U. S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

GEOLOGIC MAP OF THE SILVER BELL AND WEST SILVER BELL MOUNTAINS, SOUTHERN ARIZONA

By David A. Sawyer

Denver, Colorado

Open-File Report 96-006

1996

INTRODUCTION

The Silver Bell Mountains, 50 km northwest of Tucson, Arizona, are a mountain range in the transition from the higher-relief mountains of southeastern Arizona to the low-relief ranges of the western Arizona deserts. The Silver Bell Mountains include the area of the Silver Bell mining district (Richard and Courtright, 1966) which has produced over 100 million pounds of copper (Graybeal, 1982) since mining began in the late 19th century. Most of the mountain range and adjoining flanks are composed of Upper Cretaceous volcanic and plutonic rocks which are interpreted as parts of a ash-flow caldera; the intrusions which formed the porphyry copper deposits of the Silver Bell mining district were emplaced into the caldera margin. The latest Cretaceous and early Tertiary period of formation of most of Arizona's many copper deposits during was also a period of widespread continental silicic caldera volcanism, later fragmented into alternating mountain range exposures and buried beneath alluvial basins by late Tertiary extensional deformation. Lipman and Sawyer (1985) identified as many as seven Cretaceous caldera fragments in southern Arizona, as well as pieces of Cretaceous volcanoes in more than a half-dozen other mountain ranges in southern Arizona. Undoubtedly, much of the evidence about the character of Cretaeous volcanism is buried beneath alluvial valleys. This is the fourth detailed mapping study of these Cretaceous volcanoes: studies of the Tombstone caldera (Moore, 1994) and the Tucson Mountain caldera (Lipman, 1994) have recently been published, and a geologic map of Cretaceous volcanic rocks in the Sierrita Mountains (Fridrich and Lipman, 1991) is in preparation.

GEOLOGIC SUMMARY

The area of the Silver Bell Mountains (including the low West Silver Bell Mountains) shares a geologic framework common to southern Arizona: crustal formation during the middle Proterozoic (about 1.7 Ga), emplacement of extensive granitic batholiths at 1.4 Ga, and late Proterozoic sedimentation and diabase magmatism (Sawyer and Pallister, 1989). During Paleozoic time thin platform sedimentary sequences were laid down, dominated by carbonate rocks but with sporadic but significant clastic input, leading to thicker carbonate deposition by the Permian. Mesozoic sedimentary rocks of southern Arizona, primarily continental in nature, are preserved only in the West Silver Bell Mountains and in the valley between the Silver Bell Range and the Waterman Range to the south. Nearly the entire Silver Bell Range and more than three-fourths of the West Silver Bell Mountains are underlain by Cretaceous volcanic and plutonic rocks, making it an excellent area to examine the stratigraphy, structure, and volcanology of a late Cretaceous volcanic terrane, as well as the relationship of economically important copper mineralization to specific magmatic events.

Cretaceous magmatism in the Silver Bell area began with small-volume andesite volcanism recorded in the part of the West Silver Bell Mountains, concurrent with compressional deformation. Larger-scale magmatism in the area was initiated by emplacement at 73 Ma of the compositionally evolved El Tiro biotite granite, rapidly followed by eruption of the caldera-forming low-silica rhyolite Confidence Peak Tuff. The intracaldera Confidence Peak Tuff is down-faulted against the precaldera El Tiro granite along the western ring-fault zone of the Silver Bell caldera, except where it has been intruded by younger plutons of the quartz monzodiorite porphyry suite.

Large blocks (up to >1 km) containing semi-coherent Paleozoic sedimentary stratigraphy slid into the intracaldera Confidence Peak Tuff during caldera collapse. Following accumulation of more than 2 km of intracaldera tuff, the Silver Bell caldera was resurgently domed. Post-caldera volcanism in the Silver Bell Mountains began with composite volcano eruptions of andesites and dacites forming the Silver Bell Formation. The Cat Mountain Tuff, erupted from the Tucson Mountains caldera to the southeast ponded in parts of the Silver Bell caldera, and was deposited in a thick sequence in the western Silver Bell Mountains. Quartz monzodiorite to granodiorite porphyry plutons were emplaced along the ring-fracture zone of the Silver Bell caldera following the deposition of the Cat Mountain Tuff at about 69 Ma. Porphyry copper mineralization took place in several centers in the main Silver Bell Mountains from 69 to possibly as young as 65 Ma related to emplacement of plutons of the quartz monzodiorite porphyry suite. The final late Cretaceous volcanism in the Silver Bell Mountains was small-volume rhyolite and dacite volcanism deposited above the Cat Mountain Tuff in the northeastern part of the west Silver Bell Mountains. Regional strike-slip faulting along WNW-trending faults may have begun during the latest stages of Cretaceous volcanism. Large-scale dextral strike-slip faulting offset the Silver Bell caldera on the north side along the Ragged Top fault zone. Similar strike-slip faults(but probably of smaller displacement) offset the late Cretaceous volcanic sequence in the Silver Bell Mountains to the south in the strike valley between the Silver Bell and Waterman Mountains. During this episode of strike-slip faulting the Silver Bell Mountains were rotated 25-30 degrees clockwise as indicated by paleomagnetic investigations (Hagstrum and Sawyer, 1989). The timing of the strike-slip faulting and dextral rotation is constrained to be between the age of late Cretaceous magmatism and mid-Tertiary andesite to rhyolite volcanism that is unaffected by the faulting. During or after this time period, the Silver Bell Mountain were tilted to the east 20-30 degrees, probably concurrent with extensional deformation in the Santa Catalina and Tortolita core complexes. Basaltic andesite, andesite, and rhyolite lavas and dikes were emplaced widely in the Silver Bell and West Silver Bell Mountains from 28 to about 22 Ma, most prominently at the 25 Ma Ragged Top rhyolite dome emplaced along the Ragged Top fault. Tertiary volcanic rocks and sedimentary deposits generally overlie Cretaceous rocks in the eastern Silver Bell Mountains above angular unconformities. Basin-fill sedimentation in the adjoining Avra and Aguirre Valleys continues to the present.

