri **Intrusive rock**—Volcanic necks and dikes

Tr **Lava flow**—Aphanitic to finely porphyritic

Trt **Tuff and tuff breccia**—May contain andesite clasts

Tra **Agglomerate**—Clasts of rhyolite welded tuff; contains some siltstone and conglomerate lentils

Tat **Andesite (Oligocene)**—Coarsely porphyritic lava flow and pyroclastic rock, locally known as Turkey Track andesite

Tw **Wrong Mountain Quartz Monzonite (Paleocene)**—A two-mica- and garnet-bearing peraluminous granitic rock originally assigned to the Middle Proterozoic (Drewes, 1977) but now seen as comprising a suite of intrusive rocks of which the oldest and main phase, present in this area, is probably Paleocene. A mid-Tertiary cooling history has complicated interpretations of ages from the Rincon dome and requires full review of geologic relations among local rocks and intrusive events of similar rocks in nearby mountains (Drewes, 1991)

TYwc **Wrong Mountain Quartz Monzonite and Continental Granodiorite, undivided (Paleocene and Middle Proterozoic)**—Variously mixed rocks, including lit-par-lit injection and partial assimilation complicated in this area by multiple-stage deformation that produced both older ductile and younger brittle structural features

Kb **Bisbee Formation (Lower Cretaceous)**[1] —Shale and sandstone

Kg **Glance Conglomerate Member**—Pebble conglomerate. Clasts are derived from undeformed Paleozoic and Precambrian granitic rocks

Ps **Scherrer Formation (Lower Permian)**—Nearly white, fine-grained, quartzose sandstone

Pe **Epitaph Dolomite (Lower Permian)**[1] —Dark-gray cherty dolomite and some limestone

PPe **Earp Formation (Lower Permian and Upper Pennsylvanian)**—Reddish-gray marlstone, siltstone, shale; locally also contains a little pale-brownish-gray limestone and a thin bed of reddish-gray, rounded chert-pebble conglomerate

Ph **Horquilla Limestone (Upper and Middle Pennsylvanian)**[1] —Light-pinkish-gray, fine-grained, thin- to thick-bedded, sparsely cherty limestone

Me **Escabrosa Limestone (Mississippian)**[1] —Medium-gray, thick- to thin-bedded, coarse-grained cherty limestone

Yr **Rincon Valley Granodiorite (Middle Proterozoic)**—Massive, nonfoliated biotite or biotite-hornblende granodiorite. K-Ar age on hornblende at 1,560±100 Ma in Rincon Valley, and slightly younger in this area (Drewes, 1977). Queried rock looks more granitic and may be part of a separate pluton, possibly linked to the Oracle Granite, separated from the Rincon Valley Granodiorite by a septum of quartzitic phyllite (unit Xpq), all in a thrust plate

Yc **Continental Granodiorite (Middle Proterozoic)**—Dark-gray, coarsely porphyritic, coarse-grained granodiorite or metagranodiorite

Xp **Pinal Schist (Early Proterozoic)**—Mica schist and phyllite. Locally is mylonitic and contains migmatitic sheets; likely is site of strong thermal and dynamic metamorphic modification

Xpq **Quartzite and phyllite**—Thick, gray metasedimentary sequence probably correlative with a unit found in the upper part of the Pinal Schist on top of and east of the Rincon Mountains (Drewes, 1974, 1977)

[1] Not demonstrable at Loop Drive, but units and relations are typical of those found in Rincon Valley (fig. 1).

and sandstone (Bisbee). In the next saddle to the south the melange matrix is exposed.

Cross the third knoll and descend to the southwest.

(4e) At small gully west of the knoll, there is a stripped fault surface between the underlying melange sheet and the overlying quartzitic Pinal Schist, which is at least 1.5 km thick. This relationship indicates that the melange sheet is not a near-surface tectonic entity and therefore that it is probably related to the more deeply seated, older thrust faulting rather than to the shallow (about 1.5 km), younger extensional faulting or low-angle normal faulting.

Return to top of third knoll and head east along ridge. Bold outcrop on the northeast side of the knoll is Glance Conglomerate Member at the base of the Bisbee Formation. (Because the Mural Limestone or its equivalent is not recognized in the Rincon Mountains, the Bisbee has a formation rank, and the Glance becomes a member.) Descend to the east, toward the vehicles.

(4f) Base of melange sheet, here poorly exposed at midslope.

Return to vehicles and continue around Loop Drive.

8.1 Monument Headquarters. End of log. Return to motel.

REFERENCES CITED

Bilodeau, W.L., Kluth, C.F., and Vedder, L.K., 1987, Regional stratigraphic, sedimentologic, and tectonic relationships of the Glance Conglomerate in southeastern Arizona: Arizona Geological Society Digest, v. 18, p. 229–256.

Cooper, J.C., 1961, Turkey-track porphyry—A possible guide for correlation of Miocene rocks in southeastern Arizona: Arizona Geological Society Digest, v. 4, p. 17–33.

Creasey, S.C., and Quick, G.L., 1955, Copper deposits of part of the Helvetia mining district, Pima County, Arizona: U.S. Geological Survey Bulletin 1027–F, p. 301–323.

Davis, G.H., 1975, Gravity-induced folding of a gneiss dome complex, Rincon Mountains, Arizona: Geological Society of America Bulletin, v. 86, no. 7, p. 979–990.

Drewes, Harald, 1971a, Geologic map of the Sahuarita quadrangle, southeast of Tucson, Pima County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–613, scale 1:48,000.

———1971b, Geologic map of the Mount Wrightson quadrangle, southeast of Tucson, Santa Cruz and Pima Counties, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–614, scale 1:48,000.

———1971c, Mesozoic stratigraphy of the Santa Rita Mountains southeast of Tucson, Arizona: U.S. Geological Survey Professional Paper 658–C, 81 p.

———1972a, Structural geology of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geological Survey Professional Paper 748, 35 p.

———1972b, Cenozoic rocks of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geological Survey Professional Paper 746, 66 p.

———1974, Geologic map and sections of the Happy Valley quadrangle, Cochise County, Arizona: U.S. Geological Survey Miscellaneous Geological Investigations Series Map I–832, scale 1:48,000.

———1976, Plutonic rocks of the Santa Rita Mountains, southeast of Tucson, Arizona: U.S. Geological Survey Professional Paper 915, 75 p.

———1977, Geologic map of the Rincon Valley quadrangle, Pima and Cochise Counties, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map I–997, scale 1:48,000.

———1980, Tectonic map of southeastern Arizona: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–1109, scale 1:125,000.

———1981, Tectonics of southeastern Arizona: U.S. Geological Survey Professional Paper 1144, 96 p.

———1988, Development of the foreland zone of the Cordilleran orogenic belt near the U.S.-Mexican border, *in* Schmidt, C.J., and Perry, W.J., Jr., eds., Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 447–463.

———1991, Description and development of the Cordilleran orogenic belt in the southwestern United States and northern Mexico: U.S. Geological Survey Professional Paper 1512, 92 p.

Hayes, P.T., and Raup, R.B., 1968, Geologic map of the Huachuca and Mustang Mountains, southeastern Arizona: U.S. Geological Survey Miscellaneous Geologic Investigations Series Map I–509, scale 1:48,000.

Heyman, A.M., 1958, Geology of the Peach-Elgin copper deposit, Helvetia District, Arizona: Tucson, University of Arizona, M.S. thesis, 66 p.

Kranz, R.W., 1989, Laramide structures in Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 463–483.

Lipman, P.W., and Sawyer, D.A., 1985, Mesozoic ash-flow caldera fragments in southeastern Arizona and their relations to porphyry copper deposits: Geology, v. 13, p. 652–656.

Lutton, R.J., 1958, Some structural features in southern Arizona: Tucson, University of Arizona, M.S. thesis, 138 p.

Mardirosian, C.A., 1977, Mineral deposits of Arizona, 2nd Edition, private publication, press not identified.

Marvin, R.F., Naeser, C.W., and Mehnert, H.H., 1978, Tabulation of radiometric ages—including unpublished K-Ar and fission-track ages—for rocks in southeastern Arizona and southwestern New Mexico, *in* Callender, J.F., Wilt, J.C., and Clemons, R.E., eds., Land of Cochise: New Mexico Geological Society Guidebook, p. 243–252.

Michel, F.A., Jr., 1959, Geology of the King mine, Helvetia, Arizona: Tucson, University of Arizona, M.S. thesis, 59 p.

Pashley, E.F., 1966, Structure and stratigraphy of the central, northern, and eastern parts of the Tucson Basin, Pima County, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 273 p.

Schrader, F.C., 1915, Mineral deposits of the Santa Rita and Patagonia Mountains, Arizona, *with contributions by* J.M. Hill: U.S. Geological Survey Bulletin 582, 373 p.

Thorman, C.H., and Drewes, Harald, 1981, Geology of the Rincon Wilderness Study Area, Pima County, Arizona, *in* Mineral resources of the Rincon Wilderness Study Area, Arizona: U.S. Geological Survey Bulletin 1500, 62 p.

SILVER BELL PORPHYRY COPPER DEPOSIT, SILVER BELL MOUNTAINS, PIMA COUNTY, ARIZONA

By Spencer R. Titley[1]

INTRODUCTION

The porphyry copper deposit in the Silver Bell Mountains reveals, in one setting, many of the geological attributes and contrasts of geological styles of southern Arizona porphyry copper deposits (Titley, this volume). The Silver Bell deposit comprises five principal and separated centers of intrusion, each with its own host rock complex, its own style of hypogene hydrothermal evolution, and its own distinctive weathering and post-mineralization modification style. Four of the centers (Oxide, El Tiro, East El Tiro (Imperial), and the Daisy) have been developed for mining operations, and pits expose interiors of orebodies. The fifth center, North Silver Bell, was explored but undeveloped as of the fall of 1993, and exposes, on the modern surface, many of the characteristic habits of leached capping and modified hypogene alteration originally exposed at various levels of weathering in orebodies of this region.

This trip is organized to visit three principal sites in the northern part of the district, with brief side excursions that will depend upon time and accessibility; restricted access, changing conditions, and accessiblity to locations preclude unorganized trips without leadership in this mine. North Silver Bell and its capping and supergene alteration are the first site of extended observation; the East El Tiro (Imperial) Pit is the second site, where calc-silicate altered rock and its hypogene mineralized rock will be examined; and the third site will be within the main El Tiro Pit, where porphyries, potassium silicate altered rock, and hypogene and supergene mineralized rock will be examined.

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THE TRIP FROM TUCSON TO THE SILVER BELL MOUNTAINS

The Silver Bell orebodies are in the Silver Bell Mountains, about 35 mi west-northwest of Tucson (fig. 1.). The route from Tucson follows Interstate Highway 10 (I–10) to

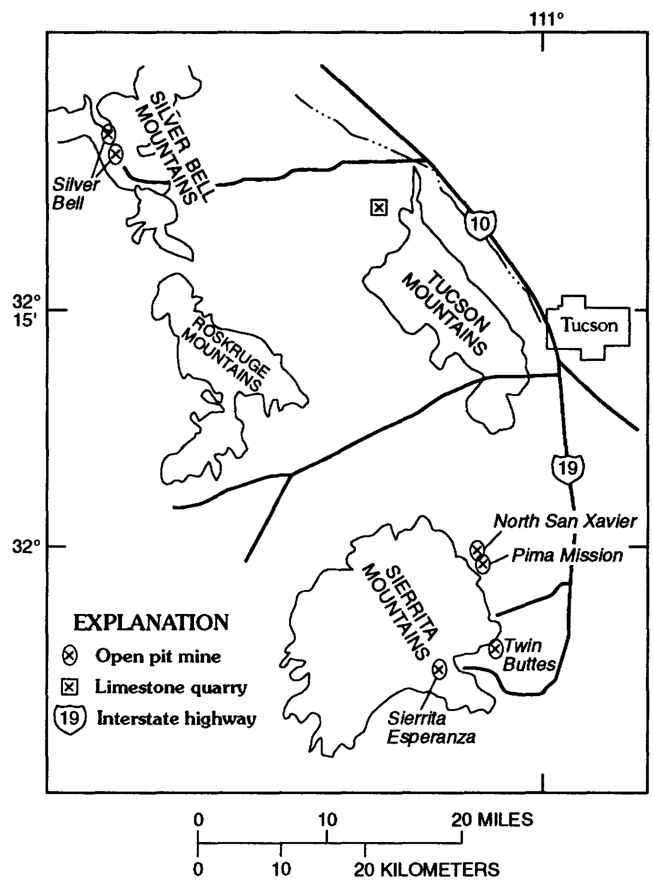

Figure 1. Location map of mines in the area west of Tucson, Ariz.

Table 1. Production at Silver Bell.

[--, data not available]

Period	Tons of ore	Cu (pct.)	Ag (ppm)	Mo (pct.)	Pb (pct.)	Zn (pct.)	Sources
				Produced grades			
[1]1885–1981	90,351,000	0.71	2.22	0.003	0.002	0.02	Keith and others (1983)
1908–1933	1,092,226	2.97	20.2	--	0.06	--	Elsing and Heineman (1936)
				Reported grades			
1954–1977	75,655,000	0.80	2.40	0.022	--	--	Graybeal (1982)

[1]Total gold produced, 1885–1981, 2,200 troy oz.

the Avra Valley exit, some 12 mi north of the Grant Road exit in Tucson. From the Avra Valley turn-off, the route proceeds generally west 23 mi across the Avra Valley to the Silver Bell Mine site.

Interstate Highway 10 parallels both the Santa Cruz River channel and the Tucson Mountains, which are directly to the southwest. The range, of typical Basin and Range character, comprises mostly subaerial volcanic strata of Laramide age. The Laramide and middle Tertiary rocks of this range dip generally northeastward, exposing pre-Laramide basement and its Paleozoic and Mesozoic strata along the southwest side of the range. Volcanic rocks of the Tucson Mountains are interpreted as remnants of a Laramide caldera; the middle Tertiary Basin and Range geomorphology disrupts the original caldera morphology.

The exit from I–10 to the Avra Valley is at the end of the Tucson Mountains where we cross the Santa Cruz River on a bridge near the last outcrops of the range. Just north of the Avra Valley Road at this point is the Arizona Portland Cement Company. One mi from the I–10 exit, just beyond the bridge across the Santa Cruz River, the road crosses a covered conveyor system that delivers cement rock from a quarry seen at about 9 o'clock about 1 mi away (fig. 1). Mississippian limestone is mined at the quarry.

The road continues across the Avra Valley, an area given over to agriculture where the predominant crops are cotton and a variety of sorghum. Water is "mined" for irrigation, and wells and large Cat engines are seen commonly alongside the road. The water table in the Avra Valley is mostly more than 100 m deep and there is very little recharge; the depth to pre-Tertiary valley basement near the valley center is unknown. At about 5.5 mi from I–10, we will pass concrete facings and a fence that protect and cover the Central Arizona Project Canal, which carries water to a reservoir near the south end of the Tucson Mountains. At that location, some of the water is purified and sent directly into the water mains serving Tucson and some is recharged into the subsurface aquifer.

SILVER BELL MINE

HISTORICAL PERSPECTIVE

The district was developed originally, probably around 1865 (Richard and Courtright, 1954), on oxidized copper ores in skarn, but the mineralized rocks of the district may have been known 100 years earlier. Disseminated copper ores were recognized by about 1909 and selectively mined together with ore in skarn-altered rocks until about 1930. Open pit production commenced by ASARCO in 1954 following a period of exploratory drilling and assessment that began in 1948. Mining of hardrock ceased about 1985, but a sludge of 90 percent pure "cement" copper was still being extracted from dump leachates in the early 1990's at a rate of about 4,000–5,000 tons of Cu/yr according to the 1990 ASARCO Annual Report. Recorded production from the district is shown in table 1; open pit copper production between 1954 and 1977 was recorded by Graybeal (1982). District production from 1885 to 1991 is shown in Keith and others (1983), and some production of disseminated ore pre-dating the open pit is recorded in Elsing and Heineman (1936). The ASARCO Annual report of 1990 shows a reserve of 101,344,000 tons of 0.47 percent Cu ore. No renewed hardrock production had taken place in the early 1990's.

Geological reports on Silver Bell go back to the early part of the century; the first encompassing report was by Stewart (1912), whose paper treated mostly the geology as understood from underground development in veins and skarn. Mid-century descriptions and the first published maps of the entire district were those by Richard and Courtright (1954, 1966), who outlined a district-scale view that included the geology of that part of the range encompassing both the Oxide and El Tiro Pits. These papers are also among the first to describe the importance of interpretation of capping and supergene processes to the discovery and evaluation process. The Richard and Courtright papers remain valuable today for these reasons, as well as for their basic geological information on bedrock relationships and structure in the district. A reconnaissance geological map of a part of the district was published by Banks and Dockter (1976); the maps and sections of El Tiro area in Graybeal (1982) represent the best expression of current knowledge and interpretations of this northern part of the district. The ores were an object of investigation in one of the earliest attempts to bring mineralogical and chemical rigor to a study of hydrothermal alteration (Kerr, 1951). This work outlined several alteration styles and centers, but had to treat mostly supergene-altered material from outcrop and consequently did not provide meaningful information on hypogene effects that were to develop in later studies based upon extensive pit exposure and drilling.

The district has been a site of topical geological studies reported in numerous theses and unpublished company reports; the mine was a training ground for many years for ASARCO geologists and engineers. The quality of exposure of complex rock relationships and the multitude of different rocks and mineralization styles have served as elegant bases from which important and fundamental questions of ore genesis may be addressed; included among such studies have been those of the mineralogy and chemistry of supergene- and hypogene-altered rock, fracture abundance, volcanogenesis, and igneous petrography. During the past decade, Silver Bell has been a site of experimentation in development of methods of remote image analysis (Abrams and others, 1984; Geosat Committee, 1992).

GEOLOGICAL OVERVIEW

Viewed from the regional perspective, the Silver Bell ores are part of a large population of porphyry copper deposits in the American Southwest, with which they have many features in common. This population represents the results of a profound regional igneous event of Laramide age (about 75–55 Ma) in the southern Cordillera of the United States and Mexico, convincingly documented from radiometric ages of numerous igneous rocks and from mapped relations and distribution of igneous rocks. This event, the Laramide revolution, is correlated with a time of high rates of normal convergence of North American and Pacific plates and was manifested on the North American craton by initiation of many centers of andesitic volcanism and evolution of a major magmatic belt in the American Southwest. The Silver Bell district is one result of this event and represents a small region containing separate igneous intrusions that display many of the habits of occurrence, igneous activity, hydrothermal evolution, and post-mineral histories found in porphyry copper deposits elsewhere in this region.

The Silver Bell district comprises a group of porphyry copper deposits localized in the peripheries of several small (<1 km) intrusions in the Silver Bell Mountains (fig. 2). Hydrothermal alteration and hypogene ores extend from the intrusions into a variety of wall rocks (fig. 2) that include older intrusions, a succession of Upper Cretaceous volcanic rocks, Paleozoic strata, and local, thin remnants of Mesozoic clastic rocks. As presently known, the mined Silver Bell ores were dominated by supergene secondary-enriched sulfide ores in potassium silicate-altered intrusions and volcanic rocks, with smaller volumes of mined, ore-grade hypogene ores evolved in calc-silicate-altered Paleozoic carbonate rocks. Present reserves and resources consist of a large tonnage of supergene and oxide-enriched ore with some ore-grade hypogene ground at deep levels. The ores to be mined initially at North Silver Bell occur in a body of supergene enriched sulfide ore.

The occurrence of a succession of Laramide pre-ore andesite and dacite volcanic and possible sill-like bodies, which are hosts to numerous quartz monzonite porphyry intrusions, permits the interpretation that the porphyry bodies represent subvolcanic intrusions. Although the pluton systems are generally isolated, geological relationships suggest they are essentially contemporaneous. The plutons, for which one K-Ar date in El Tiro Stock (fig. 3) indicates an age of 65.5±2 Ma, are part of a more widely diversified "Laramide" group of igneous rocks that include intrusions of alaskite and monzonite as well as a suite of pre-intrusion volcanic rocks.