DESCRIPTION OF MAP UNITS

All plutonic and volcanic rock names from IUGS classification (Streickeisen, 1976 and LeBas and others, 1986, respectively). All ages are recalculated to current IUGS constants (Steiger and Jager, 1977). Colors based on GSA Rock-color chart, names from ISCC-NBS system; color codes from the Munsell system.

SURFICIAL DEPOSITS

af Artificial fill--Deposits of man-made fill; includes mine waste dumps, leach pads, and mill tailings that are widespread around the Oxide and El Tiro pits. Also includes roads, and all buildings and man-made structures including the mill and town sites at Silver Bell

Qt Talus (Holocene)--Sloping accumulations of unconsolidated, angular, fragmental rocks at the base of cliffs. Most prominently developed at the base of cliffs of Ragged Top rhyolite and Cat Mountain Tuff, and consisting of blocks and boulders of these lithologies

Qc Colluvium (Holocene)--Poorly sorted, unconsolidated, heterogeneous deposits of soil material and rock fragments from clay to boulder size, that cover bedrock geology in patches at the base of slopes

Qal Alluvium (Holocene)--Unconsolidated deposits of gravel, sand, or silt formed by fluvial and mass-flow processes in stream and wash bottoms

Qab Alluvial basin fill deposits (Holocene-Pleistocene)--Coalescing distal alluvial fan and stream deposits of sand, silt, and fine gravel that grade into finer-grained basin-fill facies in the Avra, Aguirre, and Santa Cruz valleys. These alluvial basin deposits form bajada surfaces in the map area. These sedimentary deposits, and additionally Qaf and Qao, are approximately equivalent to Ft. Lowell Formation as used by Anderson (1989) in Avra Valley and the Tucson Basin

Qaf Alluvial fan deposits (Holocene-Pleistocene)--
Fluvial and mass-flow deposits forming recent fan-shaped accumulations of talus, gravel, sand, and silt at the mouths of valleys, adjoining mountain fronts. Individual fan deposits were mapped, resulting in internal contacts being shown between some discrete fan deposits

Qao Older alluvial fan and terrace deposits
(Pleistocene)--Fluvial and mass-flow deposits of talus, gravel, sand, and silt forming relict older surfaces and terraces adjoining the Silver Bell and West Silver Bell Mountains. Often mantle pediment surfaces, with intermittent bedrock exposures in drainages

QTa Alluvial deposits-undivided (Pliocene? and Quaternary)--[Cross-section only] Surficial deposits and Tertiary sedimentary units, undivided

TERTIARY ROCKS

Tsy Younger sedimentary rocks (Miocene)--Little indurated gravels, sandstones, and siltstones mainly west of the El Tiro pit. Mapped where sedimentary rocks overlie Tertiary volcanic rocks. Color is variable, depending on degree of cementation and concentration of altered clasts, but a common color is grayish-orange (10 YR 7/4). They lithologically resemble "Gila"-type conglomerates and are probably late Miocene-Pliocene in age. Probably equivalent to Tinaja beds as used by Anderson (1989) in Avra Valley and Tucson

Tai Intrusive andesite (Miocene-Oligocene)--Generally NW-trending dark-colored (greenish-black-5 GY 2/1) dikes most commonly exposed in the vicinity of the El Tiro pit. Variably oriented dikes are also sporadically exposed in the Silver Bell and West Silver Mountains. May include some more strongly alkalic mafic dikes (Banks and Dockter, 1976). Age is 25.3 +/- 0.3 Ma (Sawyer, D.A., James, E.W., and Shafiqullah, M., unpublished data) for andesite dike in El Tiro pit (not shown on map), but andesitic intrusion on SW side of Malpais Hill (sec. 18, West Silver Bell Mountains) may be younger

Tb Alkalic basalt (Miocene-Oligocene)--Youngest Tertiary volcanic rocks on west side of the Silver Bell Mountains at Malpais Hill, at an eroded cinder cone SW of the Oxide pit, and at scattered wash-bottom localities beneath the younger sedimentary rocks and older alluvial fan and terrace deposits. Blackish red (5 R 2/2) to light grey (N7) in color. Lithology is variably vesicular lava flows that are very olivine-rich (up to 5-10%) with common high TiAl augite. These basalts were considered by Banks and Dockter (1976) to be equivalent in age to lava flows in the Vaca Hills isotopically dated at between 22.2 and 19.5 Ma

Tr Ragged Top Rhyolite (Oligocene)--Complex large rhyolite dome and related dikes. Dome makes up Ragged Top and Wolcott Peaks and is strongly flow-layered, with banding approximately centered on vent areas in these peaks. Rhyolite dome intrudes the Ragged Top fault and provides an upper limit on the age of fault movement. Rhyolite is typically grayish-pink (5 R 8/2) and relatively crystal-poor, containing 5-10 percent phenocrysts of sanidine, plagioclase, and biotite. Dikes trend NNW in several swarms that cut the porphyry copper mineralization in the Oxide pit, and pass east of the El Tiro pit. Age of 25.7 +/- 1.0 Ma by K-Ar on biotite (Mauger and others, 1965)