The alaskite, for which a maximum age is set from its intrusive contact into Lower(?) Cretaceous strata, and for which a minimum age is set by intrusion of the Laramide stocks into it, composes a large coherent body that flanks the porphyry complex on its southwest margin. The alaskite, which is a wall rock of the porphyry intrusions, is prominently mineralized near the stocks. An apparently intrusive body of dacite porphyry (fig. 7), also a host to ore, appears to invade the Paleozoic succession as a sill and is crosscut by the porphyries. The dacite body is complex and petrography reveals both volcaniclastic and melt-solidification textures. Another unit is a succession of andesite-dominated flow and clastic volcanic rocks. Studies of Upper Cretaceous volcanic to hypabyssal rocks indicate that interpretations of their origin bear importantly upon concepts of the origin of Silver Bell and many other districts of the region where comparable rocks are present. Courtright (1958) and Richard and Courtright (1960) were first to observe a region-wide, consistent association of these volcanic rocks with some centers of porphyry copper occurrence. They suggested that their widespread distribution and restricted stratigraphic position were results of events that marked a pronounced shift in style of geological evolution in this region. The association of andesite-dacite and andesitic stratovolcanoes with porphyry copper deposits has subsequently been observed in many parts of the world, especially in youthful deposits of the Philippines and island arcs. Lipman and Sawyer (1985) interpreted the dacite body at Silver Bell as an intracaldera welded tuff and the porphyry bodies as ring-fault intrusions of a

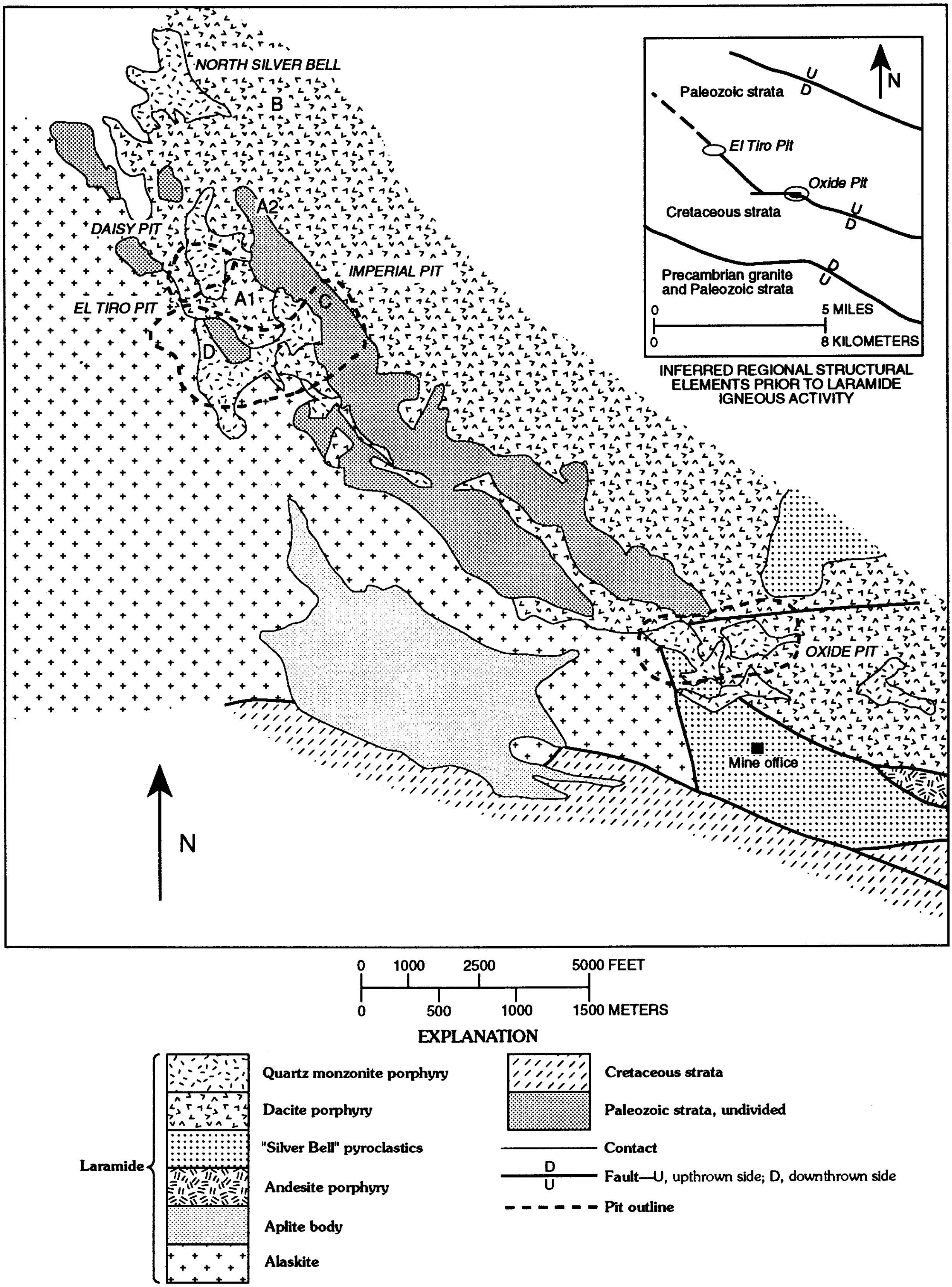

Figure 2. Generalized map of the porphyry copper deposits of the Silver Bell Mountains, Ariz. Adapted and generalized from Richard and Courtright (1966) and Graybeal (1982), and including some detail from the author's work. Letters A–D show approximate location of field trip stops in the north end of the district.

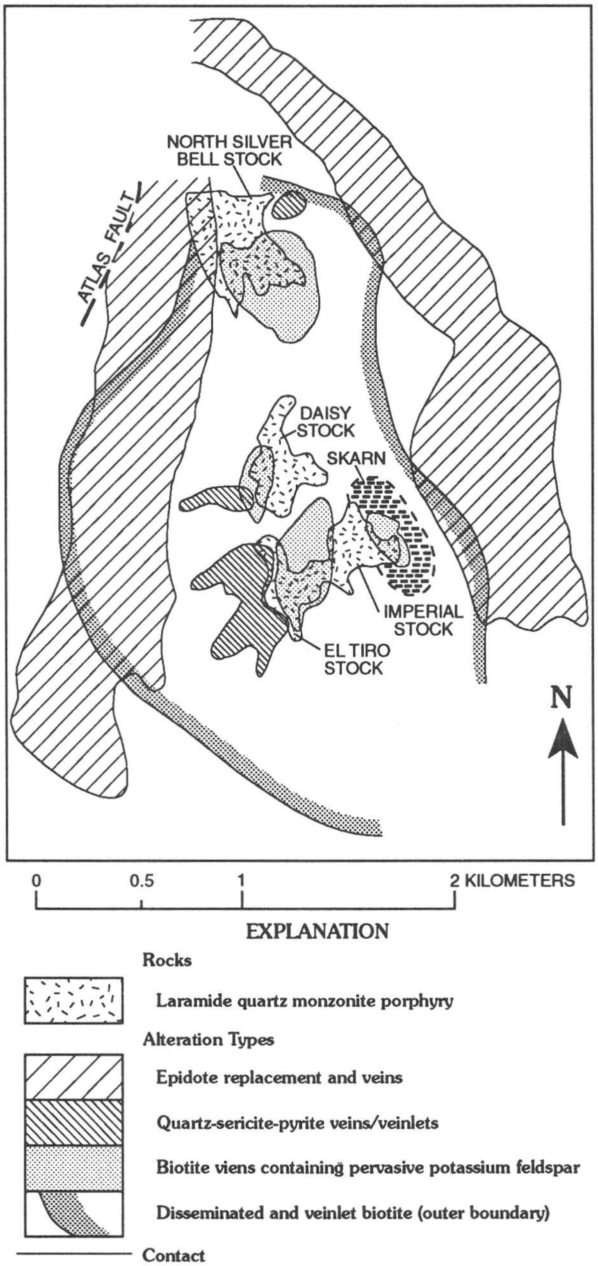

Figure 3. Map showing altered rocks of the north end of the Silver Bell district (modified from Graybeal, 1982; Titley, in press, reproduced by permission of the Geological Association of Canada). The stock-localized orebodies are contained within a larger area characterized by the presence of widespread biotite veining and the presence of biotite in potassium-silicate rocks. Each stock center, however, reveals its own intrinsic pattern of potassic and phyllic alteration, all of which overprint the older biotite and biotite-stable altered rocks.

caldera complex, and they link such interpretations with suggested calderas at some other sites of Laramide intrusion and porphyry copper deposits in the Southwest.

This important question, whether the large calderas suggested by Lipman and Sawyer (1985) or the areally more limited volcano-centered systems seen in youthful deposits of island arcs (Branch, 1976) represent the sites of porphyry ore occurrence, requires resolution. The notion of caldera histories and intrusions (Smith and Bailey, 1968) contrasts with a general theme of volcano tectonics described in detail by Rittman (1962), each in its own way influencing important perspectives of rock associations and scale. Contrasts in the setting of magma emplacement—whether related to the essentially crater-forming events of a caldera or subvolcanic intrusion during the constructional events of volcano formation—directly relate in contrasting ways to prospecting and resource assessment. By analogy with rock successions and evolutionary style of youthful porphyry copper systems in the southwestern Pacific region, the author remains inclined to the notion, from his own experience, that the porphyry copper systems evolved in compressional tectonic systems as part of andesite strato-volcano systems, rather than in the extensional tectonic rhyolite-dominated collapse systems of the "conventional" caldera. The porphyry copper deposits in the Silver Bell Mountains remain an important focus of interest in this question of regional ore controls and environments.

Primary copper mineralization at Silver Bell has been important in the skarn-altered host rocks; supergene sulfide enriched rock has been the principal mined ore of potassium silicate–altered potassium silicate host rocks. Each pluton center reveals zoned potassium silicate hypogene–altered rock where appropriate host rocks are present and the alteration type occurs in Oxide, El Tiro, and Daisy Pits. Both Imperial and El Tiro Stocks were emplaced in contact with Paleozoic carbonate strata and reveal skarn-alteration assemblages. As presently known, ore-grade hypogene mineralized rock occurs in both skarn and parts of aureoles of potassium silicate–altered rock; chalcopyrite is the only hypogene copper mineral of consequence—tetrahedrite is sparsely present and may be the predominant primary phase of silver mineralization.

Graybeal (1982) mapped the broad patterns of alteration and mineralization in the El Tiro part of the Silver Bell system; his work is generalized in figure 3. The author knows of no published information on the Silver Bell system from the 1990's that gives details of any systematic study of alteration chemistry and mineralogy or fluid inclusion habits, but Graybeal (1982) cited ASARCO studies at North Silver Bell where temperatures of 278°C were determined. Graybeal's (1982) work, however, shows important detail concerning the alteration style and habit in the north end of the district (fig. 3). The separate intrusion centers occur within a broad envelope of both biotite-stable altered rock and biotite veining. Much of this biotite occurs as spiderweblike veins in alaskite and dacite and is pseudomorphed by chlorite. Within this envelope of essentially potassic altered rock, the intrusion complexes evolved their own zoned mineralization of central orthoclase-biotite (potassic) with both overprinted and more widely distributed quartz-sericite-montmorillonite (phyllic) alteration patterns. Where carbonate rocks were affected, calc-silicate-altered rock predominates.

Silver Bell owes its economic life to significant weathering and a post-ore tectonic history that resulted, first, in supergene secondary enrichment and then cover or faulting to protect it in the middle Tertiary. Enrichment was of low-grade (<0.1–0.2 percent Cu) primary ore and evolved almost entirely with phyllic-altered alaskite and dacite. This primary ore occurred in an assemblage of about 4 weight percent total sulfide with a pyrite:chalcopyrite (py:cpy) ratio of 6–4:1. Supergene enrichment to a grade of about 0.8 percent Cu evolved as a flat-lying blanket of chalcocite about 20–30 m in thickness on average, within porphyry and alaskite; it evolved within a zone of hypogene quartz-sericite-pyrite (chalcopyrite) alteration-mineralization. Enrichment was enhanced by the high pyrite content and the high py:cpy ratio, as well as rock permeability enhanced by the original abundant fractures in which the hypogene sulfide minerals were deposited.

A broadly based interpretation of the history of emplacement and enrichment of the Laramide porphyry copper deposits of this region (Livingston and others, 1968) proposed that weathering commenced in the Eocene shortly after cessation of the primary ore-forming processes. Middle Tertiary volcanism covered and protected this old enriched rock as well as the still unaffected primary hearts of these orebodies until basin-and-range uplift exposed the older ores in their present position. Graybeal (1982) noted, however, that the time at which enrichment took place at Silver Bell is uncertain and that dated middle Tertiary dikes controlled position and thickness of some supergene enriched rock. A leached capping 50 m above the top of the enriched ore mined provides evidence of the former presence of chalcocite and indicates at least one earlier stage of enrichment. Weathered iron products draped over present land forms indicate still younger oxidation and movement of older copper blankets.

THE MINE TRIP AT SILVER BELL

NOTE: Trip participants are required to wear hard hats and safety glasses while on the mine property. Utmost care is to be taken when walking or working on rocks. Be aware of the condition and location of bench edges, rock faces, and people near you, above you, and below you.

The trip commences at the ASARCO mine office and follows the mine perimeter road some 3 mi to the entrance into El Tiro Pit complex. We will make two brief stops along the road, one for a quick overview of the leaching facility at the south end of the district, the other to look at peripheral alteration of the alaskite. About 1 mi from the pit center the road passes alaskite outcrops that show primary quartz-sericite alteration overprinted by younger chlorite alteration. The overprinting by chlorite is common in many porphyry copper systems worldwide, and it may be a retrograde thermal effect of distal waters encroaching upon the thermal center and older altered rock (Titley, 1982).

STOP A–1, NORTHEAST SIDE OF EL TIRO PIT (FIG. 2).

The purpose of this stop is to view and discuss the weathering profile of capping and oxidation seen in the southwest wall of the main El Tiro Pit, shown in figure 4. We look southwest toward the southwest wall of the main El Tiro Pit, around which we have driven to this point. Many of the features and phenomena discussed are outlined in Anderson's (1982) paper on capping. The distribution of oxidation products on the pit wall reveals, first, that the colors follow present geomorphology and, second, that the colors manifest the zoning of hematite near the surface to jarosite-predominant (yellow) oxidation products below. A thin (1–3 m) band of goethite (brown) may be seen developing above the zone of jarosite (yellow) and beneath the hematite (red) cap; this marks a pH boundary, where dilution has increased pH to produce goethite from jarosite. We are viewing the effects of destruction of parts of an enriched blanket in the present weathering cycle, the oxidized and soluble products of which are moving down through a zone of quartz-sericite pyrite, dissolving the sulfides and producing jarosite; continuous production of acid dissolves the small amount of primary copper present (0.1 percent), which moves still farther downward to a level where chalcocite is now being precipitated. Some of this solution is

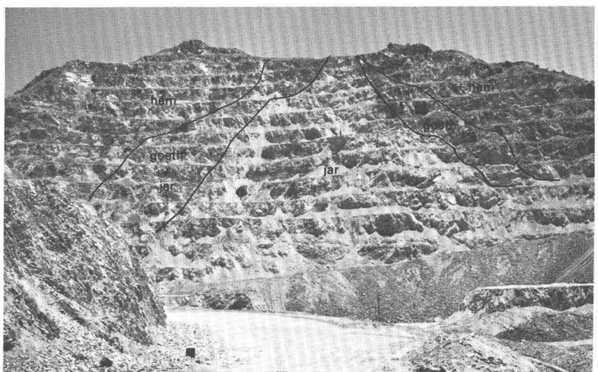

Figure 4. View of the southwest wall of the main El Tiro Pit. The wall shows the color contrasts seen across a zone of leaching of sulfide-bearing rocks. The deep red drape from the surface downward is hematite-predominant oxides derived from weathering of pre-existing disseminated chalcocite and pyrite. Beneath it lies a thin zone of mixed hematite, goethite, and jarosite derived from the chemical maturing and neutralization of the predominantly jarosite (yellow) weathering products beneath. Beneath the wall is precipitated chalcocite. hem, hematite; goeth, goethite; jar, jarosite.

dissolving chalcocite at greater depth and near present mined exposures, probably because of mine-related permeability in the pit walls and enhanced modern oxidation.

The process of supergene enrichment starts with oxidized waters of surface derivation that dissolve hypogene pyrite and chalcopyrite; the process may be enhanced by biogenic activity. This part of the process takes place above the water table across a zone of leaching, whose height is variable but commonly is tens of meters and whose base is conventionally considered the top of the water table. At water table level, or at some level where chemically reducing conditions prevail, chalcocite is precipitated, usually by replacing iron of hypogene sulfides, and upgrades the protore present. In early stages of enrichment, the chalcocite ore still contains significant amounts of pyrite. At some later stage, this blanket at Silver Bell was uplifted, the water-table lowered, and the oxidation process commenced again, moving both components of earlier enrichment and its coextensive primary copper downward. Successive cycles resulted in richer and richer copper solutions and diminution of original contained pyrite. Left behind as a hematite cap with diagnostic boxworks are the oxidized remnants of the old, now leached, fossil blanket evident as a hematite cap; the hematite is actually a mixture of hematite and jarosite the proportions of which control oxide colors that range from the deep maroon of hematite to the terra cotta of mixed jarosite and hematite. Beneath this layer of hematite is the new zone of leaching, seen as jarosite.

STOP A–2, CONTINUING, OVERLOOK AT NORTH SILVER BELL

The purposes of this stop are (1) to view the extent of surface exposure on the North Silver Bell orebody, (2) to make general comparisons of colors seen at the surface with those seen and discussed at **STOP A–1**, and (3) to infer the general position of the North Silver Bell enriched blanket from the habit of capping (fig. 5).

We continue to **STOP A–1** on a dump where we get a view of the North Silver Bell capping. The North Silver Bell deposit is an enriched sulfide blanket developed in intensely fractured and mineralized quartz-sericite altered rock associated with the North Silver Bell Stock and its dacite wall rocks. The many colors seen on the surface of the deposit are products of mixtures of different limonites (in the sense of Anderson, 1982, and as seen on El Tiro Pit wall) where hematite-covered slopes lie above deeper enrichment and where erosion has exposed the brown-yellow mixtures of goethite and jarosite.

Seen in a general way, most of the exposures of capping over North Silver Bell are the products of leaching and subsequent surface oxidation of jarosite-predominant limonites; only the hematite capping is believed to represent the former presence of chalcocite. This notion is adduced from the presence of a characteristic boxwork

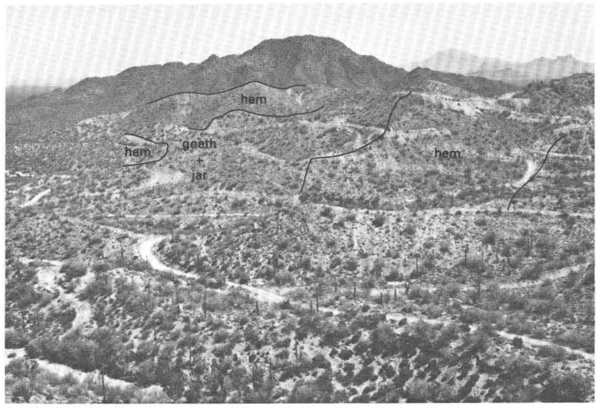

Figure 5. View of North Silver Bell area. Drill roads cover the area of surface overlying the enriched orebody. Expression of colors is largely dependent on available light; however, the pink soils and rock express hematite, and the browns express the zone of sulfide leaching in which resulting limonites are composed of a mixture of goethite and jarosite. hem, hematite; goeth, goethite; jar, jarosite.

within the hematite caps, which reveals the former existence of chalcocite. The goethite-stained rocks represent a former presence of jarosite, derived from pyrite, in a zone in which leaching of sulfides, not precipitation, was the predominant process. Although hematite is present, the surface lacks the prominent red and maroon of hematite-jarosite mixtures, seen in other Arizona deposits such as Ray and Bisbee, that appear to derive from first-cycle oxidation and enrichment, and in systems of higher (>5 percent by volume) total sulfide and (or) greater available iron content.

Enriched rock along the closest prominent ridge is overlain by hematite-stained soil and rocks and breccia knobs. Erosion into the stream valleys has cut through the high capping, exposing the sulfate and oxide weathering products.

STOP B, NORTH SILVER BELL

Our stop here will allow participants to view both obvious and subtle features developed in the weathering of copper-bearing sulfide potassium silicate rocks. We will be viewing perhaps the only remaining weathered surfaces in the United States above a supergene enriched horizon where a fossil blanket may be inferred and where the varied effects of the progress of weathering of such features may be studied.

This stop, about 2 hours in length, comprises a few walking traverses to examine the effects of weathering on both sulfide ores and on hypogene altered rocks. North Silver Bell exposes both potassic (vein biotite and orthoclase) and phyllic (quartz-sericite-montmorillonite) alteration, as well as the acid-weathering attack on these hypogene minerals. Outcrops seen will allow examination of fractured porphyry and wall rock (fig. 6). Telescoped alteration in the various porphyries has resulted in the blurring of alteration types, except for sometimes spectacular quartz-sericite. A sharp boundary of alteration types is difficult to determine in the field; quartz-sericite alteration is widespread and obscures much of an earlier stage of orthoclase (and biotite?) alteration. Orthoclase may be seen with careful observation as vein selvages to early generations of some quartz-sulfide veins.

Different capping types and their distributions can be pointed out, and there will be an opportunity to observe and collect various boxworks from sulfide assemblages. Close attention to veins may reveal the presence of supergene clay, which has been determined by X-ray and microprobe analysis to be montmorillonite (after sericite), and also veining by alunite, derived by acid alteration of feldspar. Use of the acid and nail test will reveal that many of the dull-black, brown-streaking spots and patchworks in the goethite-weathered rock beneath the hematite capping are copper-bearing. These spots and dendrites are a black copper oxy-silicate, neotosite (Anderson, 1982), which is a poorly crystallized substance of variable iron, manganese, and copper that has a composition similar to chrysocolla. It results from precipitation of copper in the absence of sulfur in the zone of oxidation, and with insufficient acid to promote the continuing solubility of copper. The remainder of the morning will be spent looking at a cross section of the weathered profile as seen in the rocks extracted from an inclined development into the blanket.

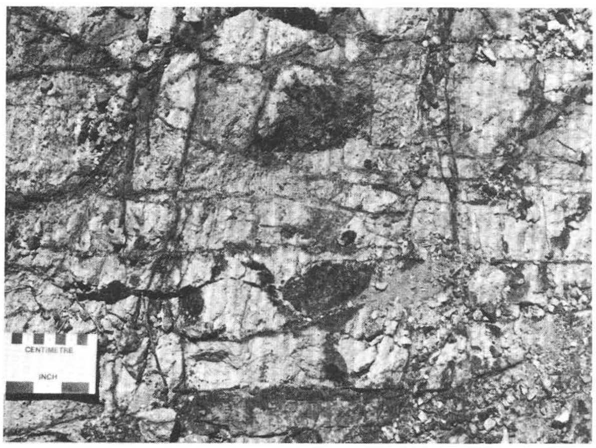

Figure 6. Horizontal surface showing typical fractures of the rocks of the enriched zone at North Silver Bell. Altered and mineralized hypogene fractures are now traced from limonite-filled hypogene-altered joints. Long dimension of photograph is north-northeast, showing orthogonal fracture set in an orientation that is characteristic of mineralized and altered fractures in deposits of this region (Heidrick and Titley, 1982). The abundance of fractures is about 0.6–1 cm^{-1} as determined from total fracture length/sample area (Titley, 1982; Titley and others, 1986).

The participants should look for various boxworks after sulfide, various oxide copper minerals including the black oxides, jarosite-goethite-hematite and their various mixtures, and alunite, which evolves after the weathering of the sulfide-bearing rocks, commonly underlying, sometimes within, the zone of hematitic cappings.

MINE STOPS IN THE IMPERIAL AND EL TIRO PITS

The remaining stops on this trip are into the pits at Silver Bell. **NOTE: Mine safety is our basic exercise and purpose. Participants are asked to exercise good sense and caution in all mine stops. Participants should wear hard hats, safety glasses, hard-toed footwear, long-sleeved shirts, and long trousers. AT ALL TIMES: Please, do not step anywhere, especially backward, without looking. Do not get within 3 m of bench edges. To the extent possible, examine rocks from rubble at the bench toes; avoid walking up the rills of muck piles; at all times, be aware of what is above you. Be careful when breaking rocks, as many will splinter; be aware of your surroundings in terms of people, rocks, and the conditions of the bench.**

The stops in the pits are selected to show the contrasts of alteration and mineralization styles in porphyry copper deposits, which are influenced by host rocks. Figure 7, adapted from Graybeal (1982), shows a cross section on which our stops are located, although they are slightly off of the section. First, in the Imperial Pit, shown at the east end of figure 7, we will see evidence of mineralization with skarn- (calc-silicate-) altered rocks, and last, in El Tiro Pit, shown on the west end of the figure 7, we will see the effects of potassium-silicate alteration in the Laramide porphyries and its felsic igneous wall rocks. We will see the effects of low total sulfide, low py:cpy mineralization of skarns, the high(er) total sulfide, greater py:cpy ratios of primary mineralization of the potassium-silicate rocks, and the habit of supergene chalcocite and its weathered products.

STOP C–1, EAST EL TIRO (IMPERIAL) PIT

The purpose of this stop is to examine the contact of the Imperial Stock with Paleozoic strata that compose the ore-host of Imperial Pit (fig. 8). We will make one stop at a high bench to look at the sharp contact of the Imperial Stock with the Paleozoic host rocks. **Be careful—please see safety admonitions above.** Critical observations here are that (1) the intrusive contact is very sharp, with virtually no endoskarn in the intrusive rock; (2) the Imperial Stock at this location is strongly shattered and quartz veined but mineralized rock is sparse; (3) the skarn protolith was completely obliterated by the alteration; various kinds of both hydrous (serpentine) and anhydrous (garnet, pyroxene) calc-silicates are present that may indicate the former pres-

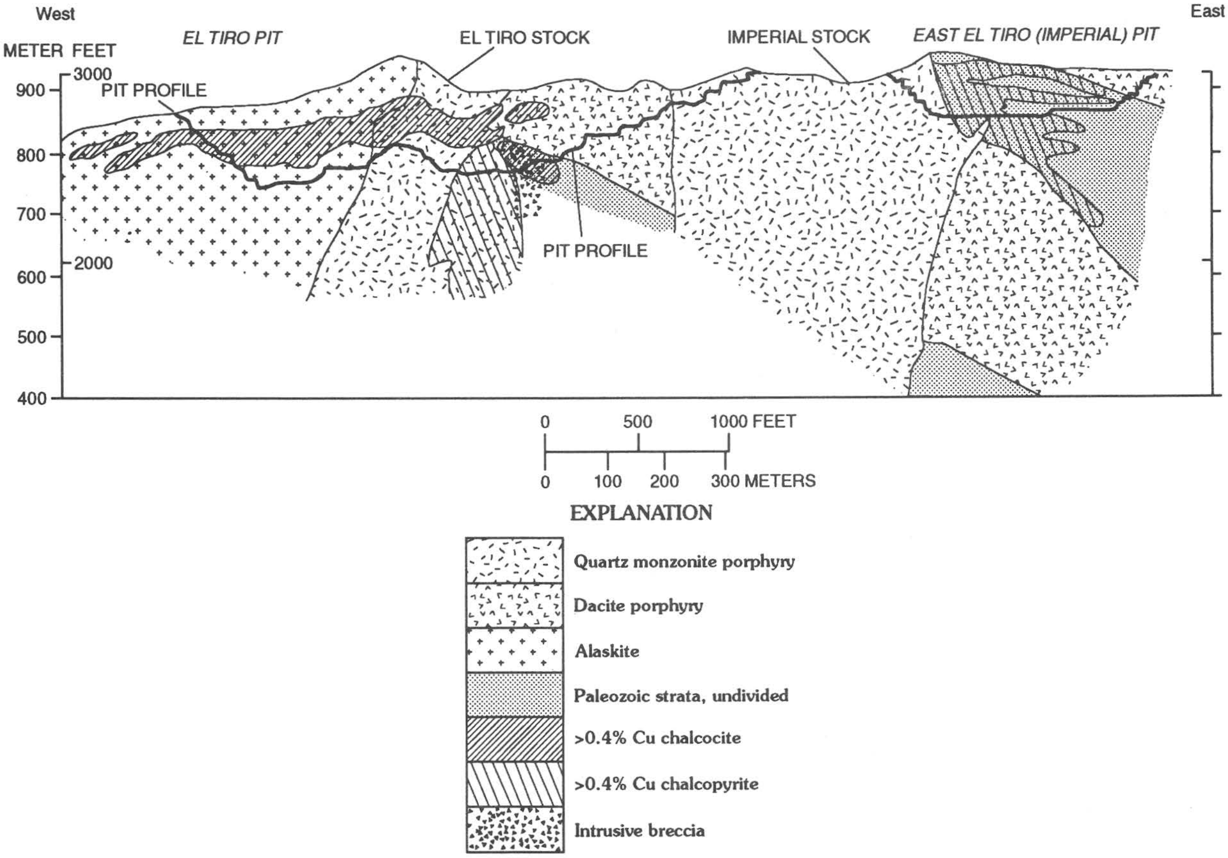

Figure 7. East-northeast–west-southwest cross section through El Tiro and Imperial Pits, looking north-northwest. Adapted and modified from Graybeal (1982). The field trip examines exposures of skarn-altered carbonates in the Imperial Pit (east end of section) and exposures of supergene sulfide-enriched rocks and primary ore in potassium-silicate altered igneous rocks in the main El Tiro Pit. This elegant cross section shows the variation of relationships of mineralization in a spectrum of different wall rocks of Laramide porphyry intrusions present in ore deposits of this region. Hypogene ore is found in carbonate wall rocks at contacts with the Imperial stock, contact breccias and hypogene ore are found within and in close proximity to El Tiro Stock, and enriched sulfide ore is present in a supergene-enriched blanket developed above quartz-sericite altered porphyry and felsic intrusive wall rocks.

ence of magnesium or calcium. We are high in the weathered zone and consequently are viewing some effects of oxidation. It is important to note, however, that we do not see the same effects of weathering here that we saw at North Silver Bell. Both a different primary rock and alteration assemblage (calc-silicate with an absence of potassium), and a very different primary metal assemblage (relatively pyrite-poor), together with calcite, lead to important constraints on Nature's efforts to produce secondary sulfide enrichment. Weathering does not enrich skarns as significantly as it does sulfide ores, though oxidized copper minerals (chrysocolla, tenorite, copper carbonates), representing some enrichment, were developed in the shallow (tens of meters) weathering environment above skarns. Compare the levels of enriched ore in El Tiro (to the west) with the level of hypogene mineralization still exposed in Imperial, shown in figure 7.

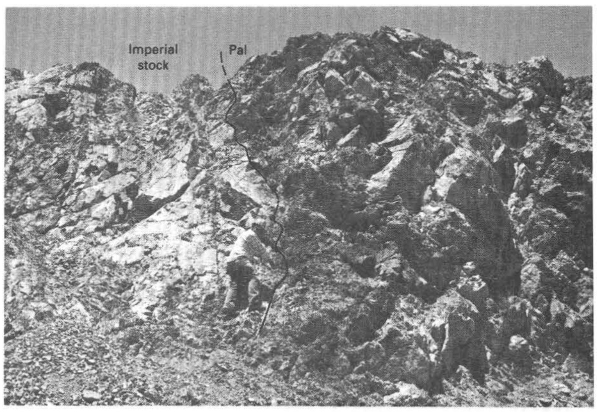

Figure 8. Nearly vertical contact of Imperial Stock (light color) with Paleozoic (Pal) strata, made dark by skarn alteration and its weathering (Imperial Pit, 2960 Bench).

STOP C–2, EAST EL TIRO (IMPERIAL) PIT

The purpose of this stop is to view contrasting alteration types in carbonate rocks as controlled by original lithologies, to examine the habits of primary skarn alteration and sulfide mineralization, and to see some alteration and mineralization habits of a deeper, in-faulted segment of the Imperial Stock. The East El Tiro (Imperial) Pit was developed almost solely to extract hypogene copper from skarn, and has mined ore from a southeastward-dipping succession of Paleozoic strata (fig. 9). Its location is near the first mining to have taken place in the district, and the pit walls have intersected old underground stopes and workings; track and timber of this early development may be seen extending out of the northeast walls of the pit. Skarn is seen in fault contact with a block of porphyry of the Imperial Stock. This rock is profoundly altered to typical assemblages found in felsic igneous rocks and contains vein-controlled quartz-molybdenite-chalcopyrite mineralized rock containing both feldspar and quartz-sericite assemblages. This close spatial association of skarn alteration and telescoped potassium-silicate alteration underscores an important question in ore genesis and the zoning of large intrusion-centered ore systems. That question addresses the equivalence of alteration types in the contrasting host rocks.

Development of skarn is closely controlled by the original composition of strata, a phenomenon that is manifested by contrasts in color and rock habit in different strata exposed on the north wall of the pit (fig. 9). The contrasts in manifestation of alteration result from differences in degree and kind of calc-silicate minerals in various sedimentary rocks. Examples of mineralogical contrasts include those between marble, quartzite, garnet-predominant, and diopside-predominant assemblages. As Paleozoic strata predominate in the epicrustal sedimentary column in this part of Arizona, there is little reason to doubt that carbonate rocks of this succession were of that age. However, pervasive silicate alteration has obscured original characteristics of the rock, which, together with tectonic deformation, has left unresolved the question of which Paleozoic rocks were altered. A study by Merz (1967) suggests that some of the marble seen belongs to a member of the Abrigo Formation (Cambrian) in this part of the system. Other alternatives, however, allow it to be Escabrosa Limestone (Mississippian). Graybeal (1982) noted that some replacement of Cambrian carbonate rocks (the Abrigo) was likely.

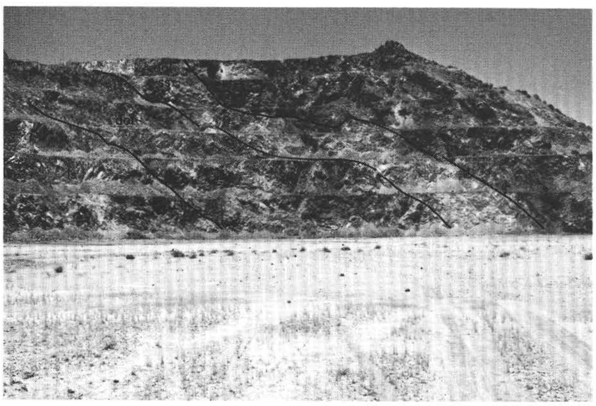

Figure 9. North wall of the Imperial Pit showing generally southeast dipping Paleozoic strata. Darkness contrasts are result of contrasting compositions of stratigraphically controlled skarn alteration (Imperial Pit, 2840 Bench). dol ss, dolomitic sandstone; dol, dolomite; ls, limestone.

We will examine material shed from the bench walls on the north side of the pit. Attention is directed toward determination of the original pervasive calc-silicate type, predominantly either garnet (andradite)-hematite, or diopside. Some chalcopyrite, as massive pods or irregular masses (centimeters to tens of centimeters across), is associated with pervasive skarn alteration types, but most chalcopyrite (and molybdenite) occurs with quartz or magnesium-silicates in veinlets having magnesium-silicate selvages, imposed on the pervasive calc-silicate assemblage; in this respect, the Imperial skarns are similar to those of other skarn ores of the region.

An important habit of occurrence of these hypogene ores in skarn, together with the low total sulfide content (2–4 weight percent), is their relatively low py:cpy ratio (1:2–5) compared with reversed values of the same ratio in the range of 2–5:l in felsic rock hosts, seen in the west pit of El Tiro complex (**STOP D**), and in virtually all comparable host rocks in porphyry copper deposits elsewhere. Supergene sulfide enrichment in skarn ores is not significant at Silver Bell, or in skarn-altered porphyry copper systems elsewhere. Some reasons for this may be the relatively lower py:cpy ratio and consequently diminished capacity for development of acid, and the neutralizing effect on acid produced by the presence of unaltered limestone or alteration calcite. The process of acid neutralization during supergene processes in various skarns has not been studied, nor has the neutralizing/buffering effect of potassium-silicate alteration in felsic rock mineralogies. However, such host rock contrasts may be important in detailing these enrichment contrasts in skarn. Skarn altered porphyry copper systems do become enriched, but the enriched rock is dominated by oxide and silicate minerals and does not represent significant vertical transport, tending instead to concentrate at or very near the surface.

STOP D, MAIN EL TIRO PIT

The purpose of this stop is to examine the principal quartz monzonite porphyry of El Tiro Pit as well as alaskite to see the effect of both potassic (orthoclase and biotite) and quartz sericite alteration. This stop, slightly off the section of figure 7 but near the center of the pit, is located near

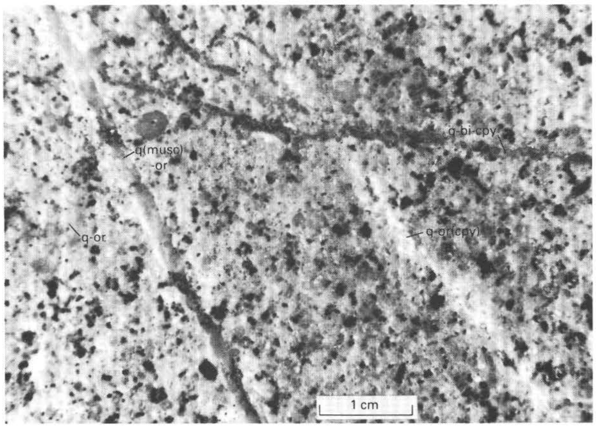

Figure 10. Slabbed surface of Silver Bell quartz monzonite porphyry of El Tiro Pit. The surface shows four vein stages, indicating their order of formation by crosscutting relationships. Earliest biotite veining (q-bi-cpy) is crosscut by quartz-orthoclase-(sulfide) veins (q-or-(cpy)); quartz-chalcopyrite veins follow (not shown), and the latest vein set is represented by texturally destructive acid alteration to quartz-sericite-pyrite (q-(musc)-or). q, quartz; or, orthoclase; musc, muscovite; bi, biotite; cpy, chalcopyrite.

exposures of deep hypogene chalcopyrite in the porphyry, as well as high-grade supergene chalcocite ores, presently undergoing post-mine oxidation to native copper, brochantite-antlerite, and cuprite.

Rocks at this stop, at the bottommost accessible bench (2550 Bench (feet)) on the southwest side of El Tiro Pit, reveal the effects of phyllic-vein-overprinted potassic vein alteration, as shown in figure 10. Fresh appearing biotite books are present in the quartz-monzonite porphyry; some is totally pseudomorphed by chlorite, some has a chlorite fringe. Some biotite books appear, under the hand lens, to be completely recrystallized to masses of granular brown biotite, and some biotite appears as veins, some of which may also be converted to pseudomorphous chlorite. Some rock fragments contain orthoclase veins that cross biotite veins and are crosscut by quartz-sericite-pyrite veins, relationships that give rise to the notion of telescoping or alteration overprinting.

The question and problem of what constitutes secondary biotite may be addressed in the rocks of this stop. The dispersed books of bright, black biotite are most probably magmatic; the granular biotite that pseudomorphs these books is likely secondary and hydrothermal. The vein biotite is subsolidus (in cracked rocks) but also primary in the sense of its inferred hypogene hydrothermal origin. No chemical data have been gathered for the Silver Bell alteration, but a generalization, which has been demonstrated from studies of biotite in a few other systems, is that hydrothermal biotite trends toward becoming enriched in magnesium as a consequence of the process. In pseudomorphous secondary biotite after magmatic biotite, the higher magnesium content may be residual, but magnesium is also concentrated (with respect to magmatic biotite) in the precipitated biotite of hydrothermal veins.

The history and origin of chlorite in this setting remains problematical. Beane and Titley (1981) have noted that the stage of chalcopyrite deposition in porphyry ores is synchronous with a time of stability of chlorite. Thus, some vein chlorite in the Silver Bell ore rocks may represent this intermediate stage of hydrothermal alteration. Chlorite may result from encroachment of late (acid?) solutions during the cooling of the hydrothermal center. In the supergene zone, chlorite may also be a reaction product that evolved deep in enriched blankets (as a precursor to supergene clays) from strictly supergene processes; nontronite may also be present at the base of rocks affected by the supergene processes; nontronite has been reported in the rocks at Silver Bell.

Mineralized rock on the floor of this bench has been shed from higher benches and is relatively high grade (>0.8 percent Cu) supergene chalcocite ore, much of which has undergone and is undergoing post-mine oxidation to cuprite, brochantite, and antlerite, and some of which is being reduced to native copper. Inspection of this ore reveals immature enrichment of a high pyrite (overall >4 percent) part of the ore system. Chalcopyrite is only rarely visible, and most chalcocite appears to have resulted from surficial replacement of pyrite. The apparent dendritic habit is believed to represent the original texture of replaced pyrite on controlling joint surfaces where the dendritic pattern is developed as a consequence of the mechanics of fracturing.

This bench is very near the base of supergene enrichment, and exposures of quartz-orthoclase-altered, chalcopyrite-bearing porphyry are found in some locations along the bench toe. In these specimens, it may be noted that there is significantly more chalcopyrite and less pyrite than that found in the enriched ore. This mineralization was localized within the orthoclase-altered phases of the porphyry. The map of figure 3 and the cross section of figure 7 show significant primary copper values beneath this part of the pit.

SUMMARY AND RECAPITULATION OF THE SETTINGS SEEN IN STOPS C AND D

The two stops in El Tiro have allowed a view of contrasted hydrothermal alteration and mineralization in two contrasting host rock types in the same intrusive settings. Deep oxidation and enrichment are seen in the porphyry-alaskite-dacite setting of the main El Tiro Pit, while apparently less deeply oxidized primary, skarn-related ore is present at higher elevations in the Imperial Stock contact zone. With regard to alteration equivalence, the cross section of figure 7 and the map of figure 3 show proximal (to stocks) mineralization of comparable grades but of strongly contrasting hypogene alteration types. Although mineralization differs, evolution from anhydrous to hydrous alteration types is seen in mineral paragenesis of both settings.

ACKNOWLEDGMENTS

The author wishes to acknowledge, with thanks, the permission of ASARCO to carry out trips on their Silver Bell property. Their always gracious hospitality and help in allowing access to their property has been significant in the continuing education of hundreds of geologists who have had the opportunity to see the full scope of features developed in these kinds of porphyry systems. Sal Anzalone and David Duncan of ASARCO deserve special acknowledgment and thanks for their continuing interest in such activities, and for the concern and assistance given to many field trips in the past.

REFERENCES CITED

Abrams, M.J., Conel, J.E., and Lang, H.R., 1984, The Joint NASA/Geosat Test Case Project—Final Report; chapter 4 *of* part 2; vol. 1: Report available from the AAPG Bookstore, P.O. Box 979, Tulsa, OK 74101.

Anderson, J.A., 1982, Characteristics of leached capping and appraisal, *in* Titley, S.R., ed., Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 275–296.

Banks, N.G., and Dockter, R.D., 1976, Reconnaissance geologic map of the Vaca Hills quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF–793.

Beane, R.E., and Titley, S.R., 1981, Porphyry copper deposits; Part II, Hydrothermal alteration and mineralization: Economic Geology 75th Anniversary Volume, p. 235–269.

Branch, C.D., 1976, Development of porphyry copper and stratiform volcanogenic ore bodies during the life cycle of andesitic stratovolcanoes, *in* Johnson, R.W., ed., Volcanism in Australasia: New York, Amsterdam, Elsevier Scientific Publishing Co., p. 337–342.

Courtright, J.H., 1958, Progress report on investigations of some Cretaceous-Tertiary formations in southeastern Arizona: Tucson, Arizona Geological Society Digest, v.1, p. 7–9.

Elsing, M.J., and Heineman, E.W., 1936, Arizona metal production: Arizona Bureau of Mines Bulletin 140, 112 p.

Geosat Committee, Inc., 1992, Evaluation of simulated JERS–1 OPS data for geologic mapping, using sites in Utah, Wyoming and Arizona; Chapter 4 *of* A report of results of the Joint GEOSAT/ERSDAC/JGI/JAPEX JERS–1 Petroleum and Mineral Geology Simulation Study: The Geosat Committee, Inc., P.O. Box 1762, Norman, OK 73070.

Graybeal, F.T., 1982, Geology of the El Tiro area, Silver Bell mining district, Pima County, Arizona, *in* Titley, S.R., ed., Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 487–506.

Heidrick, T.L., and Titley, S.R., 1982, Fracture and dike patterns in Laramide plutons and their structural and tectonic implications, *in* Titley, S.R., ed., Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 73–91.

Keith, S.B., Gest, D.E., DeWitt, Ed, Toll, N.W., and Everson, B.A., 1983, Metallic mineral districts and production in Arizona: Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch, Bulletin 194, 58 p.

Kerr, P.F., 1951, Alteration features at Silver Bell, Arizona: Bulletin of the Geological Society of America, v. 62, p. 451–480.

Lipman, P.W., and Sawyer, D.A., 1985, Mesozoic ash-flow caldera fragments in southeastern Arizona and their relation to porphyry copper deposits: Geology, v. 13, p. 652–656.

Livingston, D.E., Mauger, R.L., and Damon, P.E., 1968, Geochronology of the emplacement, enrichment, and preservation of Arizona porphyry copper deposits: Economic Geology, v. 63, p. 30–36.

Merz, J.J., 1967, The geology of the Union Hill area, Silver Bell district, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 58 p.

Richard, K.E., and Courtright, J. H., 1954, Structure and mineralization at Silver Bell, Ariz.: Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), Nov. 1954, p. 1095–1099.

———1960, Some Cretaceous-Tertiary relationships in southeastern Arizona and New Mexico: Tucson, Arizona Geological Digest, v. 3, p.1–8.

———1966, Structure and mineralization at Silver Bell, Arizona, *in* Titley, S.R., and Hicks, C.L., eds., Geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 157–164.

Rittman, A., 1962, Volcanoes and their activity: New York, John Wiley & Sons, 305 p.

Smith, R.L., and Bailey, R.A., 1968, Resurgent cauldrons, *in* Coats, R.R., Hay, R.L., and Anderson, C.A., eds., Studies in volcanology: Geological Society of America Memoir 116, p. 613–662.

Stewart, C.A., 1912, The geology and ore deposits of the Silver Bell mining district, Arizona: Transactions of the American Institute of Mining and Metallurgical Engineers (AIME), v. 43, p. 240–290.

Titley, S.R., 1982, The style and progress of mineralization and alteration in porphyry copper systems, *in* Titley, S.R., ed., Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 93–116.

———in press, Characteristics of porphyry copper occurrence in the American Southwest, *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., eds., Mineral deposit modeling: Geological Association of Canada Special Paper 40.

Titley, S.R., Thompson, R.C., Haynes, F.M., Manske, S.O., Robison, L.C., and White, J.L., 1986, Evolution of fractures and alteration in the Sierrita-Esperanza hydrothermal system, Pima County, Arizona: Economic Geology, v. 81, p. 343–370.