Tba Basaltic andesite and basalt (Oligocene)--Mafic basaltic andesite and basalt volcanic rocks within the Oligocene volcanic sequence on the east side of the Silver Bell range (R. Ashley, 1977, unpublished geologic mapping). Commonly contain a high content (20-45%) of small plagioclase phenocrysts and pyroxene or hornblende, as well as common Fe-Ti oxides. Color is commonly very dusky red (10 R 2/2)

Ta Andesite (Oligocene)--Lava flows, breccia, and related minor intrusions on the east side of the Silver Bell Mountains and on the north and east sides of the West Silver Bell Mountains, unconformably overlying late Cretaceous volcanic rocks. The blackish red (5 R 2/2) to light brownish grey (5 YR 6/1) rocks are dominantly moderately porphyritic to sparsely porphyritic hornblende and plagioclase andesites, but range from basaltic andesite to dacite. Dacites may be present in the southeastern part of the map area, and are common in the adjoining Pan Quemado and Samaniego Hills outside the map area (R. Ashley, 1977, unpublished geologic mapping, and R. Eastwood, 1970). Age of 28.6 +/- 1.4 Ma on biotite for the Petroglyph Hill andesite (Mauger and others, 1965) on the east side of the Silver Bell Mountains

Tso Older sedimentary rocks (Paleocene)--Exposed east of the Ragged Top rhyolite dome and were deformed by movement along the Ragged Top fault. These sedimentary rocks are sparingly exposed in windows through the older alluvial fan and terrace deposits. Color varies from light brown (5 YR 6/4) to moderate reddish-brown (10 R 4/6). May be as old as Paleocene-early Oligocene, but also includes sedimentary rocks interbedded with volcanic rocks of late Oligocene-early Miocene age. These sedimentary deposits are lithologically and probably temporally equivalent to the Pantano Formation as used by Anderson (1989) in Avra Valley and the Tucson Basin

POST-CALDERA VOLCANIC AND SEDIMENTARY ROCKS (UPPER CRETACEOUS)

Kmd Dacite--Olive-grey (5 Y 3/2) intermediate-composition lava flows and breccias interbedded with post-Cat Mountain Tuff sedimentary and volcanic rocks in the West Silver Bell Mountains and north end of the Silver Bell Mountains. Porphyritic to fine-grained plagioclase-bearing andesites and dacites. Probably are the youngest Upper Cretaceous volcanic rocks in the West Silver Bell Mountains

Kmr Rhyolite--Flow-layered crystal-poor rhyolite lava flows and domes overlying the Cat Mountain Tuff in the West Silver Bell Mountains. Very light grey (N8), includes minor interbedded andesite and dacite breccias

Kms Sedimentary rocks--Pale yellowish brown (10 YR 6/2) volcaniclastic sandstone, breccia, and conglomerate overlying Cat Mountain Tuff and interbedded with rhyolite lava

Kcu Upper rhyolite ash-flow tuff--Simple cooling unit of grayish pink (5 R 8/2) high-silica rhyolite ash-flow tuff that in a single locality on the east side of the Silver Bell Mountains above the Cat Mountain Tuff. Source and correlation with other Cretaceous rhyolite ash-flow tuffs undetermined

Kcw Cat Mountain Tuff--Low-silica rhyolitic ash-flow tuff (70-74 percent SiO2) that ponded above the Silver Bell Formation volcano within the Silver Bell caldera. Generally strongly welded, and dense, it makes up most of the highest peaks of the Silver Bell and West Silver Bell Mountains. Welding and crystallization characteristics are variable, but in the central Silver Bell Mountains it is a compound cooling unit containing several partial cooling breaks. It is readily distinguished by its pale reddish brown (10 R 5/4) (especially pumice) to moderate reddish brown (10 R 4/6) color, prominent eutaxitic fabric, and a moderately crystal-rich phenocryst content (25-30%). Dominant phenocrysts are sanidine (10-15%), quartz (10%), and plagioclase (5-10%); minor biotite is usually altered and often inconspicuous in hand-specimen. Where altered, as adjoining the Oxide pit, the color is commonly light grey (N7). The Cat Mountain Tuff in the Silver Bell Mountains was first correlated as such by Richard and Courtright (1954, 1960), but later ASARCO workers (Watson, 1964, 1968; Graybeal, 1982) renamed it the Mount Lord Ignimbrite and considered it to have been erupted from a source in the Silver Bell Mountains. Dockter (1977) lumped units in the West Silver Bell Mountains with the ash-flow tuff (ignimbrite) and renamed the grouping the Mount Lord Volcanics. Recent work, cited in Sawyer (1987), Hagstrum and Sawyer (1990), and Lipman and Fridrich (1990) has demonstrated that the tuff of the Mount Lord Volcanics was derived from a source outside the Silver Bell Mountains, and that it correlates with the intracaldera Cat Mountain Tuff of the Tucson Mountains. Hence, Cat Mountain Tuff is equivalent to the tuff member of the Mount Lord Volcanics of Dockter (1977), and should be used on the basis of precedence of stratigraphic usage. Overlying rhyolite lavas (Kmr) and interfingering sedimentary rocks (Kms) are considered as local, informal units. Age of 59.7 +/- 1.8 Ma on alkali feldspar by K-Ar is a minimum; based on stratigraphic constraints and best K-Ar and U-Pb zircon ages, bracketed between 72.7 and 68.6 Ma. This is consistent with K-Ar alkali feldspar ages from 72-68 Ma in the Tucson Mountains, as well as (within analytical uncertainty) a recent 40Ar/39Ar age on biotite of 73.1 Ma in the Tucson Mountains (Lipman, 1994)