TUCSON MOUNTAINS CALDERA—A CRETACEOUS ASH-FLOW CALDERA IN SOUTHERN ARIZONA

By Peter W. Lipman[1]

OVERVIEW

Mesozoic igneous rocks in southeastern Arizona constitute the least metamorphosed and structurally disrupted sector of the Cordilleran volcanic arc. Until recently, studies of these rocks have mainly involved either detailed work on small areas adjacent to mineral deposits or broad studies focused largely on regional stratigraphy and tectonics. A current major challenge is to apply modern volcanological concepts, initially developed at more completely preserved Cenozoic volcanic centers, to the surviving fragments of Mesozoic igneous rocks (Lipman, 1992). About a dozen ash-flow caldera systems have recently been identified for the Jurassic and Laramide (late Cretaceous–early Tertiary) igneous areas of southeastern Arizona, on the basis of new field work and analogies with Cenozoic calderas (Lipman and Sawyer, 1985; Lipman and Hagstrum, 1992).

Detailed mapping and petrologic studies of three such areas of Laramide age near Tucson have now been largely completed, including the Silver Bell Mountains (Sawyer, 1987; Hagstrum and Sawyer, 1989), the Sierrita Mountains (Lipman and Fridrich, 1990), and the Tucson Mountains (Hagstrum and Lipman, 1991; Lipman, 1993), which are the focus of this field trip (fig. 1). Igneous rocks of the Silver Bell Mountains have been interpreted as remnants of a large ash-flow caldera where late granitic intrusions along ring faults host major porphyry copper deposits. At the Sierrita caldera and its associated tuffs (Red Boy Rhyolite), Tertiary tilting is inferred to provide an oblique section through an upper crustal magmatic system and associated copper deposits. In this field trip, we examine evidence indicating that the Tucson Mountains contain a trap-door caldera that was the source of the Cat Mountain Tuff; along the most deeply subsided northern margin, the caldera-related Amole pluton is associated with widely distributed disseminated copper mineralization.

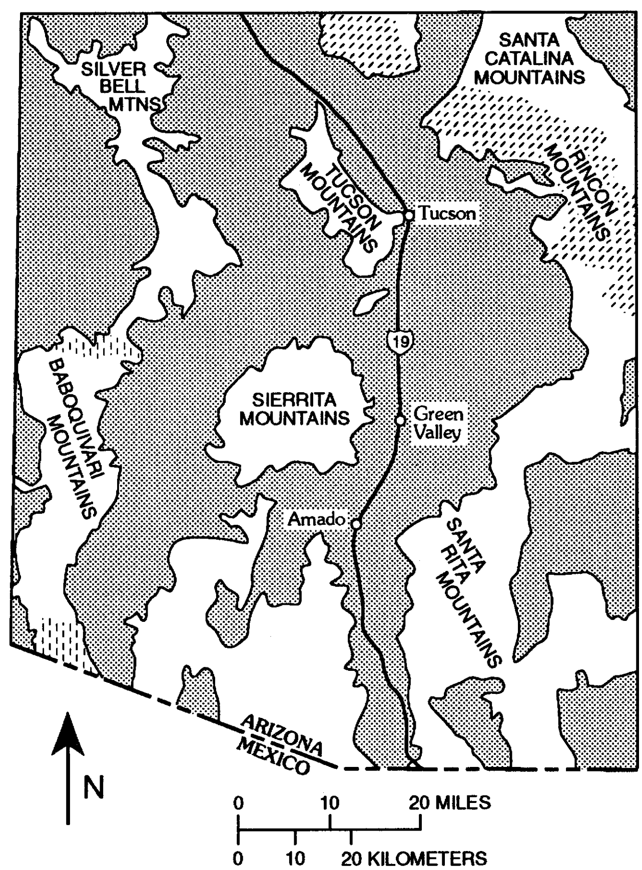

Figure 1. Index map for the Tucson, Silver Bell, and Sierrita Mountains. Stipple pattern indicates basin-fill deposits between mountain ranges. Dashed pattern indicates outcrops with mid-Tertiary mylonitic fabric; dashes are approximately parallel to strike of lineation (modified from Reynolds, 1988).

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THE TUCSON MOUNTAINS CALDERA: ANATOMY OF AN ASYMMETRIC TRAP-DOOR SUBSIDENCE STRUCTURE

The Tucson Mountains, a low desert range just west of Tucson (fig. 2), are underlain largely by Upper Cretaceous volcanic rocks now interpreted as parts of the fill of a large ash-flow caldera (Lipman and Sawyer, 1985; Lipman, 1993). In the Tucson Mountains and elsewhere in southern Arizona, much of the challenge in working on the altered and incompletely preserved Mesozoic volcanic rocks is to be able confidently to apply and utilize observations and relations that are demonstrably valid for younger volcanic deposits.

The origin of the igneous rocks in the Tucson Mountains has been much discussed. The range was mapped in its entirety by Brown (1939), and several areas were restudied by University of Arizona graduate students in the 1960's, working largely under the direction of Evans Mayo (Kinnison, 1958; Bikerman, 1963; Mayo, 1963, 1971a,b; Assadi, 1964; Knight, 1967). Brown (1939) mapped an upper unit, the Cat Mountain Rhyolite (Cat Mountain Tuff, of general present usage), overlying a lower breccia unit that he called the Tucson Mountain Chaos and interpreted as related to regional thrusting. Mayo (1963, 1971a) reinterpreted the breccia as volcanically erupted intrusive breccia related to a regional "volcanic orogeny." Bikerman (1963) recognized the ash-flow origin of the Cat Mountain Tuff, but inferred that the chaos breccia represented stoped subvolcanic fragments, rafted from deeper levels by the rising pyroclastic magma that later erupted the Cat Mountain Tuff. A similar interpretation was developed in more detail by Mayo (1971b). Brown, Mayo, and Bikerman all considered the chaos to be a basal layer beneath the Cat Mountain Tuff. Drewes (1981, pl. 9) remapped the central Tucson Mountains, also showing the breccia blocks to underlie the Cat Mountain Tuff in a matrix that he assigned to the Silver Bell Formation—mapped by him as a regional Upper Cretaceous andesitic unit extending at least from the Silver Bell Mountains to the north and to the Santa Rita and Sierrita Mountains to the south.

Lipman (1976) inferred, largely from published descriptions, that the Tucson Mountain Chaos might be landslide breccia associated with collapse of an upper Cretaceous ash-flow caldera within which the Cat Mountain Tuff had ponded. New field and petrologic studies confirm such an interpretation and also show that the slide breccias, rather than underlying the Cat Mountain Tuff, have a matrix of nonwelded tuff and interfinger with welded tuff at multiple horizons. A major implication of this interfingering is that the exposed thickness of the caldera-filling Cat Mountain Tuff is at least 3–4 km, many times that previously reported. Megablocks are as much as 0.5 km across and include Paleozoic sediments, Jurassic silicic volcanics, Cretaceous sedimentary rocks and andesitic lavas, and tuff of Confidence Peak erupted from the slightly older Silver Bell caldera to the northwest. Predominant breccia types vary greatly between various caldera sectors. Small bodies of rhyolitic rock in the northern Tucson Mountains, previously mapped as irregular intrusions by Brown and Drewes (Amole Latite, Latite Porphyry), are reinterpreted as discontinuous lenses of Cat Mountain Tuff that fill interstices between large disrupted masses of Mesozoic sedimentary rock. The result of this interpretation is to include a sizeable additional area as caldera-fill breccia.

A small segment of the structural boundary of the caldera may be represented by an arcuate fault along the west flank of the range that drops Cretaceous sedimentary rocks against Jurassic rocks on Brown Mountain (fig. 2). Cretaceous sedimentary rocks, exposed low along the west flank of the mountain range, may represent part of the caldera floor, or they may be low on the western caldera wall between the exposed outer ring fault and concealed inner structures to the east. An unresolved problem, if the sediments are part of the caldera floor, is the apparent absence of in-place precaldera andesitic lavas above the sediments, even though such lavas occur widely as slide blocks within the caldera fill. Because no remnants of the actual caldera wall are exposed, the structural and lithologic assemblages present on different sectors of the original caldera wall are now conjectural and best interpreted from the caldera-filling breccias.

Along the northeast and southeast flanks of the Tucson Mountains, the Cat Mountain Tuff is conformably overlain by andesitic to rhyolitic lavas that are interpreted as erosional remnants of a thick caldera-fill sequence emplaced

EXPLANATION

Extracaldera units

J — **Jurassic(?) sedimentary and volocanic rocks**

Pz — **Paleozoic sedimentary rocks**

Caldera-floor rocks

K — **Cretaceous Amole Arkose of the Bisbee Group**

Caldera-related igneous rocks of Laramide age

Intracaldera Cat Mountain Tuff

Intracaldera landslide breccia deposits ("Tucson Mountain Chaos")—Contains megablocks as much as 0.5 km across

Caldera-filling lava flows—Range in composition from andesite to rhyolike

Contact

Base of caldera-filling tuffs and breccias

20 **Strike and dip of bedding in Cat Mountain Tuff**

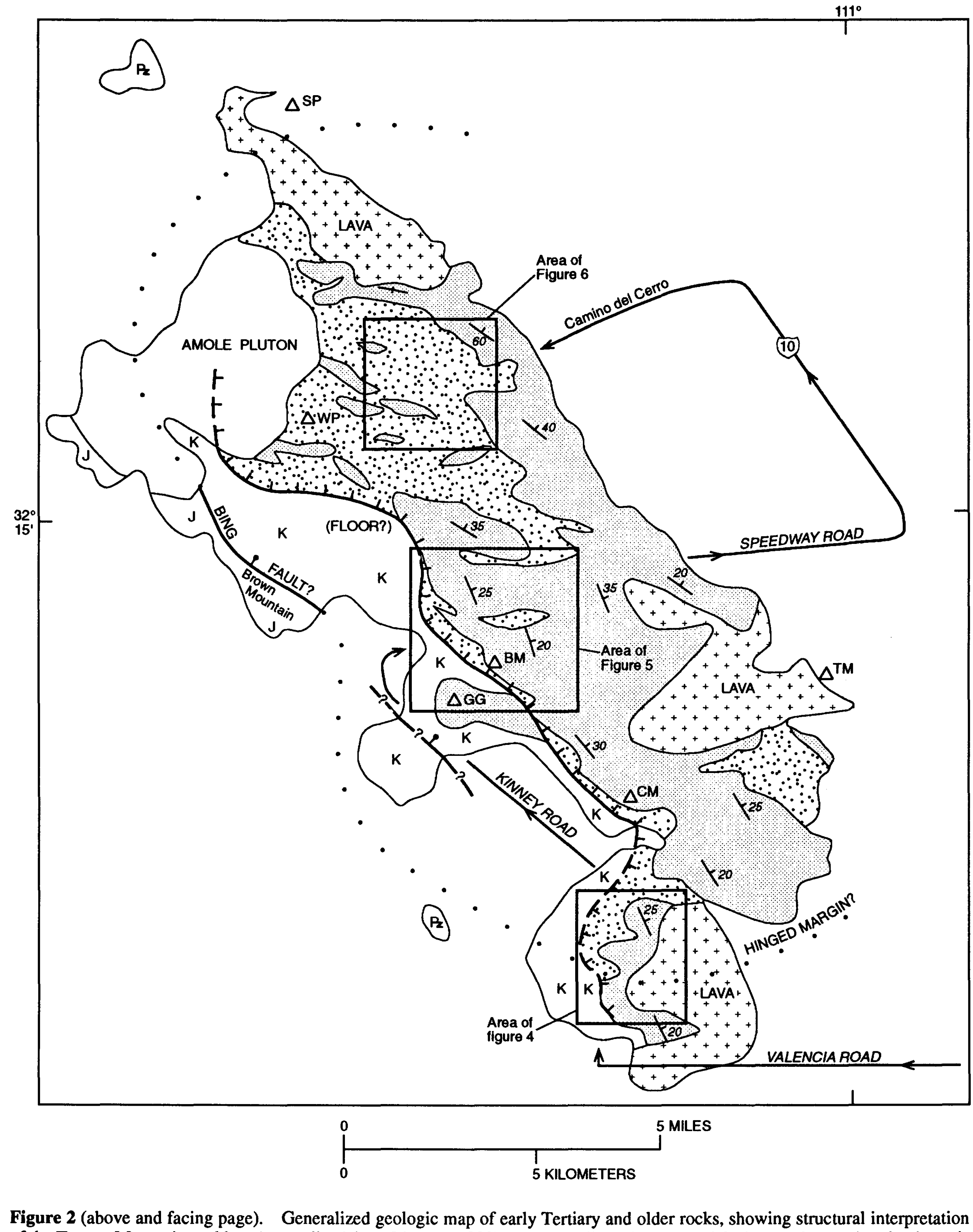

Figure 2 (above and facing page). Generalized geologic map of early Tertiary and older rocks, showing structural interpretation of the Tucson Mountains caldera (generalized from Lipman, 1993). Many small Tertiary normal faults not shown. Amole pluton is interpreted as ring intrusion. Hachured contact indicates base of caldera-filling tuffs and breccias. Geographic localities: BM, Bren Mountain; CM, Cat Mountain; GG, Golden Gate Mountain; SP, Safford Peak; TM, Tumamoc Hill; WP, Wasson Peak.

soon after collapse and involved in caldera resurgence. These lavas obscure the northern and southern caldera margins. The large zoned granodioritic-granitic Amole pluton exposed along the northwest flank of the Tucson Mountains appears to be a resurgent ring intrusion that arches the caldera fill, including postcaldera lavas, upward to the east and north. The ages of the caldera-related volcanic rocks are constrained as Late Cretaceous (70–75 Ma) by published conventional K-Ar ages (Bikerman and Damon, 1966), and new ^{40}Ar-^{39}Ar determinations (L.W. Snee and P.W. Lipman, unpub. data, 1992) confirm the near synchroneity between eruption of the Cat Mountain Tuff (73.1±0.2 Ma on biotite) and solidification of the apparently cogenetic resurgent Amole pluton (73.0±0.1 Ma on potassium feldspar).

Within northern parts of the caldera fill, slide breccias predominate over ash-flow tuff (fig. 2), documenting repeated oversteepening of caldera walls during subsidence in this sector. In contrast, along the inferred southern caldera margin, the thickness of tuff decreases to only about 100 m, and megabreccia is virtually absent. These relations suggest a hinged southern caldera margin and overall trapdoor geometry. Thus, virtually the entire mountain range is interpreted as an oblique section through the structurally disrupted interior of a caldera; the caldera margins are largely concealed by Tertiary basin fill. Although poorly constrained, especially to the east, the overall inferred dimensions of the Tucson Mountains caldera are about 2025 km, slightly smaller than the Pleistocene Long Valley caldera, and well within the spectrum of late Cenozoic calderas in the Western United States (fig. 3).

Most of the Cretaceous rocks are tilted eastward, presumably largely in response to Tertiary faulting involving extension and rotation within the upper plate of the westward-directed middle Tertiary detachment that is exposed along the foot of the Santa Catalina–Rincon core complex east of Tucson. In the southeastern Tucson Mountains, dips in the caldera-related Cretaceous rocks are typically only 10°–20° steeper than overlying middle Tertiary volcanics, as on Tumamoc Hill. In contrast, north of Wasson Peak, the caldera sequence strikes east-west, dips nearly vertically, and is overlain by the gently dipping mid-Tertiary volcanics of Safford Peak in a much more pronounced angular unconformity. These relations indicate that much of the tilting of the northern caldera sequence predated the mid-Tertiary volcanism, and several features suggest that this deformation is related to late asymmetrical resurgent emplacement of the Amole granitic pluton: (1) all the steeply tilted rocks, including postcaldera lava flows, are intruded by the Amole pluton; (2) paleomagnetic studies indicate that the steep tilting of the volcanics within the caldera predates solidification of the Amole pluton, which has not been significantly tilted or rotated since acquiring stable magnetization (Hagstrum and Lipman, 1991); (3) some faults that cut the tilted volcanics seemingly do not displace the granitic rocks.

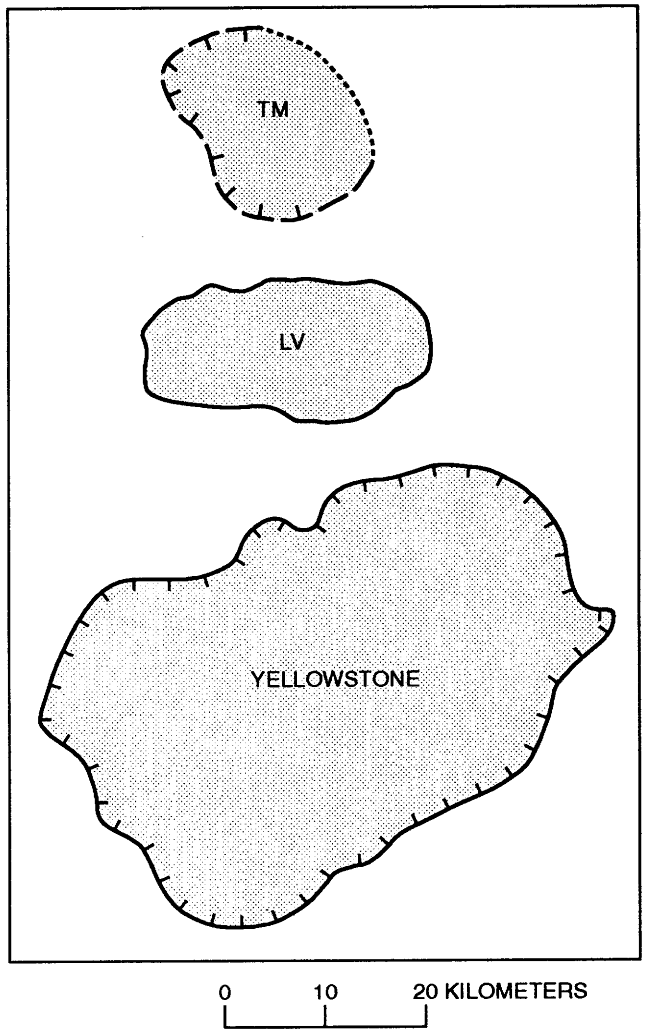

Figure 3. Inferred map outline of the Tucson Mountains caldera (TM), in comparison with young calderas of the Western United States. (LV, 0.7-Ma Long Valley; 0.6-Ma Yellowstone).

In several parts of the Tucson Mountains, a gridwork of northwest- and northeast-trending faults disrupts the caldera-filling volcanics, but where determinable, most faults have relatively small displacements (25–100 m). These faults complicate detailed estimation of the thickness of the caldera fill, because reliable stratigraphic markers are generally lacking. Many of these faults are likely related to middle Tertiary extension, but some may have formed in response to disruption of the caldera during the Cretaceous subsidence event, as indicated by: (1) the geometrically unusual gridwork pattern of faulting; (2) local extreme welding, ductile flowage, and rotation of pumice fabric in the tuffs into near-vertical orientations adjacent to faults; (3) truncation or filling of some faults by "Silver Lily" dikes of typical east-northeast trend and presumed Laramide age.

The three main field trip stops, at Bilby Road, Gates Pass, and Sweetwater Wash, permit examination of representative sections through the northward-thickening fill of the trap-door subsidence structure. At Bilby Road in the southern Tucson Mountains, a 0.5-km hike provides a complete caldera section from the floor, through the intracaldera tuff (only about 150 m thick) and volumetrically minor associated breccia, into postcaldera lavas. The Gates Pass stop, in the central part of the mountain range, offers a 2- to 3-hour loop hike that provides a partial section from the caldera floor up through lower parts of the caldera fill, where it consists mainly of thick and relatively lithic-poor welded tuff, and leading to a panoramic view of the northern Tucson Mountains from a scenic highpoint. The Sweetwater Wash section in the northern and thickest part of the caldera fill provides a representative 2-km segment of caldera-fill breccia, where the tuff is volumetrically minor.

TUCSON MOUNTAINS FIELD GUIDE

The field trip route (fig. 2) begins from Interstate 10 (I–10), in central Tucson, proceeds south and west to examine the southern caldera margin at Bilby Road (**STOP 1**), returns to Tucson through thick welded tuff in the central part of the caldera at Gates Pass (**STOP 2**), then proceeds into the thick caldera-fill breccias in the northeast Tucson Mountains by way of Camino del Cerro to Sweetwater Wash (**STOP 3**).

Miles

0.0 Start at I–10 and Grant Road. Proceed south on I–10. Jagged crest of Tucson Mountains at 3 o'clock consists almost entirely of intracaldera Cat Mountain Tuff. The general structure is a homoclinal sequence dipping 15–35 eastward.

Flat-topped and pointed hills between 1 and 2 o'clock are A Mountain and Tumamoc Hill, capped by middle Tertiary lavas (basaltic andesite).

4.0 Junction, I–10 and I–19 (south to Nogales); bear right on I–19 for 4.3 mi to Valencia Road junction; turn west onto Valencia Road for 3.4 mi. First roadcut outcrops are upper part of east-dipping Cat Mountain Tuff. At crest of low pass in southern Tucson Mountains, 1.1 mi ahead, outcrops at 3 o'clock are also Cat Mountain Tuff. Continue 0.7 mi west of pass to Mark Road.

13.5 Turn right (north) for 0.5 mi on Mark Road (continues to north as Joseph Avenue). Then turn right (east) on Bilby Road (unpaved). Small exposures along road ahead are in steeply dipping Cretaceous sandstone of the Bisbee Group (Amole Arkose), interpreted as in-place rocks of the caldera floor.

14.3 **STOP 1: southern caldera margin.** Park in wide area at road end. We are at base of small hill of Cat Mountain Tuff. By walking east on the pipeline continuation of Bilby Road, we can examine a complete section of relatively thin Cat Mountain Tuff near the southern margin of the caldera fill, where the structural margin of the caldera is probably only a hinged inflection (fig. 4).

SOUTHERN CALDERA MARGIN

The contact between Cretaceous sandstone and nonwelded greenish-gray basal Cat Mountain Tuff can be located within about 1 m in the small gully just south of the pipeline road, unless it is covered by recent rainstorm slopewash. Just higher in this small gully and nearby are meter-sized blocks of Paleozoic limestone, limestone conglomerate (Glance Formation?), and Cretaceous andesitic

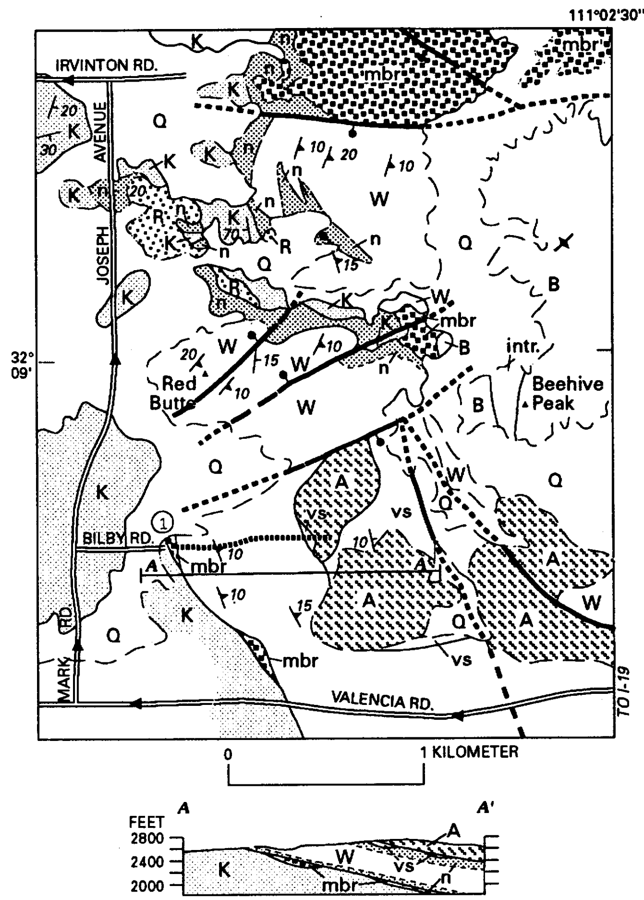

Figure 4. Preliminary generalized geologic map and cross section, Bilby Road area (**STOP 1**). K, Cretaceous Amole Arkose of the Bisbee Group. Caldera-related igneous rocks of Late Cretaceous age: w, welded Cat Mountain Tuff; n, nonwelded to partly welded tuff; mbr, intracaldera landslide megabreccia deposits containing megablocks of Paleozoic limestone, Cretaceous andesitic volcanics, and Cretaceous sandstone ("Tucson Mountain Chaos"); R, flow-laminated (spherulitic) rhyolite megablocks within landslide deposits, of probable Jurassic age; vs, bedded volcaniclastic sedimentary rocks; A, lava flows of porphyritic andesite; B, crystal-rich rhyolitic tuff of Beehive Peak (middle Tertiary?); Q, colluvium and fan gravels; intr., intrusive rocks.

lavas enclosed by nonwelded tuff matrix near the base of the Cat Mountain. The green-gray color of the basal tuff is characteristic of altered tuff that was originally glassy. Higher on the slope, the tuff becomes red-brown and collapsed pumices define a compaction foliation, indicative of primary welding and devitrification.

As we continue east, across the crest of the first hill, the low slopes ahead are roughly a dip surface in the gently east-dipping tuff (10°–20°), but tuff exposed in small gullies is variable in appearance due to weak tectonic brecciation and variable hydrothermal alteration. The total thickness of the Cat Mountain Tuff here is only about 150 m (fig. 4). No large faults are present. The Cat Mountain Tuff here is a simple cooling unit having no obvious internal breaks and is no thicker than many outflow sheets. The relatively thin tuff section is nevertheless considered to be inside its source caldera, on the basis of the presence at its base of sparse megablocks, interpreted as derived by insliding from walls of the caldera during collapse. Relations at this site alone would be inconclusive were it not for the presence of larger and more voluminous megablocks to the north in association with the great northward increase in thickness of the tuff unit (as much as 4–5 km). The relatively thin tuff unit and sparse megablocks near Bilby Road suggest we are near a weakly developed south margin of the Tucson Mountain caldera, which probably was a morphologically subdued structural hinge, rather than a well-developed ring fault bounding a steep topographic wall. Hinged and asymmetrical trap-door collapse of calderas is well established in many better preserved volcanic fields (Lipman, 1984).

Looking to the north, Golden Gate Pass (where we will hike at **STOP 2**) is visible between Golden Gate and Bren Mountains, and farther north the most distant ridges are on the west slopes of Wasson and Amole Peaks, just west of the third stop (Sweetwater Wash) in thick caldera fill.

The ridge ahead to the east is capped by plagioclase-phyric andesite lava that conformably overlies the upper gray partly welded to nonwelded vapor-phase-crystallized Cat Mountain Tuff. Poorly exposed in the gully at midslope are discontinuous lenses of fine-grained volcaniclastic sedimentary rocks that have largely been derived by local reworking of the partly welded light-gray upper part of the Cat Mountain Tuff. Such sediments also occur between flows of postcaldera lavas that conformably overlie the Cat Mountain Tuff farther north in the Tucson Mountains. On the basis of these generally conformable relations, and the presence elsewhere of a sizeable angular unconformity between these lavas and much less altered middle Tertiary lavas, the conformable lavas are latest Cretaceous (or earliest Tertiary) in age and are interpreted as representing post-caldera volcanism that is broadly part of the Tucson Mountain caldera cycle. Further evidence favoring such a close genetic relation between these lavas and the caldera cycle is provided by relations with the Amole pluton at the north end of the Tucson Mountains. There, similarly conformable lavas and the underlying Cat Mountain Tuff have both been steeply tilted and strongly deformed by emplacement of the pluton, yet the pluton is indistinguishable from the tuff in ^{40}Ar-^{39}Ar age at 72 Ma (Lipman, 1993; L.W. Snee and P.W. Lipman, unpub. data).

Return to cars, and retrace route west on Bilby Road.

14.5 Turn right (north) on Mark Road. After turn, the high point at 12 o'clock is geographic Cat Mountain. A conspicuous break in slope between two cliffs high on the mountain is a partial cooling break between two densely welded zones of Cat Mountain Tuff. As we proceed ahead, note that the lower welded zone thins and weakens to the southeast.

The two light-colored knobs in the foreground are megablocks of flow-layered (spherulitic) rhyolite of probable Jurassic age, enclosed within the basal Cat Mountain Tuff. Such bodies have previously been interpreted as intrusive into the Cat Mountain Tuff, but their origin as allocthonous blocks within the tuff is demonstrated by many field relations, including (1) welding foliation in the tuff matrix that wraps around the blocks; (2) welding zonations in the enclosing tuff, becoming less welded toward the megablocks that were cool at the time of incorporation in the tuff; (3) truncated flow layering at contacts with the tuff; (4) thin films and veins of tuff matrix that penetrate fractures in the rhyolite blocks; and (5) association of the rhyolite masses with other block lithologies such as Paleozoic limestone.

15.7 Notched roadcut outcrops are weakly welded Cat Mountain Tuff, dipping gently beneath and around the megablocks of flow-layered rhyolite to the east.

16.1 T-intersection with Irvington Road; turn left (west) for 0.8 mi, to T-intersection with Sunset Road; turn right (north). After turn, high peak ahead is Golden Gate Mountain, capped by densely welded Cat Mountain Tuff. Lower slopes are nonwelded to partly welded tuff, overlying Cretaceous sedimentary rocks on the caldera floor along pediment.

17.3 Ajo Way; turn right (east). Continue east 0.5 mi to stoplight at Kinney Road; turn left (north). As we head northwest on Kinney Road, watch the changes in welding zonation on the lower south slopes of Golden Gate Mountain. A lower dark-brown welded zone emerges northwestward from within the thick buff-colored tuff that is so conspicuous on the southeast side of the mountain.

20.3 Entering Tucson Mountain Park. The lower welded zone on the middle west slopes of Golden Gate Mountain is now a conspicuous cliff. The irregular outcrops lower on the slope are slumped masses of Cat Mountain Tuff that cover in-place Cretaceous sedimentary rocks. The gradual appearance of additional cooling units and increased welding northward within the Cat Mountain Tuff is characteristic of the north-south section provided by present-day exposures in the Tucson Mountains and reflects the overall trap-door character of the inferred caldera subsidence, with only a hinged southern caldera margin and maximum subsidence in northern parts of the caldera.

21.2 Low pass west of Golden Gate Mountain. Highest hills straight ahead in the far distance are the Silver Bell Mountains, capped by outflow Cat Mountain Tuff that is preserved within the slightly older Silver Bell caldera (Sawyer, 1987). The capping tuffs of the Silver Bell Mountains have at times been designated the Mount Lord Tuff (Ignimbrite), but correlation with the Cat Mountain Tuff (which has precedence as a name) is now firmly based on stratigraphic position with respect to the tuff of Confidence Peak (erupted from the Silver Bell caldera), petrographic and chemical distinctions, and distinctive paleomagnetic pole positions (Hagstrum and Sawyer, 1989; Hagstrum and Lipman, 1991).

23.3 Junction with Gates Pass Road; turn right (east). **Optional roadside stop** to consider overall structural and stratigraphic complexities of the intracaldera Cat Mountain Tuff.

On the left (to the northeast), the complex alternation of cliffs and slopes on the rugged western flank of the Tucson Mountains is not easily traced laterally. These complexities reflect intricate laterally variable interleaving of cliff-forming densely welded tuff (relatively lithic-poor) with less welded bench-forming tuff containing megablocks. No sizeable faults cut these slopes. All lithic-rich zones within the Cat Mountain Tuff are weakly welded, due to thermal quenching by relatively cool blocks slumped from caldera walls.

Pedimented lower slopes contain monolithologic breccia blocks of tuff of Confidence Peak. These blocks, of the latest Cretaceous unit deposited prior to eruption of the Cat Mountain Tuff, were the first wall materials to slump into the collapsing caldera and may have moved only short distances from their original location.

The lithologic composition of breccias interleaved with the Cat Mountain Tuff vary greatly laterally and vertically in the caldera fill. Basal zones containing Paleozoic carbonate megablocks are especially conspicuous, and were early recognized and designated as "Tucson Mountain Chaos" (Brown, 1939). The diversity of additional lithologic types associated with the carbonate blocks was studied in great detail by Mayo (1963, 1971b), and the presence of andesitic material was emphasized by Drewes (1981), who interpreted the matrix as andesitic in composition and correlated the entire megablock assemblage with his regional andesitic Silver Bell Formation.

New work shows that the matrix to the blocks is nonwelded Cat Mountain Tuff, as indicated by textural, petrographic, and chemical data, and all the megablock areas are interpreted as contemporaneously deposited facies of intracaldera Cat Mountain Tuff. In addition to the lithologically diverse megablock areas, previously recognized as "Tucson Mountain Chaos," intracaldera megabreccia assemblages include (1) large areas of predominantly andesitic megablocks along the southeastern and northeastern mountain flanks that have previously been mapped as in-place Cretaceous andesite; (2) the masses of flow-layered rhyolite already noted that previously were interpreted as intrusions; and (3) large areas in the northern Tucson Mountains that consist predominantly of Cretaceous sedimentary rocks (Amole Arkose), and have previously been mapped as in-place deposits irregularly intruded by "Amole Latite." All these assemblages are now interpreted as distinctive intracaldera-breccia of the Cat Mountain Tuff.

25.0 Tight turn to left, with parking area at right. We hike back down the road from Gates Pass to this point as part of the **STOP 2** traverse.

25.5 **STOP 2: central part of caldera fill at Gates Pass (figs. 5 and 6).** Turn left (north) into parking area about 25 m east of pass. This will be a 2- to 3-hour loop-trail hike to examine relations between tuff and megablocks in lower parts of the caldera fill in the central part of the Tucson Mountains.

Proceed 0.45 miles (750 m) on foot from **point A** across the pass (3,172 ft elevation) and down section along paved road, to second parking area **(point B)** at major bend in the road **(road traffic is heavy and visibility is poor; extreme caution needed)**. At this point we will be in Cretaceous sedimentary rocks, seemingly part of the caldera floor. The trip route will follow a foot trail to a saddle between Bren Mountain (3,988 ft) and Golden Gate Mountain (4,288 ft), remaining within the Cretaceous sedimentary rocks. Then, we will angle back toward Gates Pass on a higher foot trail to the east, providing excellent exposures of diverse block lithologies within the Cat Mountain Tuff. Eventually, we will climb to the top of the 3,530-ft point, providing a panoramic view of the northern Tucson Mountains and adjacent ranges. Finally, continuing along the foot trail, we will return to Gates Pass.

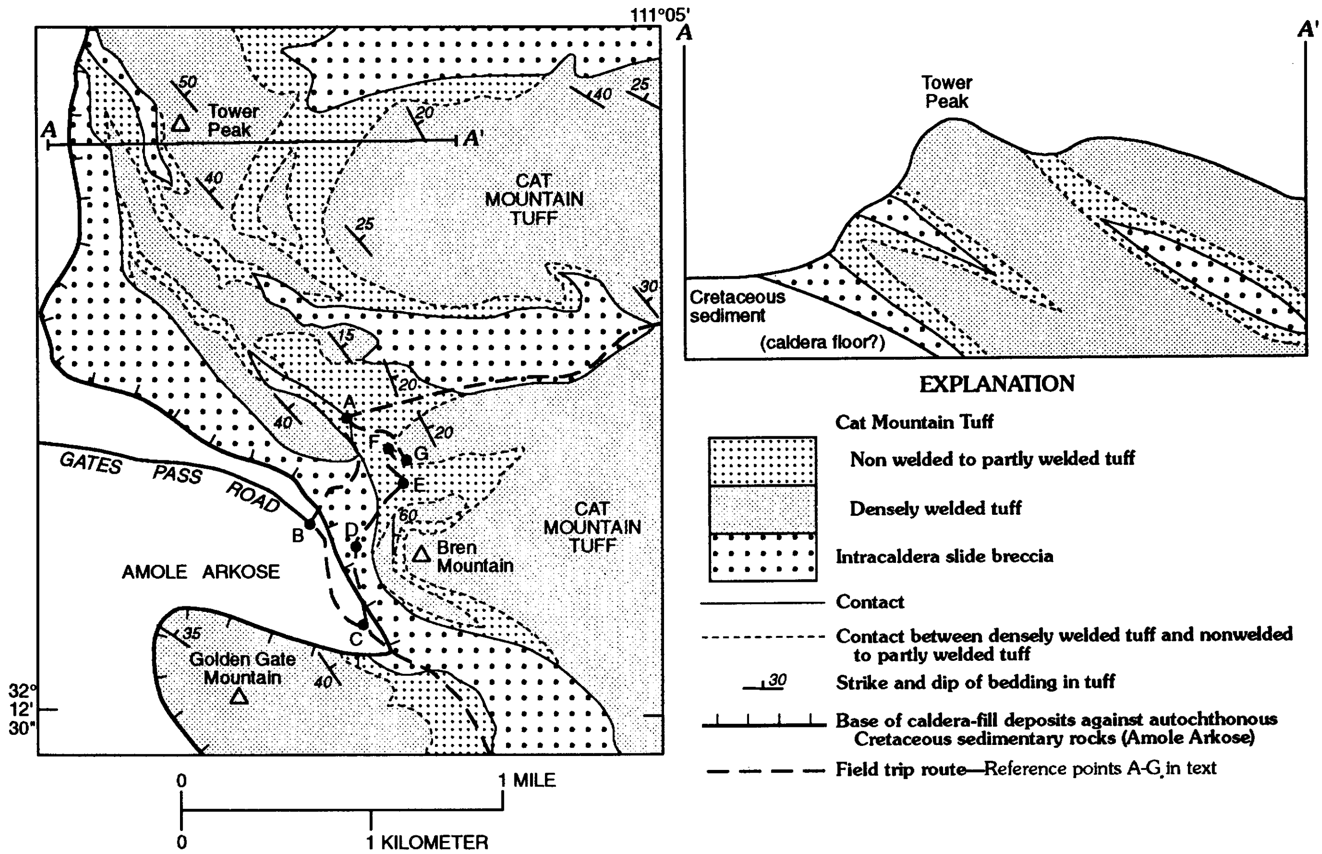

Figure 5. Preliminary geologic map of Tucson Mountain caldera fill in the Gates Pass area (**STOP 2**). Diagrammatic cross section through the west margin of the Tucson Mountain caldera north of Gates Pass illustrates interfingering between Cat Mountain Tuff and intracaldera slide breccias.

CENTRAL PART OF CALDERA FILL AT GATES PASS

Leaving the Gates Pass parking area, we cross the pass, carved in a large megablock of steeply dipping Cretaceous sandstone. This sandstone is a unit of the Bisbee Group, locally called the Amole Arkose (Brown, 1939). The Amole Arkose includes interbedded sandstone, siltstone, and local finely bedded limestone. Most contacts between the block and adjacent tuff are poorly exposed, but along the road about 50 m west of the pass, the block of Amole Arkose is in contact with lithic-rich, weakly welded Cat Mountain Tuff. The Cat Mountain Tuff is a compositionally uniform low-silica rhyolite (70–72 percent SiO_2), containing phenocrysts of quartz, feldspar, and sparse biotite (where not obscured by alteration).

The Cat Mountain Tuff here also contains blocks of andesitic lava at least several meters across. Note that as the tuff becomes less lithic-rich upward from road level, it also becomes more welded as indicated by collapsed-pumice foliation. Such features are typical of caldera-filling tuff, in which large lithic fragments act as heat sinks to inhibit welding (fig. 4).

About 0.15 mi (250 m) west of the pass, along the road, prominent rugged outcrops at road level are a densely welded zone of Cat Mountain Tuff containing relatively sparse lithic fragments. This welded zone is both overlain and underlain by less welded tuff containing abundant large blocks of andesite and other rock types. Note the irregular foliation and decrease in welding adjacent to blocks beneath the most densely welded tuff, in contrast to a sparsity of blocks within the most welded tuff. The disaggregated mass of reddish sandstone here was probably derived from the Jurassic Recreation Redbeds, which are exposed in place on Brown Mountain near the Arizona-Sonora Desert Museum, about 5 km to the northwest.

Looking back across the road to the north, note similar densely welded tuff dipping southeastward beneath the megablock zone just examined in roadcuts. Some faults may be present in this area, but are not mappable for any distance.

At 0.35 mi (550 m) west of the pass, the road bends to the left, and a block of Paleozoic limestone several meters across is exposed, along with other brecciated sedimentary lithologies, in obscure contact with weakly welded, quartz-bearing tuff.

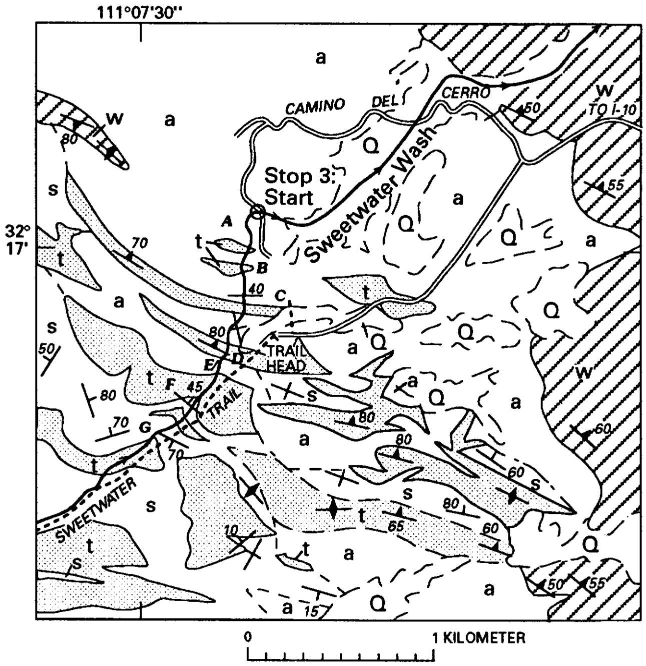

Figure 6. Generalized geologic map of the Sweetwater Wash area, at head of Camino del Cerro (**STOP 3**). Caldera-related igneous rocks of Laramide age: w, welded Cat Mountain Tuff; t, nonwelded to partly welded tuff; unpatterned, intracaldera land-slide megabreccia deposits ("Tucson Mountain Chaos") containing dominant megablocks of Cretaceous andesitic volcanics (a) and sandstone (s); Q, colluvium and fan gravels; A–G, points discussed in text.

Just before the road bends northwest, where there is a large parking area on the south side (**point B**), are exposures of gently dipping Amole Arkose that are apparently in place on the caldera floor, or possibly low on the wall.

From this parking area, walk south up the trail to the saddle that separates Bren Mountain (on the northeast) from Golden Gate Mountain (on the southwest). The trail is entirely within Amole sediments of the caldera floor that are discontinuously exposed beneath the colluvial debris.

At the trail crossing the main gully, the many boulders of densely welded Cat Mountain Tuff are typical of the cliffs above and similar to the late welded tuffs (Mount Lord Volcanics) that cap the crest of the Silver Bell Mountains 50 km to the northwest. The good exposures ahead along the east side of the gully are Amole Arkose. Detailed mapping of these sedimentary rocks by Assadi (1964) for an M.S. thesis at the University of Arizona, and also by Harald Drewes of the U.S. Geological Survey (1981, pl. 9), shows that they are broadly folded around north-northwest-trending axes.

About 100 m upvalley along the trail, exposed in a side gully to the east between exposures of Amole Arkose, is a large dark-gray block of limestone (Permian?) enclosed within the nonwelded lower part of the Cat Mountain Tuff, beneath large massive cliffs of lithic-poor welded tuff. Linear yellowish-brown outcrops, trending along the slope just above the limestone megablock, are exposures of a dike of Cretaceous dacite, part of a regional swarm (Silver Lily Quartz Latite) in this sector of the Tucson Mountains. This area was mapped in great detail by Mayo (1971b, fig. 3).

At the saddle (**point C**), bear left (east) on a more obscure trail that leads toward the limestone megablock and back towards Gates Pass. Note the eastward and southeastward dips indicated by slabby jointing of the tuff on Golden Gate Mountain to the west. The section to the east is probably raised by a small fault through the saddle. The peak visible through the pass to the south, just east of the large trailer park development, is geographic Cat Mountain; it consists entirely of densely welded Cat Mountain Tuff overlying megablocks and in-place Amole sedimentary rocks at the base of the slope adjacent to the trailer park. In the far distance are the Santa Rita Mountains, site of another Cretaceous caldera fragment (Lipman and Sawyer, 1985); a high point in the range (Mount Hopkins, elevation 8,550 ft), barely visible to the right, consists mostly of granitic rocks along the east margin of that caldera.

Heading back along the upper trail toward the conspicuous block of Paleozoic limestone, the trail crosses Cretaceous sandstone near the contact between in-place Amole Arkose (caldera floor?) and overlying megablock debris in a tuffaceous matrix along the basal Cat Mountain Tuff.

Large dark-brown outcrops, just to the right (south) of the Paleozoic limestone, are blocks of Cretaceous andesitic lava, again as megablocks enclosed in a tuff matrix.

About 75 m along the trail, in a small gully just before the limestone block, are reddish sediments of Jurassic Recreation Redbed type, juxtaposed with fragments of laminated limestone of a type locally characteristic of the Amole Arkose.