Kcl Lower rhyolite ash-flow tuff--Local deposit, similar to Cat Mountain Tuff, interfingering with Silver Bell Formation NE of Oxide pit; light grey (N7) in color due to alteration

ROCKS OF THE SILVER BELL CALDERA SYSTEM (UPPER CRETACEOUS)

INTRUSIVE ROCKS--

Kop Orthoclase quartz monzodiorite porphyry--Small pluton and dikes of orthoclase megacryst-bearing quartz monzodiorite porphyry. A pluton of this rock is located between the Oxide and El Tiro pits, and dikes east of this pluton cut the intracaldera Confidence Peak Tuff; related dikes are intersected in deep drillholes in the East Extension of El Tiro pit. These dikes crosscut all other Late Cretaceous intrusive units. Phenocrysts consist of Carlsbad-twinned orthoclase crystals (up to 1-3 cm in length), biotite, rounded quartz, and plagioclase set in a moderate orange pink (10 R 7/4) nearly aphanitic groundmass

Kqp Quartz monzodiorite porphyry suite-Compositionally and texturally variable plutons and dikes that are host to porphyry copper mineralization in the Oxide, El Tiro, and North Silver Bell mineralized centers. These intrusive rocks, light brownish grey in color (5 YR 6/1) when unaltered, gradationally range in modal composition from granodiorite porphyry through quartz monzodiorite porphyry to monzogranite porphyry, compositions straddling the granodiorite/quartz monzodiorite boundary being most abundant. Crystal contents vary from 40-70 percent, and generally small (2-5mm) phenocrysts are set in a fine-grained groundmass. Phenocrysts are plagioclase, orthoclase, biotite, relatively sparse quartz and hornblende (usually replaced by secondary biotite), and common titanite, all set in an aplitic or hypidiomorphic granular intergrown alkali feldspar-quartz groundmass.

These plutons served as the locus for mineralization/ alteration and are variably affected by superimposed secondary supergene as well as hypogene potassic, quartz-sericite-pyrite, and propylitic alteration and mineralization. Major dike swarms of texturally and compositionally variable quartz monzodiorite porphyry suite dikes strike NE-ENE from the North Silver Bell and El Tiro mineralized centers, and NE-ENE and ESE from the Oxide mineralized center. Though the quartz monzodiorite porphyry suite is host to mineralization, perhaps only the youngest intrusive phases within the suite may have generated the disseminated porphyry Cu-Mo-Ag ores; a hydrothermal biotite and pyrite-rich biotite quartz monzonite dike cuts host quartz monzodiorite porphyry in the El Tiro pit on bench 2550

Ages for the quartz monzodiorite porphyry suite range from 68.6 Ma on biotite from an unaltered pluton west of the Oxide pit to 63.5 Ma on the plutons affected by porphyry copper hydrothermal alteration and mineralization in the Oxide and El Tiro pits. K-Ar ages for quartz monzodiorite porphyry suite plutons include 68.6 +/- 2.7 Ma on biotite from the least altered pluton of the suite (Mauger and others, 1965); this is considered the best approximation of emplacement age. Other ages from the altered and mineralized plutons of the suite include: 67.1 +/- 1.0 Ma, 64.8 +/- 2.2 Ma (Mauger and others, 1965), and 63.8 +/-1.5 Ma (Sawyer, D.A., James, E.W., and Shafiqullah, M., unpublished data) for typical potassically altered quartz monzodiorite porphyry in the El Tiro pit; and 64.9 +/- 1.5 Ma for the late biotite quartz monzonite porphyry in the El Tiro pit (Sawyer, D.A., James, E.W., and Shafiqullah, M., unpublished data); one age on the potassically altered quartz monzodiorite porphyry from the Oxide pit gives an age of 63.8 +/- 1.6 Ma (Sawyer, D.A., James, E.W., and Shafiqullah, M., unpublished data) identical to the age of the porphyry in the El Tiro pit. Most of the pit ages almost certainly represent later hydrothermal re-setting of the primary emplacement age

Kmp Monzodiorite porphyry--Early mafic fine-grained greyish olive green (5 GY 3/2) intrusive pluton and dikes related to the quartz monzodiorite porphyry suite; gradational with typical quartz monzodiorite porphyry where most common in the vicinity of the Oxide pit. Crystal content ranges from 25-40 percent phenocrysts of plagioclase and biotite; sparse orthoclase, hornblende, and clinopyroxene are set in a groundmass of aligned plagioclase microlites; high magnetite content. Usually strongly altered in vicinity of mineralized areas to epidote, chlorite, and calcite propylitic assemblage

Kgp Granodiorite porphyry--Earliest postcaldera intrusions, compositionally similar to Silver Bell Formation andesite and dacite. Two largest bodies of granodiorite porphyry are laccolithic intrusions on the north and southeast flanks of the Silver Bell Mountains; a small intrusion in the center of the Silver Bell caldera predates the deposition of the Cat Mountain Tuff. Phenocrysts comprise 50-80 percent of the rock, and plagioclase is dominant, with subordinate biotite greater than quartz, hornblende, and orthoclase. Typically affected by chlorite-calcite-smectite propylitic alteration and greyish green (10 G 4/2) as a result; epidote locally present