Beyond the Paleozoic block is voluminous float of porphyritic andesite, derived from blocks of Cretaceous volcanics upslope. **Be alert for a fork in the trail (point D); stay high.** At this point the trail is obliquely traversing the contact zone between in-place Cretaceous sediments and overlying megablock-rich Cat Mountain Tuff. Below the trail, the sediments are stratigraphically and structurally coherent; at trail level and above, blocks of Amole Arkose are incorporated as fragments, along with the other rock types just noted, in a tuff matrix.

The trail then crosses below a large mass of brecciated and mostly structureless (locally flow laminated) rhyolitic lava of probable Jurassic age. This block is at least 15 m across.

The trail continues northward, mainly through talus of welded Cat Mountain Tuff from cliffs above, to a spur ridge that descends directly toward the parking area below. Above the trail on this spur is another large mass of light-colored rhyolitic lava. The trail then climbs obliquely upward, through the margins of this rhyolite mass, where contacts are locally exposed between the rhyolite and partly welded Cat Mountain Tuff containing small angular fragments of andesite. Here, the Cat Mountain has compaction foliations that dip anomalously steeply northward, wrapping around the rhyolite block.

The trail continues ahead toward a prominent spur, where it crosses about 25 m above the upper contact of another large mass of light-colored brecciated rhyolite. On the way, the trail crosses several smaller masses of Cretaceous andesitic lava and Amole sandstone, enclosed by somewhat altered, partly welded Cat Mountain Tuff.

From the rhyolite block, the trail continues obliquely upward through partly welded light-colored tuff, toward more thoroughly welded, brown, cliff-forming outcrops, then descends below the cliffs. Dips in these welded tuffs are variable, from 30° to 50° east; some variation may be due to slumping on the steep slopes, but much is interpreted as due to variable draping around and over the large megablocks below trail level.

Looking north across the main road, we can see several prominent cliff-forming welded horizons in the Cat Mountain Tuff, separated by benches or gentler slopes, along which large megablocks are also present (fig. 3). Thus, the megablocks occur at multiple horizons within the Cat Mountain Tuff, not just beneath it as previously thought. This relation becomes increasingly pronounced northward along the range front and to the northeast. Also, looking northward, try to distinguish where we saw welded tuff and megablocks at road level.

Continue eastward to the conspicuous saddle (**point E**), then descend northward following an obscure and rather eroded trail. Descending and contouring northward, we pass another large block of Cretaceous sandstone that is mostly above the trail. Consider how irregular the contact is between the densely welded tuff above us and the zone of megablocks below. How much is due to depositional irregularities, versus possible faults in the saddle?

The trail then makes a series of switchbacks up through a variably welded and altered Cat Mountain Tuff, to a prominent shoulder southeast of Gates Pass parking area (**point F**).

Across Gates Pass to the northeast, the ridge crest is capped by densely welded Cat Mountain Tuff. The dip is steeper than it appears, 20°–30° or greater, because this ridge is nearly parallel to the strike of the tuff. Below the cliffs of welded tuff, several large, light-colored knobs and more obscure darker ones are masses of volcanic rock enclosed in tuff; the light knobs are Jurassic rhyolite like that just crossed along the trail, and the dark exposures are Cretaceous andesite. This zone of decreased welding containing megablocks is stratigraphically entirely above the level at which we are standing.

Continue up to the viewpoint southeast from the shoulder (10 minutes), following the eroded trail that first makes a switchback upward and then contours counterclockwise around the south side of the hill. This trail provides access to excellent exposures of densely welded Cat Mountain Tuff, previously seen only in talus, and also some welcome afternoon shade if the day is hot.

All slopes in sight to the south and east are Cat Mountain Tuff. The subtle variations in jointing and color, though not well understood, probably largely reflect initial variations in welding and crystallization of the thick caldera-filling tuff.

From the top of this knob (**point G**), we can see the Silver Bell Mountains, 50 km to the northwest, and some of the ASARCO tailing ponds from the porphyry copper open-pit operations. This is an excellent place to discuss relations between the Silver Bell and Tucson Mountains calderas. In a nutshell, tuff erupted from the Silver Bell caldera (tuff of Confidence Peak) is present as megablocks within the younger Tucson Mountains caldera, and the welded tuff member of the Mount Lord Volcanics that caps the Silver Bell Mountains is now interpreted as outflow Cat Mountain Tuff from the Tucson Mountain caldera. These correlations are confirmed by distinctions in petrography, minor-element compositions, and paleomagnetic pole positions (table 1; Hagstrum and Sawyer, 1989; Hagstrum and Lipman, 1991).

Also visible from here are Brown Mountain, the Arizona-Sonora Desert Museum, and the approximate location of the possible caldera boundary fault that drops the Cretaceous against Jurassic sediments (fig. 2). The hills to the northeast expose the south margin of the Amole pluton, which appears to have resurgently uplifted the northwest side of the caldera; the granite was perhaps localized along this ring fault.

Major remaining field problems are the total thickness of the caldera fill including postcollapse lava flows of Late Cretaceous or early Tertiary age, the structural position of the Amole Arkose (true caldera floor, or low on the wall), and the amount of rotation and transport of the Cretaceous rocks along middle Tertiary detachment faults.

Retrace the route downslope to the shoulder; then follow the trail northeast to Gates Pass parking area (**point A**). Continue east on Gates Pass Road.

As we proceed east from the pass, variably colored rocks in the gully to the left are megablocks of diverse rock types along a welding break within Cat Mountain Tuff. The largest and most conspicuous blocks in this area consist of flow-layered and locally spherulitic rhyolitic lava of probable Jurassic age. These were previously considered to be intrusions.

26.5 Leaving Tucson Mountains Park. Continue east 1.2 mi to junction with Camino del Oeste; continue ahead on Speedway Road (continuation of Gates Pass Road).

28.3 Contact in small gully between dacite lava and underlying east-dipping Cat Mountain Tuff to west, dropped along small northwest-trending fault against more Cat Mountain Tuff to east.

29.2 Passing Painted Hills Road. Hills to south are Upper Cretaceous (?) dacite lava dome of Twin Hills, conformably overlying the ash-flow fill of the Tucson Mountains caldera.

32.3 Central Tucson: intersection, I–10 and Speedway Boulevard; proceed north on I–10, past starting point (Grant Road), to Camino del Cerro turnoff (or turn north earlier on Silver Bell Road)

37.1 Camino del Cerro intersection with I–10. Turn left (west on Camino del Cerro. After turn, at 11 o'clock, Wasson Peak at north end of the high Tucson Mountains ridge consists mainly of Cretaceous sandstone megablocks (Bisbee Group; Amole Arkose) low in caldera-fill section. At 2 o'clock is Safford Peak, a high point and possible vent within the main area of middle Tertiary dacitic lava.

38.0 Silver Bell Road. The conspicuous low hills at about 12 o'clock constitute an east-west-trending ridge of the main welded upper part of the Cat Mountain Tuff. From this ridge of Cat Mountain Tuff north to the base of the hills of mid-Tertiary dacites, the low ridges consist of vertically dipping Cretaceous lavas (andesite-dacite) and minor interleaved sediments that represent postcaldera volcanism. From the main Cat Mountain Tuff ridge south all the way to Wasson Peak, hills are lower parts of the caldera-fill assemblage, dominated by andesitic and sedimentary megablocks. The entire Cretaceous sequence dips nearly vertically from Wasson Peak to the lower slopes of Safford Peak, as indicated by welded-tuff foliations, map patterns, and attitudes of sedimentary interbeds between the postcaldera lavas.

38.9 Crest of low rise, where there is a convenient (small) pull-out on right. A good place for panoramic view of the relations just described.

41.2 End of pavement; enter first bedrock hills underlain by upper grayish partly welded Cat Mountain Tuff, dipping to northeast. Continue 0.6 mi to secondary unmarked gravel road on left (south); take this road approximately 1.2 miles to Sweetwater trailhead (high-clearance vehicles required). Alternative route (as described at end of guide): continue ahead (northwest) on main gravel residential road directly to crossing of Sweetwater Wash and beginning of **STOP 3** traverse (parking for only a few vehicles).

43.0 **STOP 3: thick megabreccia in northern caldera fill at Sweetwater Wash (fig. 6).** Leave cars for a several-hour loop walk to examine representative stratigraphic, compositional, and structural relations between diverse megablocks and tuff matrix below the main welded horizon of lithic-poor Cat Mountain Tuff. We will be in the interior of typical thick caldera fill within the northern sector of the caldera.

SWEETWATER WASH

In the upper part of the section, clast types are predominantly andesitic lavas and volcaniclastic sediments; in places, the matrix between clasts is pulverized rock of the same type as the clasts, but elsewhere it is quartz-bearing tuff of the same phenocryst and chemical type as the Cat Mountain Tuff. Farther up the wash (down section), sparse blocks of Paleozoic limestone (mainly Permian Concha Limestone?) and red sandstone (Jurassic Recreation Redbeds) occur along a transition in predominant clast type downsection to more quartzose sandstones of the Bisbee Group (Amole Arkose). Such Paleozoic and older Mesozoic clasts are scattered sparsely through both sedimentary- and volcanic-dominated megabreccia assemblages. The widespread occurrence of the youngest precaldera clasts (andesite) in a stratigraphically high position is somewhat surprising, as these rocks would be expected to have slid first; perhaps two distinct sources from different parts of the caldera margin were involved. Walk up Sweetwater Wash through the transition in clast types, to just within the boundary of Saguaro National Monument, passing through several sizeable interleaved bodies of ash-flow tuff.

To reach the start of the described traverse in Sweetwater Wash, from Sweetwater trailhead (end of gravel road) walk back on access road about 200 m east of house visible to the north; then follow the side trail north to its end. Continue counterclockwise cross-country around the house about 100 m to the powerline; follow the powerline 100 m north to a gravel subdivision road and continue north on the road about 200 m to the wash. Walk up the wash, examining variable rock types and looking for tuff matrix. Distances in the wash are approximate, and locations below are only roughly integrated with the generalized geologic map (fig. 6).

Point A: At 150 m upwash from road, cross below powerline.

Point B: At 100 m upwash from powerline, note reddish-brown volcaniclastic andesite in the stream bottom. Just upwash is light-brown quartz-bearing tuff forming a large lens within the breccia. At fork ahead, follow left (southwest) drainage.

Point C: At 200 m upwash from powerline, tan house on southeast side of wash. We are in large clasts of well-bedded volcaniclastic sedimentary rocks, striking east-west and dipping about 40° N. This is almost conformable with the regional strike of the interleaved tuff lenses, but dips in the sediments are less steep than in nearby tuff where welded pumice lenses dip 70°–80°.

Point D: At 200 m farther upwash is an area where rocks have abundant tuff matrix surrounding diverse clasts. The tuff has well-developed compaction foliation striking about N. 60° W. and dipping 60°–80° NE. This is a mappable, through-going tuff lens. Large rounded hill, ahead on southeast side of wash, is an even larger welded tuff lens.

Point E: Another 100 m upwash, crossing into the top of the thick hill-forming tuff lens. Even this tuff contains scattered large blocks of lava and sedimentary rock. The foliation of the tuff is somewhat obscure at stream level, about N. 40° W., 50° NE.

Point F: Just before boundary of Saguaro National Monument, as marked by fence across wash, bedded sedimentary rocks are exposed below a tuff lens. The bedding is strikingly conformable with the tuff contact and internal foliation. This mass of sedimentary rock is at least 50 m thick and traceable for several hundred meters along strike. It is structurally coherent and little brecciated, yet upwash is more tuff and more chaotic rock. Many will wonder whether these sediments may not represent in-place material deposited between eruptions! Many large masses of bedded sediment in this part of the caldera have such semiconformable orientations; bedding in other masses is grossly misoriented with respect to fabric and contacts of the tuff.

Point G: At 100 m upwash from contact with large sedimentary slab. Drainage forks; bear left (southwest). Lower part of right fork also has interesting exposures of tuff enclosing chaotic andesitic and sedimentary material.

(Possible place to terminate traverse; climb 100 m south to Sweetwater trail, and return to cars)

Farther up left fork of wash, several large blocks of limestone conglomerate (Jurassic-Cretaceous Glance Formation?) are conspicuous loose boulders. We are now entering the outer part of the broad contact-metamorphic halo of the Amole pluton, which is first exposed about 3 km to the west. As a result, the tuff matrix between blocks becomes increasingly bleached and indurated, and pyroclastic textures are obscured. Such hornfelsed tuff has been mapped previously as "Amole Latite" and interpreted as irregular dikelike intrusions (Brown, 1939; Mayo, 1971a; Drewes, 1981).

About 200 m upwash (main southern one) is a large mass of tuff, and at west boundary with it is a large block (20 m) of chert-bearing limestone (Permian Concha Formation?). At 50 m farther upward are several smaller blocks of red sandstone (Jurassic Recreation Redbeds).

Terminate traverse; climb southeast to Sweetwater trail and return to cars

Looking upvalley from trail, all slopes are underlain by megablocks interleaved with tuff matrix. The tuff generally holds up the most rugged ridges and makes light patches, especially where most hornfelsed. The breccia makes more subdued tan slopes, reflecting its predominant component of Cretaceous sandstone of the Bisbee Group. Also look northeast, to appreciate the distance (about 3 km) and thickness of the breccia section below the base of the main upper welded Cat Mountain Tuff.

Walking out on the trail, it should be obvious that the large slab of seemingly conformable sediments is sandwiched between two lenses of lithic-poor massive tuff. Could this slab have been emplaced hovercraft-style during the course of the pyroclastic eruption—rafted, cushioned, and lubricated by erupting tuff within the caldera?

Return to vehicles at trailhead, and retrace route to Camino del Cerro and I–10.

End of Tucson Mountain trip.

Alternative route from mile 41.8: continuation to Sweetwater Wash along Camino del Cerro (suitable for ordinary passenger cars, but parking available only for small number of vehicles).

1.9 Crossing wash. Main gravel road veers to left (west). Hill on right is good exposure of main densely welded part of Cat Mountain Tuff, containing strikingly large and crystal-poor flattened pumices (table 1, field No. 87L–9). Road is in andesitic megabreccia, just below contact with tuff.

42.8 Crossing wash. Road forks; continue left (southwest). Megablocks of andesitic-dacitic lava are well exposed both up and down wash.

42.9 Cross same wash again; continue ahead.

43.1 Road forks; continue ahead to left (southeast), still in andesitic megabreccia.

43.3 Stop in wash at bottom of small steep hill (room for only about six cars in wash area; larger groups should park at intersection (43.1 mi)).

Make foot traverse up Sweetwater Wash, described above.

Table 1. Representative analyses, igneous rocks of the Tucson Mountains caldera, Ariz. (recalculated volatile free).

[Major oxides by XRF methods by J. Taggart; minor elements by energy-dispersive (KEVEX) methods by D. Yager; Fe_2O_3T, total iron; LOI, loss on ignition; ppm, parts per million; --, not determined]

Unit..........	Cat Mountain Tuff				Tuff of Confidence Peak	
Location ... or rock type	Cat Mountain	del Cerro	"Amole L"	"Amole L"	Megablocks	
Field No. ...	84S130*	87L-9	87L-3	87L-4	87L-1	87L-8
SiO_2	74.5	71.5	73.6	73.3	73.2	73.3
Al_2O_3	13.0	14.5	13.0	13.7	13.6	14.2
Fe_2O_3T	1.68	2.11	1.93	1.98	1.81	1.62
MgO	0.85	0.43	0.65	0.66	0.24	0.71
CaO	1.86	.92	1.98	1.43	2.25	1.45
Na_2O	2.87	4.53	3.38	4.02	3.87	3.71
K_2O	4.39	4.46	4.23	3.64	3.65	4.09
TiO_2	.22	.36	.25	.36	.24	.26
P_2O_5	.05	.11	.06	.09	.08	.08
MnO	.11	.03	.07	.05	.05	.03
LOI	2.98	1.51	1.29	1.35	2.52	1.77
Rb (ppm)	170	124	149	183	117	128
Sr	120	211	170	372	242	296
Y	22	24	19	15	12	12
Zr	130	315	125	110	80	91
Nb	12	8	12	14	11	10

Unit..........	Postcaldera lavas			Amole pluton		Silver Lily dike
Location ... or rock type	Andesite	Dacite	Rhyolite	Granodiorite	Granite	Dacite
Field No. ...	87L-76A	87L-71	87L-73	87L-75	84S122*	87L-7
SiO_2	54.3	62.8	72.5	57.6	70.0	67.3
Al_2O_3	16.7	18.6	14.8	16.7	15.0	16.7
Fe_2O_3T	9.06	3.27	1.54	7.45	3.22	2.92
MgO	5.65	0.96	0.29	3.65	1.23	0.88
CaO	7.43	4.26	.26	6.29	2.04	2.48
Na_2O	2.79	4.37	3.69	3.65	3.18	4.27
K_2O	2.22	4.12	5.66	2.77	4.57	4.03
TiO_2	1.17	.64	.21	1.04	.39	.39
P_2O_5	.36	.23	.06	.33	.12	.18
MnO	.13	.05	.03	.10	.02	.09
LOI	4.78	.96	1.14	.80	1.24	.90
Rb (ppm)	---	---	---	---	177	145
Sr	---	---	---	---	400	493
Y	---	---	---	---	21	20
Zr	---	---	---	---	168	435
Nb	---	---	---	---	10	12

*D.A. Sawyer, unpub. U.S. Geological Survey analyses, 1989.

REFERENCES CITED

Assadi, S.M., 1964, Structure of Golden Gate Mountain, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 62 p.

Bikerman, M., 1963, Origin of the Cat Mountain Rhyolite: Arizona Geological Society Digest, v. 6, p. 83–89.

Bikerman, M., and Damon, P.E., 1966, K-Ar chronology of the Tucson Mountains, Pima County, Arizona: Geological Society of America Bulletin, v. 77, p. 1225–1234.

Brown, W.H., 1939, Tucson Mountains, an Arizona desert range: Geological Society of America Bulletin, v. 50, p. 697–760.

Drewes, Harald, 1981, Tectonics of southeastern Arizona: U.S. Geological Survey Professional Paper 1144, 96 p.

Hagstrum, J.T., and Lipman, P.W., 1991, Late Cretaceous paleomagnetism of the Tucson Mountains—Implications for vertical-axis rotations in south-central Arizona: Journal of Geophysical Research, v. 96, p. 16069–16081.

Hagstrum, J.T., and Sawyer, D.A., 1989, Late Cretaceous paleomagnetism and clockwise rotation of the Silver bell Mountains, south-central Arizona: Journal of Geophysical Research, v. 94, p. 17847–17860.

Kinnison, J.E., 1958, Geology and ore deposits of the southern section of the Amole mining district, Tucson Mountains, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 123 p.

Knight, L.H., 1967, Structural geology of the Cat Mountain Rhyolite in the northern Tucson Mountains, Pima County, Arizona: Tucson, University of Arizona, M.S. thesis, 68 p.

Lipman, P.W., 1976, Caldera-collapse breccias in the western San Juan Mountains, Colorado: Geological Society of America Bulletin, v. 87, p. 1397–1410.

———1984, The roots of ash-flow calderas: windows into granitic batholiths: Journal of Geophysical Research, v. 89, p. 8801–8841.

———1992, Ash-flow calderas as structural controls of ore deposits—Recent work and future progress, *in* Thorman, C.H., ed., Application of structural geology to mineral and energy resources of the central and western United States: U.S. Geological Survey Bulletin 2012–L, p. L1–L12.

———1993, Geologic map of the Tucson Mountains caldera, southern Arizona: U.S. Geological Survey Map I–2205, scale 1:50,000, 2 sheets, interpretive text.

Lipman, P.W., and Fridrich, C.J., 1990, Cretaceous caldera systems—Tucson and Sierrita Mountains, *in* Gehrels, G.E., and Spencer, J.E., Geologic excursions through the Sonoran desert region, Arizona and Sonora: Arizona Geological Survey Special Paper 7, p. 51–65.

Lipman, P.W., and Hagstrum, J.T., 1992, Jurassic ash-flow sheets, calderas, and associated mineralization in southeastern Arizona: Geological Society of America Bulletin, v. 104, p. 32–39.

Lipman, P.W., and Sawyer, D.A., 1985, Mesozoic ash-flow caldera fragments in southeastern Arizona and their relation to porphyry copper deposits: Geology, v. 13, p. 652–656.

Mayo, E.B., 1963, Volcanic orogeny of the Tucson Mountains (a preliminary report): Arizona Geological Society Digest, v. 6, p. 61–82.

———1971a, Defense of "volcanic orogeny": Arizona Geological Society Digest, v. 9, p. 39–60.

———1971b, Feeders of an ash flow sequence on Bren Mountain, Tucson Mountain Park, Arizona: Arizona Geological Society Digest, v. 9, p. 137–170.

Reynolds, S.J., 1988, Geologic map of Arizona: Arizona Geological Survey Map 26, scale 1:1,000,000.

Sawyer, D.A., 1987, Late Cretaceous caldera volcanism and porphyry copper mineralization at Silver Bell, Pima County, Arizona—Petrology and geochemistry: Santa Barbara, University of California at Santa Barbara, Ph.D. thesis, 400 p.

TUCSON WASH—AN INTRODUCTION TO NEW WORK IN THE SAN MANUEL AND MAMMOTH DISTRICTS, PINAL COUNTY, ARIZONA

By Eric R. Force[1] *and* William R. Dickinson[2]

INTRODUCTION

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 middle Tertiary age. We will be seeing its relation to a middle 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. A four-wheel-drive vehicle is required at times to navigate the dry washes. All stops are in the Mammoth 7 1/2-minute quadrangle (fig. 1).

The Mammoth and San Manuel districts occupy the northern boundary area between the San Pedro trough and the Catalina–Rincon Mountains metamorphic core complex (fig. 2). The faults we will see in conjunction with the orebody geology are an integral part of the overall middle Tertiary crustal extension described by Dickinson (1991).

Three generations of extensional faulting have taken place in the area, making it exceptionally extended and complex terrain. Each generation of faulting resulted in the deposition of a conglomeratic formation (table 1) as the result of the great structural relief produced by faulting. These formations record the progress of tectonic events. Careful geologic book-keeping enables understanding of the complex sequence and geometry; both authors, however, find themselves repeatedly returning to the area 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 from 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 (1992), and a thesis by Weibel (1981). The regional context was described by Dickinson (1991). Force and others (in press) discuss the tilting history of the San Manuel porphyry system; this field trip provides a preview of the paper in press. Dickinson (1993) and Force and Cox (1992) contain the most up-to-date maps for the field trip area. Figure 1 shows the geology as presently understood by Dickinson (1993).

ROAD LOG

Miles

The starting point of this log is the western road from Arizona State Highway 77 to downtown Oracle, that is, the first cutoff coming from Tucson.