Kdi Diorite--Fine-grained holocrystalline intermediate-composition intrusive rock, light bluish grey in color. Present as small plutons cutting earlier Mesozoic sedimentary and volcanic rocks in the western Silver Bell Mountains. Late Cretaceous age assignment based upon large mass of lithologically identical intrusive rock cutting Silver Bell Formation and outflow Confidence Peak Tuff at the east end of the West Silver Bell Mountains. Age assignment is queried where identical lithologies cut older deformed rocks

POST-COLLAPSE VOLCANIC AND SEDIMENTARY ROCKS

Silver Bell Formation

Ksb Andesite breccia lens--Thin but widely distributed lens of debris-flow deposits that interfinger with the base of the Cat Mountain Tuff. Dusky green (5 G 3/2) clasts are composed of Silver Bell Formation andesite and dacite, and the breccia deposit is clast-supported. In a few localities, tuff (Kcl) is injected in dilatant fractures in the breccia

Ksa Andesite/dacite lava flows and breccia--Ventfacies accumulations of porphyryitic to (less commonly) aphanitic andesite and dacite. Lava flows and breccia are too complexly interlayered to depict at map scale. Colors range from dusky green (5 G 3/2) to greyish purple (5 P 4/2). Breccias are similar in lithology to lava flows, and most formed by disruption of flows as they moved distally away from vent areas. These traction breccias are clastsupported (generally >90 percent); clasts are dominantly angular to subangular. Porphyryitic andesite and dacite (2050 percent phenocrysts) dominate and have typical phenocryst assemblages of plagioclase (locally glomerophyric), biotite (2-4 percent), and hornblende (0-6 percent). Pyroxene is sparse to absent, while Fe-Ti oxides are relatively abundant. Sparse phenocrystic quartz is diagnostic for the dacites

Ksd Dacite domes and lava--Flow-layered quartz-bearing porphyryitic dacite, greyish green (10 G 4/2) in color, occurs in discrete areas interpreted as dome accumulations and related lavas. Phenocrysts of plagioclase, biotite, sparse quartz, and Fe-Ti oxides comprise 10-25 percent of the rock

Ksv Volcaniclastic sedimentary rocks--Distal volcaniclastic facies of the Silver Bell intermediatecomposition volcanoes. Largely consists of matrix-supported debris-flow and mudflow deposits, characterized as having matrix >50%. The most common lithology is greyish purple (5 P 4/2) andesitic mudflow deposits, with typical (but rounded) porphyritic dacite and andesite clasts. Some heterolithologic mudflow and debris-flow deposits (commonly greyish green, 10 G 4/2) ontain prevolcanic clasts. Other minor lithologies are bedded fine-grained andesitic sandstones and thin-bedded mudflow deposits.

Kcr Claflin Ranch Formation sedimentary rocks-Sedimentary deposits overlying the Confidence Peak Tuff. Generally underlies Silver Bell Formation, but lowest volcaniclastic Silver Bell deposits locally interfinger with the top of the Claflin Ranch Formation. Claflin Ranch sedimentary rocks constitute moat-filling sediments of the Silver Bell caldera. They are particularly thick on the north side of the Silver Bell Mountains (up to 700 m thick) and thin to the south over the resurgent dome of the caldera In its thickest section, the Claflin Ranch Formation consists of debris-flow deposits, volcaniclastic sediments (matrix largely derived from erosion of the Confidence Peak Tuff), and subordinate pyroclastic fall-out and flow deposits. Elsewhere, it is predominantly pyroclastic-flow and fall-out deposits and reworked epiclastic derivatives, with minor intercalated sedimentary rocks. Matrix of heterolithologic debris-flow deposits also appears to be derived from the Confidence Peak Tuff, while provenance of clasts is quite variable and includes indurated, welded Confidence Peak Tuff, lower Cretaceous sedimentary rocks (arkosic sandstones and dark algal limestones), and common Precambrian schist. Precambrian granite clasts are absent despite their present widespead distribution 3 km to the north across the Ragged Top fault. Colors are variable, depending on clast type and content, but dominant matrix colors range from yellowish grey (5 Y 8/1) to greyish orange (10 YR 7/4). Confidence Peak Tuff

Kpi Intracaldera tuff--Lithic-rich low-silica rhyolite welded ash-flow tuff that ponded to a thickness greater than 1.2 km inside the Silver Bell caldera. Considered by previous workers (Richard and Courtright, 1966; Watson, 1964, 1968; Graybeal, 1982) to be intrusive dacite porphyry; exposed depositional upper contact and ubiquitous presence of pumice and vitroclastic texture demonstrate its volcanic character. Typically medium bluish grey (5 B 5/1) in color where fresh, to light grey (N 7) where altered. Crystalrich (30-45 percent) containing phenocrysts of plagioclase (22-30 percent, An 42-39), resorbed or fragmental quartz (1525 percent), biotite (3-8 percent, everywhere chloritically altered), Fe-Ti oxides (1-2 percent); and though inconspicuous in hand specimen, 1-2 percent sanidine. Alkali feldspar and quartz are common in the devitrified groundmass. Silica content of the Confidence Peak Tuff is relatively uniform at 72-74 percent SiO_2; the intracaldera tuff shows no discernible zonation in chemical composition. Low Zr contents (80-100 ppm) are diagnostic of bulk tuff chemical analyses when compared to the Cat Mountain Tuff The intracaldera Confidence Peak Tuff is a single compound cooling unit; no complete internal cooling breaks have been found. It forms the matrix to, and envelops, caldera-collapse megabreccia blocks and lens, principally composed of Paleozoic sedimentary rocks. Lithic contents are usually high in the tuff, from 20 percent up to 50 percent, and are dominantly composed of fine-grained Mesozoic? and Paleozoic sedimentary rocks; sparse Precambrian metamorphic lithic fragments are also present. The thick intracaldera Confidence Peak Tuff is usually propylitically altered, and epidote is common as an alteration product near its exposed base.