0.0 Road junction. The Oracle Granite forms the blocky outcrops here and several miles ahead. It is about 1.45 Ga and forms the basement for much of the area in sight, including parts of the Santa Catalina Mountains to the south and the Black Mountains and Black Hills to the north. Dikes of aplite and younger Precambrian diabase cut 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, near the southern boundary of the area of figure 1, they are the overlying Kannally Member of the San Manuel

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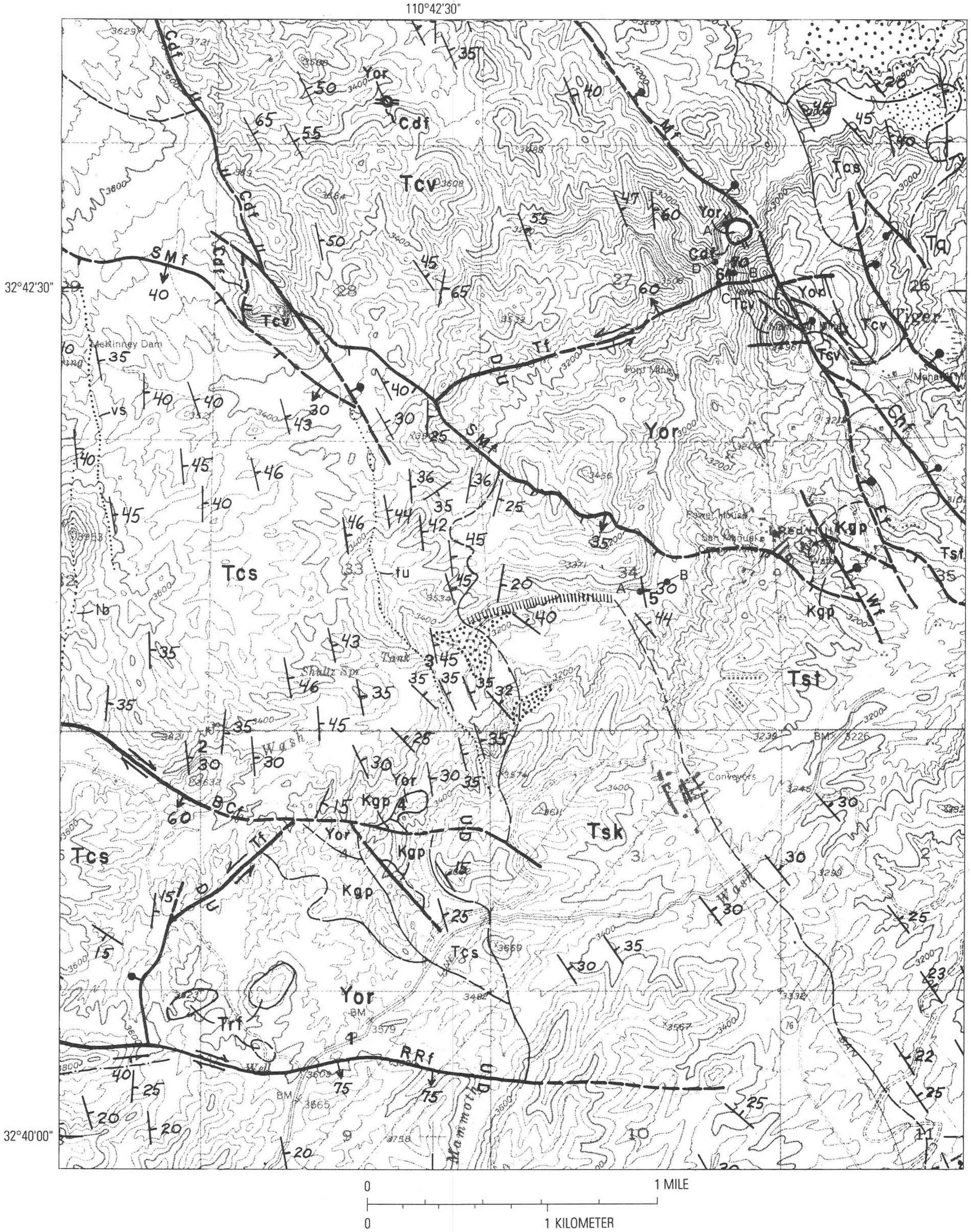
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Mammoth
0
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Formation (Miocene), consisting of conglomerate containing Oracle Granite clasts and dipping about 20° NE.

7.1 Low road cuts in two sedimentary breccia lenses within the San Manuel Formation. One breccia was derived entirely from diabase, the other from quartzite. Their sources are not presently exposed.

7.2 Intersection. We will be turning left here later, but for now we will continue straight. At this point, we cross the Red Rock fault (fig. 1), an important structure that is apparently coeval with the San Manuel fault, and pass into the so-called Purcell window, which consists of Precambrian and Laramide igneous rocks in the upper plate of the San Manuel fault.

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

At this point we are above the Kalamazoo segment of the porphyry copper deposit, which began test production in 1991. The upper boundary of ore is about 2,700 ft 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.

Return to 7.2

7.7 Same location as 7.2; turn right (north).

8.1 Prospect adit along a rhyolite dike in Oracle Granite. The hilltop above, and two other hilltops nearby, are underlain by shallowly emplaced rhyodacitic intrusions of Tertiary age (fig. 1).

8.5 Cross the Turtle fault (fig. 1), which is not well exposed here, into the Cloudburst Formation conglomerate of mostly late Oligocene age. The Turtle fault dips steeply northwest and is apparently coeval with Cloudburst accumulation, because lower parts of the Cloudburst are cut by the fault but upper parts of it lap across the fault. The Turtle fault divides the rocks of the region into two blocks that have different tilting histories, and therein lies a tale about the San Manuel porphyry system, which will be discussed at **STOP 4**. We will see the fault plane at **STOP 6B**.

Figure 1 (facing page). Geology (from Dickinson, 1993) of part of Mammoth 7 ½-minute quadrangle showing the location of field trip stops. Rock units: Yor, Oracle Granite (Middle Proterozoic); Kgp, San Manuel porphyry (latest Cretaceous); Tcv and Tcs, Cloudburst Formation, lower volcanic member and upper sedimentary member, respectively (upper Oligocene and lower Miocene), includes tu, tuff, lb, lava-breccia, and vs, volcanic sand; Trf, rhyodacitic felsite; Tsk and Tst, San Manuel Formation, lower Kannally Member and upper Tucson Wash Member, respectively (lower Miocene); Tq, Quiburis Formation (post-mid-Miocene); younger gravels shown as stipples. Structures: Tf, Turtle fault, Cdf, Cloudburst fault, SMf, San Manuel fault, BCf, Black Canyon fault, RRf, Red Rock fault, Mf, Mammoth fault, Ef, East fault, Wf, West fault, Chf, Cholla fault. Stippled areas, Quaternary fluvial terraces.

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 middle Miocene).	Basin-range faulting on Mammoth and Cholla faults.
San Manuel Formation (lower Miocene).	Normal faulting on low-angle (at present) San Manuel fault, and coeval steep faulting on Red Rock and Black Canyon faults.
Cloudburst Formation (lower Miocene to upper Oligocene).	Detachment on sub-horizontal (at present) Cloudburst detachment fault and steep Turtle fault.

9.1 Turn right (east) down Tucson Wash at Black Canyon Ranch. Travel for the next several miles is in this sandy wash. A four-wheel drive vehicle is commonly needed in the wash, and mileages along the route trip in the wash are approximate because the route changes depending on current conditions. 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 the Cloudburst Formation forms the steep bluffs above the narrow wash. This stop is an introduction to the Cloudburst Formation where it is little altered (though veins contain manganese oxides and barite, especially at the east end). The Cloudburst Formation is approximately 12,000–15,000 ft thick. We are in rocks typical of the upper member at this stop; the lower member consists of interlayered intermediate-composition volcanic rocks and volcaniclastic conglomerate. The Cloudburst is the oldest of three tilted conglomeratic middle 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 6A**. North of the Turtle fault the Cloudburst dips rather steeply, as it does at this stop,

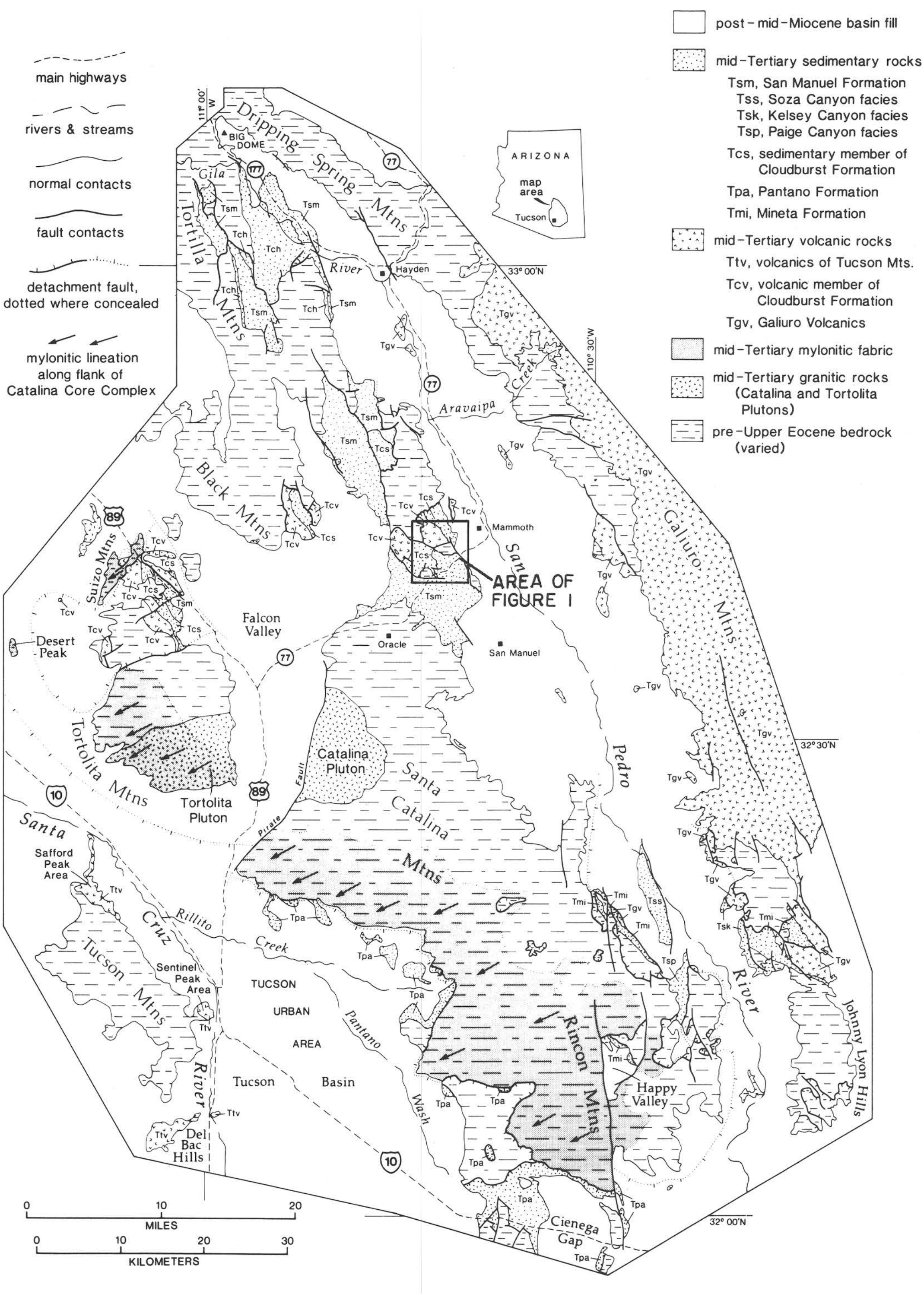


Figure 2. Some geologic features in the region of the field trip (from Dickinson, 1991). Highway 77 as shown is the old road (**STOP 1**). Area of figure 1 is outlined.

but south of the Turtle fault it dips more gently, as it does at **STOP 4**.

Clasts in the Cloudburst here include Precambrian rocks (Oracle, diabase), Laramide San Manuel porphyry intrusion, and Tertiary volcanic rocks. Deposition of streamflood and minor debris-flow deposits was in shallow channels on a broad alluvial fan and braidplain. Clast imbrication shows predominantly east-northeastward transport in this member. At the west end of the outcrop, slickensides can be seen along splays of the Black Canyon fault (fig. 1), which is apparently coeval with the San Manuel fault.

10.3 **STOP 3.** In this area near Shultz Spring, the Cloudburst Formation (upper member) has been altered and weakly mineralized (Force and Cox, 1992). It is the largest area of middle Tertiary alteration on the upper plate of the San Manuel fault.

Concentric zones of alteration elongate north-northwest (fig. 3) contain different iron minerals in conglomerate matrix and clast rims. The most strongly altered rocks in the center of the system are pyritic (zone 3 in fig. 3). Peripheral zones contain specular hematite + chlorite in green-gray to black matrix (zone 2) and chloritic green matrix (zone 1). Some adularia is present in zones 2 and 3. Leslie Cox found that weak Ba-Ag-Pb-Mo-Au mineralization is areally centered on the most intense alteration (Force and Cox, 1992). Zinc maxima are slightly to the west.

At this stop, 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 conglomerate with a green matrix (chloritic).

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. One is tempted to think, as Force did originally, 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 (Force and Cox, 1992). 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; figs. 1, 3). A 22.5-Ma K-Ar potassium-feldspar date (Weibel, 1981) on the tuff is a minimum age, because we observed alteration-phase adularia (Shultz Spring event), which was not noted by Weibel and was apparently included in his potassium feldspar separation for radiometric dating.

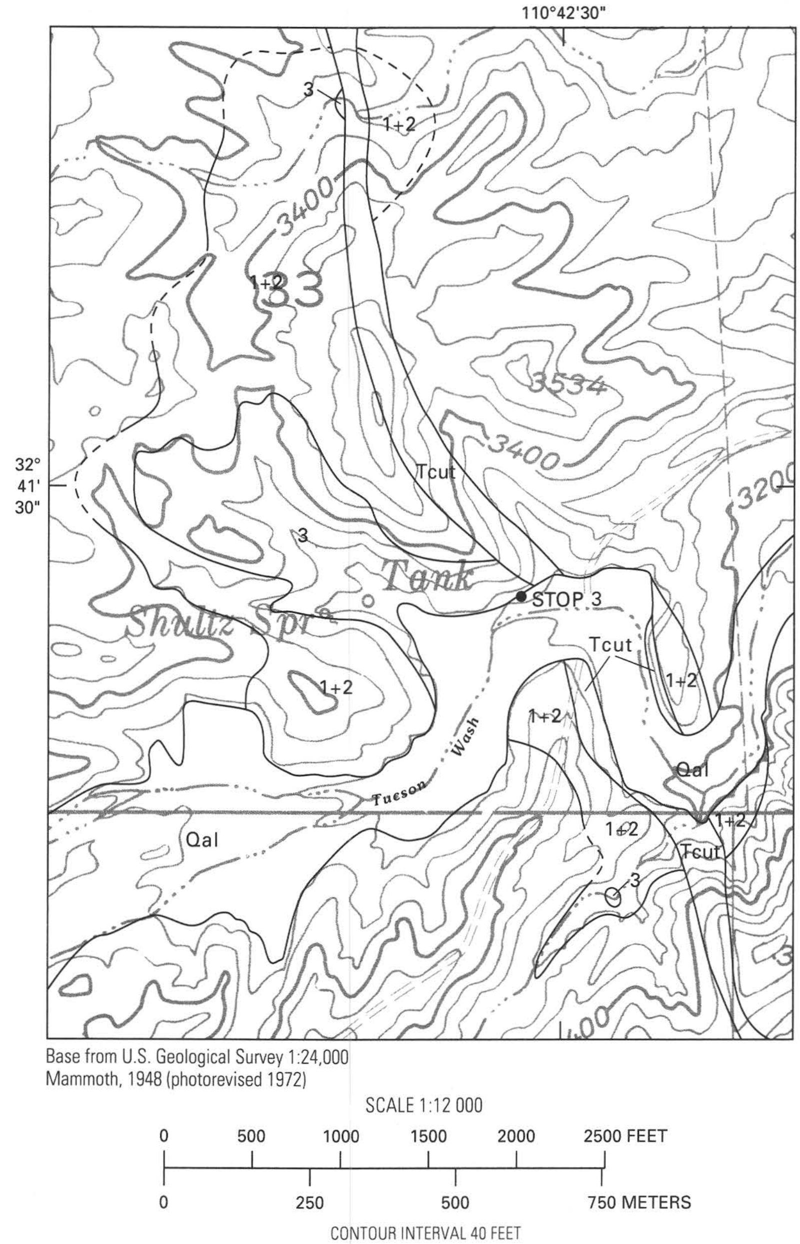
10.6 Turn right (southwest) up subsidiary wash, which we refer to informally as "Lowell Wash." We have somewhere crossed the buried Turtle fault and are in Cloudburst Formation conglomerate that dips gently eastward above basement rocks of the Purcell window.

11.0 **STOP 4**. Cloudburst Formation conglomerate unconformably overlies Oracle Granite, which contains 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 the overlying Cloudburst Formation.

Just upstream is exposed an intrusive contact of San Manuel porphyry in Oracle Granite like that at **STOP 1** (less than 1 mi to the south). We may or may not have permission to see 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.

TILTING OF SAN MANUEL PORPHRY

In this wash, and the one to the west where exceptionally fresh San Manuel porphyry crops out, J.T. Hagstrum (*in* Force and others, in press) conducted a paleomagnetic study of the Laramide intrusion (prior to the initiation of Kalamazoo mining). He found that the San Manuel porphyry has been rotated 33°±12° to the northeast 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 northeast. Force and others (in press) then re-examined the geological evidence of tilting history and found that originally subhorizontal middle Tertiary horizons and strata that directly overlie the San Manuel porphyry intrusive and its host rocks have mean dips of about 30° NE (table 2), similar to those at this stop. Precambrian and Paleozoic layers and strata that were originally sub-horizontal (including the diabase bodies; Howard, 1991) in the region have a mean dip of 45° NE (table 2). Thus, the tilt of a Laramide intrusion should be between 30° and 45°; greater tilts would require a severe



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 (1992). Unit Tcut is a tuff in the upper Cloudburst Formation; no other units except Quaternary alluvium (Qal) are shown.

and reversing pre-Laramide tilting history. Indeed, pre-porphyry conglomerate and volcanic rocks of Late Cretaceous age three miles to the east across the San Manuel fault are tilted an average of 35° (Dickinson, 1993; Force and others, in press; based on U-Pb dating of intrusive porphyry by D.M. Unruh, U.S. Geological Survey), in accord with the paleomagnetic data.

Why did Lowell (1968) advocate greater tilt? Bear in mind that many data and relations we use in our sedimentary and paleomagnetic "tiltmeters" did not exist in 1968. Lowell's restoration (his fig. 2) rotates 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 that time it was not realized that this fault separates two blocks that have 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.

What then is the meaning of Lowell's cross section (1968, his figs. 2 and 5) showing an apparently recumbent porphyry body? In addressing this problem, we find that both the porphyry copper orebodies and the igneous bodies are basically tablo-cylindroidal in shape (fig. 4), 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. The intersection of a vertical cross section and a dipping body with a nearly parallel strike must be nearly horizontal, but this has nothing to do with tilting history.

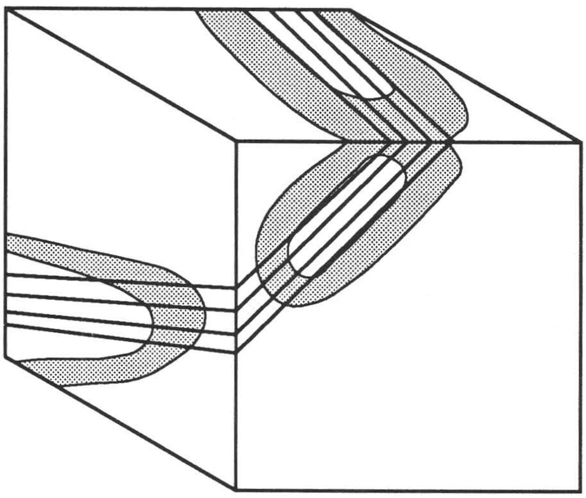


Figure 4. Schematic block diagram of San Manuel–Kalamazoo porphyry copper ore (shaded) and productive (type A of Lowell and Guilbert, 1970) intrusion of San Manuel porphyry (ruled) in its present orientation, showing the tablo-cylindroidal shape of the system. The southeastern (left) side of the block shows the attitude of ore and porphyry implied by Lowell (1968, fig. 2) along the same direction. The front edge of the block corresponds approximately to relations against the Cholla fault. The San Manuel fault is not shown, that is, the fault is shown restored.

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.	N. 35° W., 30° NE.
Cloudburst Formation (upper member) bedding.	N. 20° W., 30° NE.
Cloudburst-Oracle unconformity.	N. 41° W., 30° NE.
American Flag Formation.	N. 24° W., 35° NE.
Paleozoic sedimentary bedding of Black Hills (south-southeast of Mammoth).	N. 52° W., 48° NE.
Precambrian diabase sills	N. 20°–40° W., 40°–50° NE.
Apache Group sedimentary bedding (north-northwest of Mammoth).	N. 30° W., 45° NE.

We find that a rotation of 30°–35° about the most likely rotation axis for middle Tertiary tilting yields the cross-sectional relation that Lowell (1968) considered evidence of a 70° tilt. Table 3 shows the present attitude of the tablo-cylindroidal igneous bodies and orebodies, and the axis about which we rotated them to get the original attitude. This original attitude is similar to that of other mineralization-related Laramide dikes of the region, as given by Heidrick and Titley (1982).

Then 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 was the best choice for the purpose of matching across the fault. It is possible, however, that a better picture of ore geometry and tectonic history may lead to further discoveries in this district.

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

Feature	Attitude
Present plane.	N. 58° E., 47° SE.
Rotation axis for restoration.	Trend N. 40° W., horizontal plunge; rotate northeast side up 30° to 35°.
Original plane.	N. 81° E., 62° SE.

This revision of Lowell's (1968) tilting history may also have implications for exploration in other porphyry districts. The San Manuel porphyry intrusion was originally a steeply dipping quasi-tabular body rather than an equant upright body. The zones of alteration and mineralization that Lowell and Guilbert (1970) modeled as a bullet-shaped system, based on San Manuel-Kalamazoo as a recumbent example, occur there instead as envelopes around certain parts of this dipping tabular body. Thus, the zonation of their model system is topologically correct, but the top and shape of the model may not be good exploration guides.

Return to mile 10.6 in Tucson Wash.