Ages of 58.8 +/- 2.0 and 56.6 +/- 2.8 Ma from K-Ar dating of biotite (Mauger and others, 1965) are too young based upon stratigraphic constraints and must have been reset. U-Pb ages on zircon fractions gave inconclusive discordant ages but the age of the Confidence Peak Tuff is bracketed between 72.7 and 68.6 Ma in age by well-dated units; probably within +/- 1 Ma of 72.7 Ma

Kpb Caldera-collapse megabreccia, composed of Paleozoic sedimentary rocks--[Cross-section only] Blocks, lenses, and masses of Paleozoic sedimentary rocks up to 1.4 km in length that were deposited within the Silver Bell caldera concurrent with the eruption of the intracaldera Confidence Peak Tuff. Confidence Peak Tuff occurs stratigraphically above, below, and locally interfingers/injects these megabreccia deposits; however, most contacts within the megabreccia horizon of the intracaldera fill are block on block, having Paleozoic sedimentary stratigraphy juxtaposed by the caldera-collapse process. To better illustrate stratigraphic juxtapositions, the caldera-collapse megabreccia composed of Paleozoic sedimentary rock is divided into clasts of upper Paleozoic rocks and clasts of lower Paleozoic rocks

Kpu Caldera collapse megabreccia, composed of upper Paleozoic sedimentary rocks--Blocks, lenses, and masses of upper Paleozoic (Devonian-Permian) sedimentary rocks. Includes or may include the following units: Devonian Martin Formation, Mississippian Escabrosa Limestone, Pennsylvanian Horquilla Limestone, Pennsylvanian-Permian Earp Formation, Permian Colina Limestone, and Permian Scherrer Formation. Permian Concha Limestone and Rainvalley Formation have not been identified in the caldera-collapse megabreccia, but are reported stratigraphically in place in the West Silver Bell Mountains (Clarke, 1966). Color variable depending on which Paleozoic protolithology included in breccia

Kpl Caldera-collapse megabreccia, composed of lower Paleozoic sedimentary rocks--Blocks, lenses, and masses of lower Paleozoic (Cambro-Ordovician) sedimentary rocks. Includes or may include the following units: Cambrian Bolsa Quartzite and Cambrian Abrigo Formation. Color variable

Kpo Outflow tuff--Sequence of nonwelded ash-flow and air-fall deposits in the West Silver Bell Mountains that are correlated with the intracaldera Confidence Peak Tuff on the basis of their stratigraphic position, petrographic and chemical similarity, and magnetic polarity. Yellowish grey (5 Y 8/1) in color. The stratigraphy of these deposits contrasts with the strongly welded intracaldera tuff and consists dominantly of small-volume pyroclastic flow deposits, with intervening bedded air-fall tuffs, debrisflow deposits, and epiclastic sedimentary rocks delineating cooling breaks. They have a total thickness of about 250 m. Generally strongly affected by low-temperature alteration, these porous tuffs have proportions of phenocryst species and lithic contents that are similar to the intracaldera Confidence Peak Tuff. Their stratigraphic position is bracketed beneath the Silver Bell Formation and above precaldera rocks, in the same interval as the intracaldera Confidence Peak Tuff

Kps Sedimentary rocks--Mappable sedimentary rock accumulations interleaved with (though not at map scale) and beneath outflow Confidence Peak Tuff in the West Silver Bell Mountains. Color is generally dusky red (5 R 3/4) to very dusky red purple (5 RP 2/2), except where composed of reworked andesitic material and is more greyish green (5 G 5/2)

PRECALDERA MESOZOIC IGNEOUS AND SEDIMENTARY ROCKS

Keg El Tiro Granite (Upper Cretaceous)--Precaldera biotite granite cut by the ring-fracture zone of the Silver Bell caldera. Previously called alaskite (Richard and Courtright, 1966; Graybeal, 1982), the mafic-poor nature of this pluton near the open-pit mining areas is a function of hypogene and supergene alteration destroying common biotite (2-3 percent crystals). Other crystals include 35-50 percent perthitic K-feldspar, 25-35 percent quartz, and 2030 percent plagioclase. Modal composition of this granitoid is a syenogranite, close to monzogranite in composition. The granite, when fresh, is pinkish grey (5 YR 8/1) weathering to a moderate reddish orange (10 R 6/6). It is generally coarse-grained and homogeneous in texture except for some large masses of aplite just west of the El Tiro pit. The biotite granite intrudes Mesozoic sedimentary rocks of uncertain age, probably lower Cretaceous or Jurassic on the SW side of the pluton. Granite has a concordant U/Pb age on zircon of 72.7 +/- 1 Ma (Sawyer, D.A., James, E.W., and Shafiqullah, M., unpublished data). K-Ar age of 66.1 +/- 2.5 Ma on biotite (Mauger and others, 1965) is too young

Mzg Mesozic granitic intrusive rocks--West Silver Bell Mountains. Texturally variable plutons, dikes, and sills that are approximately granitic in composition, and moderate orange pink (10 R 7/4) in color. Not studied in detail; age relations not known , but are locally inferred to be Cretaceous (Banks and Dockter, 1976)

Mzsv Mesozoic sedimentary and volcanic rocks undivided rocks in the West Silver Bell Mountains and the southwest side of main Silver Bell Mountains. Lithology and age complex and poorly known. Unit in West Silver Bell Mountains includes significant andesite lava, volcaniclastic sedimentary rocks, and arkosic sedimentary rocks, typically colored grayish olive (10 Y 4/2). These rocks are stratigrapically above rocks lithologically correlated with the Lower Cretaceous Amole Arkose in the Tucson Mountains (Ka?). In the West Silver Bell Mountains these rocks were folded and deformed prior to the deposition of the Confidence Peak Tuff. The package also includes dark reddish brown (10 R 3/4) arkosic sandstones and volcanic conglomerates conformably underlying outflow Confidence Peak Tuff ashfall and ashflow tuffs in the Western Silver Bell Mountains; they are above a major unconformity separating these conformable rocks from earlier, more deformed Mesozoic and Paleozoic rocks. Similar lithologies, andesitic mudflow deposits, and heterolithologic mudflow deposits are locally interbedded with the base of the outflow Confidence Peak Tuff sequence

Mzr Mesozoic rhyolitic volcanic rocks--Distinctive pink to white aphanitic to crystal-poor volcanic rocks and small intrusions, commonly fault-bounded, occurring in the area of the undivided Mesozoic sedimentary and volcanic rocks in the West Silver Bell Mountains. Prominent light grey (N 7) thin rhyolite welded tuff in the Mzsv unit. Attitude of tuff indicates that it is folded, and an angular unconformity separates unit from overlying outflow Confidence Peak Tuff

Ka? Amole Arkose? (Cretaceous?)--Dominantly consists of arkosic sandstones and conglomeratic sandstones, containing relatively little volcaniclastic material. Varies from pale reddish brown (10 R 5/4) to grayish orange (10 YR 7/4) to white (N 9). Local greenish grey (5 G 6/1) limestone exposed southwest of El Tiro and Oxide pits and in one prominent exposure south of tailings dams. Arkosic sandstones are lithologically correlated with parts of the Amole Arkose in the Tucson Mountains (R. Risley, 1987, and oral communication, 1983); similar Mesozoic lithologies occur in Waterman Mountains (Hall, 1985). In the area southwest of the Oxide pit on the west flank of the Silver Bell Range, Mesozoic sedimentary rocks include lithologic correlatives of lower Cretaceous sedimentary rocks

JTr? Recreation Red Beds? (Jurassic-Triassic?)--Red-bed siltstones and sandstones, principally from the southwest side of Oxide pit to the south side of the tailings dam east of the Silver Bell townsite. Distinctively colored from moderate red (5 R 5/4) to dusky red (5 R 3/4). Similar Mesozoic lithologies in the southern Waterman Mountains are correlated with the Recreation Red Beds by Hall (1985)

PALEOZOIC SEDIMENTARY ROCKS

Pzs Sedimentary rocks, undifferentiated (Permian)-West Silver Bell Mountains. Small area at the SW end of the West Silver Bell Mountains where Paleozoic carbonate rocks and siltstones are exposed. Includes rocks mapped as Permian Scherrer Formation, Permian Concha Limestone, and Permian Rainvalley Formation by Clarke (1966). Varies from grey limestone to light brown siltstone

PRECAMBRIAN ROCKS

Yd Diabase (Middle Proterozoic)--Greenish black (5 GY 2/1) diabase dikes and small plutons cutting Proterozoic granite in the area of Precambrian rocks north of the Ragged Top fault.

Regionally, similar diabase dikes cut Late Proterozoic Apache Group sedimentary rocks, but this relationship is not observed in the Silver Bell Mountains

Ya Apache Group (Middle Proterozoic)--Sedimentary rocks unconformably overlying Proterozoic (Yg) granite north of the Ragged Top fault on the east side of Ragged Top. Rocks are pale reddish brown (10 R 5/4) to white (N9) interlayered arkosic sandstone, conglomerate, and siltstone similar to that found in the Dripping Spring Quartzite in the nearby Slate Mountains

Yg Porphyryitic granite (Middle Proterozoic)--Coarse-grained moderate red (5 R 4/6) granite occurring in outcrop and subcrop over a large area north of the Silver Bell Range and Ragged Top across the Ragged Top fault. Rock is a lithologic equivalent to Proterozoic "Oracle"-type granite containing large crystals of pink K-feldspar, quartz, plagioclase, and biotite, and lacking any tectonic fabric. Support for correlation of this unit with the regional 1.4 Ga suite of anorogenic granite plutons comes from a common Pb model age on K-feldspar of 1.38 Ga on two K-feldspars from this pluton (D.A. Sawyer, unpublished data)

Xs Schist (Early Proterozoic)--Quartz-muscovite schist, light bluish grey (5 B 7/1) strongly foliated and folded. Exposed in a few washes on the east side of the Silver Bell Range south of the Ragged Top fault. Derived from pelitic parent lithology. Lithologic correlative of "Pinal"-type schist regionally exposed in southern Arizona