11.4 Same location as 10.6.

12.5 to 12.6 **STOP 5**, in two parts.

At **STOP 5A** we will 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 directly overlies the Cloudburst Formation in a narrow block, perhaps between two splays of the San Manuel fault. The authors have differing interpretations regarding this structure. Force prefers the interpretation that a northern splay is at **STOP 5B** around the corner and a southern splay is somewhere under alluvium of the wash (south). Dickinson prefers the interpretation that the only fault is that exposed at **STOP 5B**. The latter interpretation is shown in figure 1; exposures are insufficient for a definitive test.

The provenance of clasts in this member of the San Manuel Formation is intriguing. 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 this unit also contains clasts of porphyry ore. Thus, derivation was from the northeast, in the area of **STOP 6**. These clasts become larger toward the fault plane; at **STOP 5B** large slide blocks constitute "clasts" in the formation. Apparently, during movement on the San Manuel fault, coarse debris was being shed into a basin on the downthrown block to the southwest (table 1).

At **STOP 5B** we see on the left (west) the San Manuel fault, separating truncated bedding of the Tucson Wash Member of San Manuel Formation in the upper plate from Oracle Granite in the lower plate (fig. 5). The San Manuel fault here is a narrow zone in which black calcite has grown. The dip of the fault is about 30° SW (into the hill). Oracle Granite shows propylitic assemblages characteristic of the outer part of the alteration aureole of the San Manuel deposit; note the dumps of the San Manuel mine forming the southern margin of the wash.

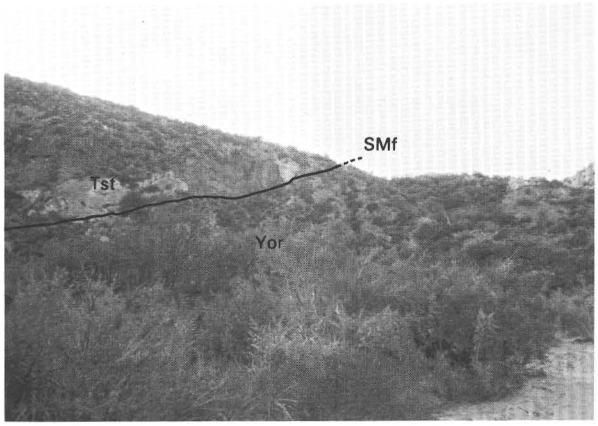


Figure 5. Annotated photo of San Manuel fault (SMf) from **STOP 5B** looking west. Yor, Oracle Granite; Tst, San Manuel Formation, Tucson Wash Member, showing blocks against the fault plane.

13.3 Ford Mine (see **STOP 3**). Oracle Granite in this interval is weakly altered, and locally cut by aplite dikes.

13.7 to 14.0 **STOP 6**, in four parts. We recommend driving the farthest point for this stop and walking back, examining the outcrops in the order described. The relations of some faults that will be seen at this stop are shown in figure 6.

RELATION OF MAMMOTH VEIN SET TO CLOUDBURST DETACHMENT FAULT

At **STOP 6A** (14.0 mi), the Cloudburst detachment fault (fig. 1) is exposed on both sides of the wash, in four main outcrop areas that constitute a single window (figs. 7, 8). The fault is nearly horizontal regionally (fig. 9), but shows vertical relief of about 100 ft in this exposure. 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 the physiographic ledge of resistant microbreccia (characteristic of detachment faults) is absent, probably because of extensive rhyolite-related alteration. The detachment probably formed with a gentle westward dip, and younger extension coeval with the San Manuel fault rotated it to nearly horizontal.

Rhyolite intrudes the fault plane in some places and is offset in others (fig. 8), 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. Extrusive rhyolite (which we

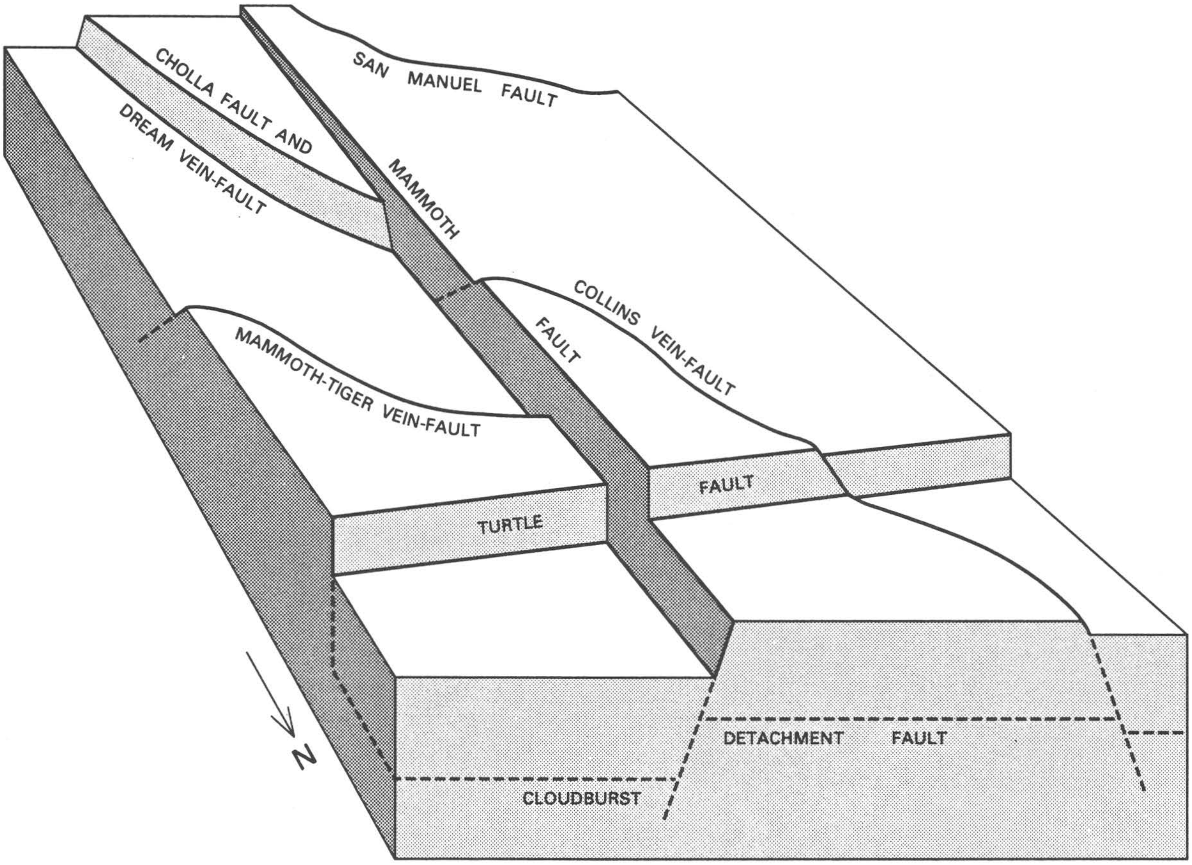


Figure 6. Block diagram showing the relation of some of the faults in the **STOP 6** area (from Force and Cox, 1992).

Figure 7. Cloudburst detachment fault (Cdf) from **STOP 6A** looking southeast. Yor, Oracle Granite; Tcv, Cloudburst Formation, lower volcanic member.

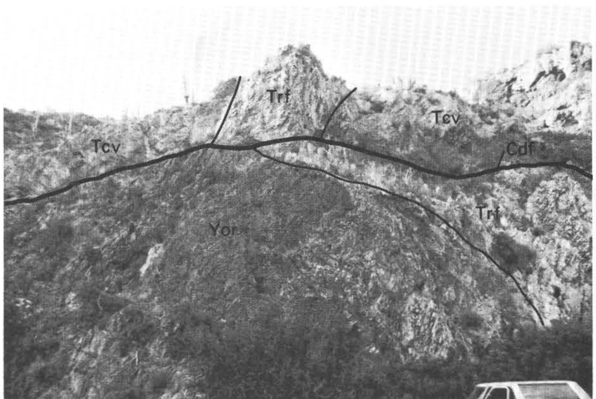


Figure 8. Cloudburst detachment fault (Cdf) from **STOP 6A** looking north, showing (slight?) offset of rhyolite. Yor, Oracle Granite; Tcv, Cloudburst Formation, lower volcanic member; Trf, intrusive rhyolite.

drive past at mile 14.5) in the Cloudburst Formation, which accumulated during detachment faulting (table 1), also shows the general synchroneity of faulting and intrusion.

At **STOP 6B** (13.75 mi) on the east side, we encounter the Turtle fault (fig. 1). It dips steeply northward and separates shattered Oracle Granite to the south from Cloudburst

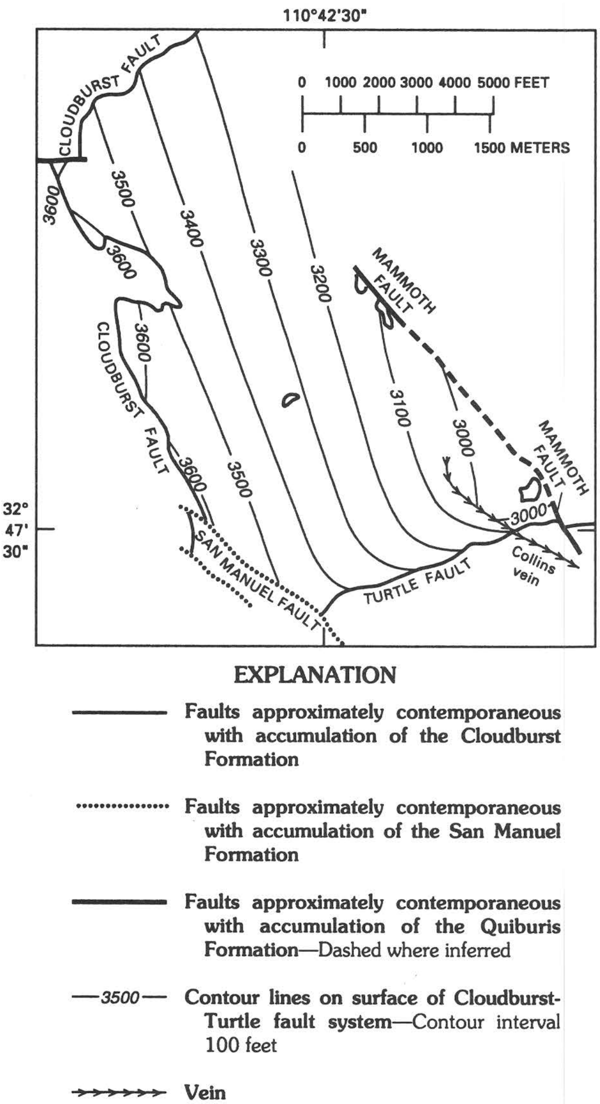


Figure 9. Structure contour map of Cloudburst-Turtle detachment system (from Force and Cox, 1992).

Formation to the north. Here we are in the volcanic lower member of the Cloudburst, and some conglomerates 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 in the upper plate of the San Manuel fault that the Turtle fault separates different tilt domains, and the same is true here in 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 will see at **STOP 6D**. At **STOP 6A** we saw 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

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.

fault. Thus, the Turtle fault is apparently a side-ramp of the Cloudburst detachment (fig. 6), or in other words, it is the southern boundary of the Tar Wash or Cloudburst allochthon of Dickinson (1991). This, in turn, suggests that movement on the Turtle fault was largely strike-slip.

At **STOP 6C** (13.7 mi), the Mammoth vein set (fig. 1) crosses the wash. Brecciated rhyolite and quartz veinlets are exposed at wash level on the 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 width. Adularia is common in these bands and toward vein margins.

Above the wash, more substantial vein material is exposed. Fallen blocks on the floor of the wash may contain vanadinite, wulfenite, and other minerals for which the Mammoth vein set is renowned.

The Mammoth vein set has produced a variety of metals intermittently since 1879. About two million tons of ore had been mined as of 1959. The earliest production was mostly of gold; later on, molybdenum, vanadium, lead, and zinc each became major products (table 4).

Above the wash, to the east, are the workings of the Collins cut on the Mammoth vein set, worked most recently for silica with byproduct gold. 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 the unconformity of **STOP 4**. This relation was used by Force and Cox (1992) in recalculating the slip vector for the San Manuel fault, about 7,750 ft, which 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. 10). In higher parts of the vein set (that is, the top of parallel to the rhyolite swarm, forming the Mammoth vein set. Vein-related alteration is vertically coextensive with detachment-related thermal alteration. The richest part of the district (according to Peterson, 1938) coincides with the lower-plate segment adjacent to the intersection of the Turtle and Cloudburst faults (according to Force and Cox, 1992), and some mineralization is found along this set of faults. Thus, mineralization is clearly influenced by detachment faulting. The connection between detachment faulting and mineralization is not quite so direct as in some districts where most mineralization is along the detachment fault plane and formed concurrently with its movement, and where intrusions are absent (Spencer and Welty, 1986). However, some mineralogic and chemical features of the Mammoth vein set are quite comparable to detachment-driven mineralization in other districts. Among these features are oxide-dominated assemblages, the abundance 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, 1992). 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 the U.S. Geological Survey is investigating this relation in studies of fluid inclusions.

Return to the cars and continue down the wash.

14.5 Rhyolitic ash-flow tuffs cross the wash. These rhyolitic extrusive rocks are more areally extensive than the rhyolitic intrusive ones, but even in the heart of the Mammoth district, extrusive rhyolite, mostly tuffaceous, is common.

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

15.7 Rhyolite in wash to left (north), originally intrusive into Cloudburst Formation. This monolith was buried by basin fill of the Quiburis Formation, which 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 rhyolite.

16.2 Good exposure of Quiburis Formation, the youngest of the extensional conglomerate units of the area (table 1). The Quiburis is post-middle Miocene and formed in response to basin-and-range faulting along the Mammoth and Cholla faults. It fills the present San Pedro trough. The rocks dip gently to the east, but we know they are steeper than their original 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 a borrow pit. The outcrops here include a sandy facies of the Quiburis Formation that is 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. Return via Highway 77 toward Tucson. If time is available, we will follow the signs to the San Manuel Mine and then to the overlook. Some features we have seen are visible in the pit (fig. 11).

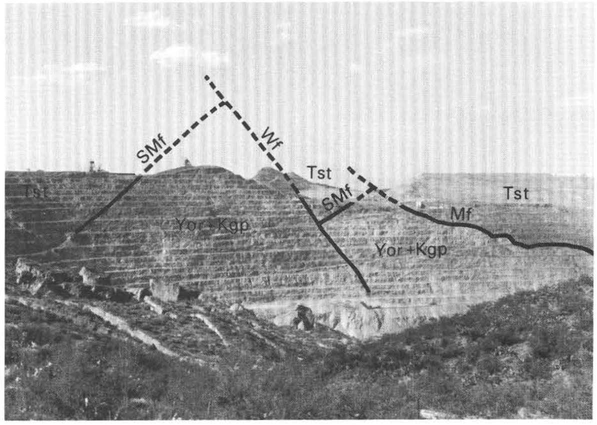


Figure 11. San Manuel mine looking north from overlook. Rock units: Yor+Kgp, Oracle Granite and San Manuel porphyry; Tst, San Manuel Formation, Tucson Wash member. Structures: SMf, San Manuel fault; Wf, West fault; Mf, Mammoth fault (called East fault in mine).

REFERENCES CITED

Creasey, S.C., 1950, Geology of the St. Anthony (Mammoth) area, Pinal County, Arizona, *in* Arizona zinc and lead deposits, part 1, chapter 6: Arizona Bureau of Mines Bulletin 156, p. 63–84.

———1965, Geology of the San Manuel area, Pinal County, Arizona: U.S. Geological Survey Professional Paper 471, 64 p.

Dickinson, W.R., 1991, Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona: Geological Society of America Special Paper 264, 106 p.

———1993, Summary geologic map of Black Hills near Mammoth, Pinal County, Arizona (1:24,000): Arizona Geological Survey Contributed Map CM93B.

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, 28 p.

Force, E.R., Dickinson, W.R., and Hagstrum, J.T., in press, Tilting history of the San Manuel–Kalamazoo porphyry system, southeastern Arizona.

Heidrick, T.L., and Titley, S.R., 1982, Fracture and dike patterns in Laramide plutons and their structural and tectonic implications—American Southwest, *in* Titley, S.R., ed.,

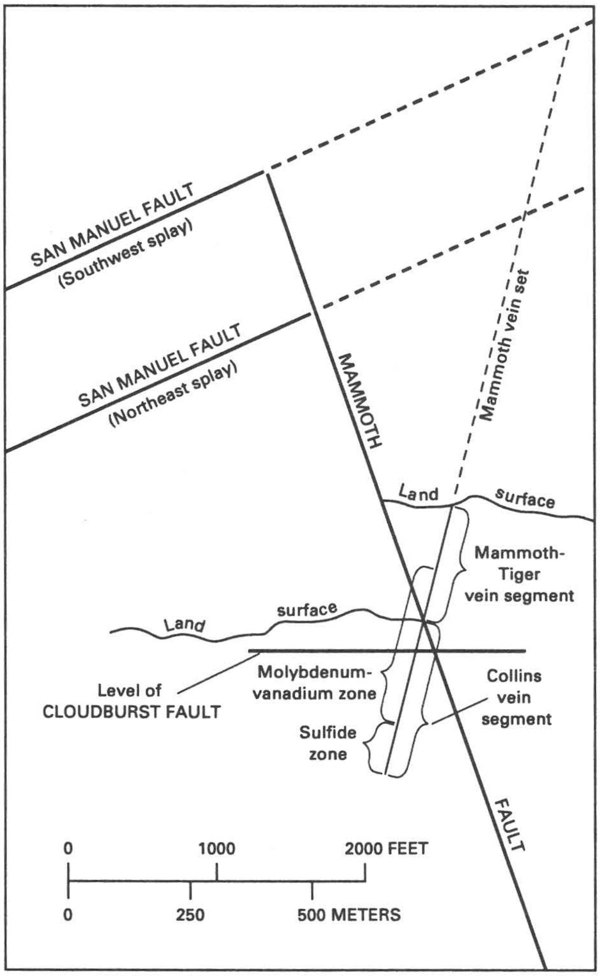


Figure 10. Reconstruction of the Mammoth vein set showing elemental zonation and Cloudburst detachment level (from Force and Cox, 1992).

the Mammoth-Tiger segment) only gold and silver were recovered. In intermediate parts, wulfenite and vanadinite predominated, and at **STOP 6C** we are in this portion of the Collins segment. In the lowermost parts (that is, the bottom of the Collins segment), lead and zinc sulfides predominated. Keith Long (oral commun., 1993) reported a still lower oxide zone, suggesting some symmetry about the Cloudburst detachment

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

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

Turn around and walk about 0.1 mi downwash.

At **STOP 6D** (13.8 mi) we will turn west on foot up Cloudburst Wash, a tributary of Tucson Wash. Here we see Cloudburst Formation, still in the lower member, but here containing nonlahar-type conglomerates, and locally containing cobbles of Oracle Granite. Cobbles of Tertiary volcanic rocks are 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 units are moderately altered to epidote-chlorite assemblages. Barite is locally present.

High on the slope to the left (southwest), the Mammoth vein set (Collins segment) 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. Adjacent to the vein, the Cloudburst Formation is heavily impregnated with epidote and chlorite.

Because of the high degree of induration of these rocks, the Cloudburst Formation was once thought to be Laramide. The chlorite-epidote-altered rocks have a hornfels-like character. Our traverse is only about 100–200 ft above the subhorizontal Cloudburst detachment fault. Detachment faulting is a type of tectonic denudation that typically juxtaposes hot, more deeply seated lower-plate rocks against colder, shallower upper-plate rocks faster than the geothermal gradient can adjust. Hence, the appearance of new minerals in the upper plate is a type of contact metamorphism. Alteration weakens upward in upper-plate rocks; epidote disappears at an elevation of about 3,200 ft near this stop. Additional epidote-chlorite growth is related to the vein set at a high angle to the detachment fault, but this alteration type also disappears at about the same elevation.

If there is time, we will 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. A scramble around the waterfall brings the surefooted enthusiast to the Mammoth vein crossing the wash (and a dangerous adit that has an open shaft).

Now that we have seen all the components, it is worth considering the tectonic context of the Mammoth vein set. All of the exposures of Cloudburst Formation at **STOP 6** are just above a single fault system that must rapidly change orientation from a steep north dip on the Turtle-fault part at **STOP 6B**, to horizontal on the Cloudburst-fault part at **STOP 6A** (fig. 6). The upper-plate rocks were baked in response to juxtaposition against tectonically denuded, hot lower-plate rocks. 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

Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 73–92.

Heindl, L.A., 1963, Cenozoic geology in the Mammoth area, Pinal County, Arizona: U.S. Geological Survey Bulletin 1141–E, 40 p.

Howard, K.A., 1991, Intrusion of horizontal dikes; tectonic significance of middle Proterozoic diabase sheets widespread in the upper crust of the southwestern United States: Journal of Geophysical Research, v. 96, p. 12461–12478.

Keith, S.B., Gest, D.E., DeWitt, Ed, Toll, N.W., and Everson, B.A., 1983, Metallic mineral districts and production in Arizona: Arizona Bureau of Geology and Mineral Technology, Bulletin 194, p. 34–35.

Long, K.R., 1992, Preliminary descriptive deposit model for detachment fault-related mineralization: U.S. Geological Survey Bulletin. 2004, p. 52–56.

Lowell, J.D., 1968, Geology of the Kalamazoo orebody, San Manuel district, Arizona: Economic Geology, v. 63, p. 645–654.

Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Economic Geology, v. 65, p. 373–408.

Peterson, N.P., 1938, Geology and ore deposits of the Mammoth mining camp area, Pinal County, Arizona: Arizona Bureau of Mines Bulletin 144, 63 p.

Schwartz, G.M., 1953, Geology of the San Manuel copper deposit, Arizona: U.S. Geological Survey Professional Paper 256, 63 p.

Spencer, J.E., and Welty, J.W., 1986, Possible controls of base- and precious-metal mineralization associated with Tertiary detachment faults in the lower Colorado River trough, Arizona and California: Geology, v. 14, p. 195–198.

Steele, H.J., and Rubly, G.R., 1947, San Manuel prospect: American Institute of Mining and Metallurgical Engineers Technical Publication 2255, 12 p.

Thomas, L.A., 1966, Geology of the San Manuel ore body, *in* Titley, S.R., and Hicks, C.L., eds., Geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 133–142.

Weibel, W.L., 1981, Depositional history and geology of the Cloudburst Formation near Mammoth, Arizona: Tucson, University of Arizona, M.S. thesis, 81 p.

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