Acknowledgments

Many thanks are extended to ASARCO, Inc. for their generous logistical support, and for the cooperation of Mine Manager B.K. Malone of the Silver Bell Unit which made this study possible. S.A. Anzalone and J.D. Sell were especially helpful in their encouragement and for the technical questions they raised about the Silver Bell area. Unpublished ASARCO, Inc. geologic mapping of B.N. Watson and S.R. Davis was of excellent quality and useful in compiling parts of the geologic map. Programmatic support of the Geothermal Resources program of the U.S. Geological Survey through L.P. Muffler was essential during the field, laboratory, and writing stages of the project. P.W. Lipman provided the initial inspiration for the project, coordinated support, and always challenged me to aim higher. My University of California, Santa Barbara dissertation advisors W.S. Wise, R.V. Fisher, and G.A. Tilton provided helpful field and manuscript criticism. Colleagues from the Arizona Geological Survey, University of Arizona, and from the mining and exploration community in Tucson helped me to sift through my ideas on numerous field trips out to Silver Bell. Reviews by Richard B. Moore, Peter W. Lipman, and Steve J. Reynolds helped to improve the manuscript. Any remaining problems or errors are solely the responsibility of the author.

REFERENCES

Anderson, S.R., 1989, Potential for aquifer compaction, land subsidence, and earth fissures in Avra Valley, Pima and Pinal Counties, Arizona: U.S. Geological Survey Hydrologic Investigations Atlas HA-718.

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

Clarke, C.W., 1966, The geology of the El Tiro Hills, West Silver Bell Mountains, Pima County, Arizona [M.S. thesis]: Tucson, University of Arizona, 51 p.

Davis, S.R., 1977, Geology and Geochemistry of North Silver Bell: (Unpublished ASARCO, Inc. manuscript and map).

Dockter, R.D., 1977, Mount Lord Volcanics, Pima County, Arizona, in Changes in stratigraphic nomenclature by the U.S. Geological Survey: U.S. Geological Survey Bulletin 1435-A, p. A117-A120.

Eastwood, R.L., 1970, A geochemical-petrological study of mid-Tertiary volcanism in parts of Pima and Pinal Counties, Arizona [Ph.D. dissertation]: Tucson, University of Arizona, 212p.

Galey, J., and Henrickson, R., 1976, Geologic Map of the Silver Bell district: (Unpublished ASARCO, Inc. map).

Graybeal, F.T., 1982, Geology of the El Tiro area, in Titley, S.R., ed., Advances in the geology of the porphyry copper deposits: University of Arizona Press, Tucson, p. 487-507.

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.

Hall, D.L., 1985, Stratigraphy and sedimentary petrology of the Mesozoic rocks of the Waterman Mountains, Pima County, Arizona [M.S. thesis]: Tucson, University of Arizona, 92 p.

Joseph, N.L., 1982, Epithermal veins in the Silver Bell district, Pima County, Arizona [M.S. thesis]: Tucson, University of Arizona, 52 p.

Kingsbury, H.M., Entwistle, L.P., and Schmitt, H., 1941, Geology and ore deposits of Silverbell, Arizona: (Unpublished ASARCO Inc. report), 86 p.

Le Bas, M.J., LeMaitre, R.W., Streckeisen, A., Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkalisilica diagram: Journal of Petrology, v. 27, p. 745-750.

Lipman, P.W., 1994, Geologic map of the Tucson Mountains caldera, southern Arizona: U.S. Geological Survey Miscellaneous Investigations Map I-2205.

Lipman, P.W. and Fridrich, C.J., 1990, Cretaceous caldera systems--Tucson and Sierrita Mountains: Arizona Geological Survey Special Paper 7, p. 51-65.

Lipman, P.W. and Sawyer, D.A., 1985, Mesozoic caldera fragments in southeastern Arizona: Geology, v. 13, p. 652-656.

Mauger, R.L., Damon, P.E., and Giletti, B.J., 1965, Isotopic dating of Arizona ore deposits: American Institute of Mining, Metallurgical, and Petroleum Engineers Transactions, v. 232, p. 81-87.

Oppenheimer, J. and Sumner, J., 1980, Depth-to-bedrock map, Basin and Range province, Arizona: University of Arizona, Laboratory of Geophysics, 1:1,000,000-scale.

Richard, K. and Courtright, J.H., 1954, Structure and mineralization at Silver Bell, Arizona: American Institute of Mining, Metallurgical, and Petroleum Engineers Transactions, v. 199, p. 1095-1099.

Richard, K. and Courtright, J.H., 1960, Some Cretaceous-Tertiary relationships in southeastern Arizona and New Mexico: Arizona Geological Society Digest, v. 3., p. 1-7.

Richard, K. and Courtright, J.H., 1966, Structure and mineralization at Silver Bell, Arizona, in Titley, S.R. and Hicks, C., eds., Geology of the porphyry copper deposits: University of Arizona Press, Tucson, p. 158-163.

Risley, R., 1987, Sedimentation and stratigraphy of the lower Cretaceous Amole Arkose, Tucson Mountains, Arizona: Arizona Geological Society Digest, v. 18, p. 215-228.

Sawyer, D. A.,1987, Late Cretaceous caldera volcanism and porphyry copper mineralization at Silver Bell [Ph.D. dissertation]: Santa Barbara, University of California, 400 p.

Steiger, R.H., and Jager, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p.359-362.

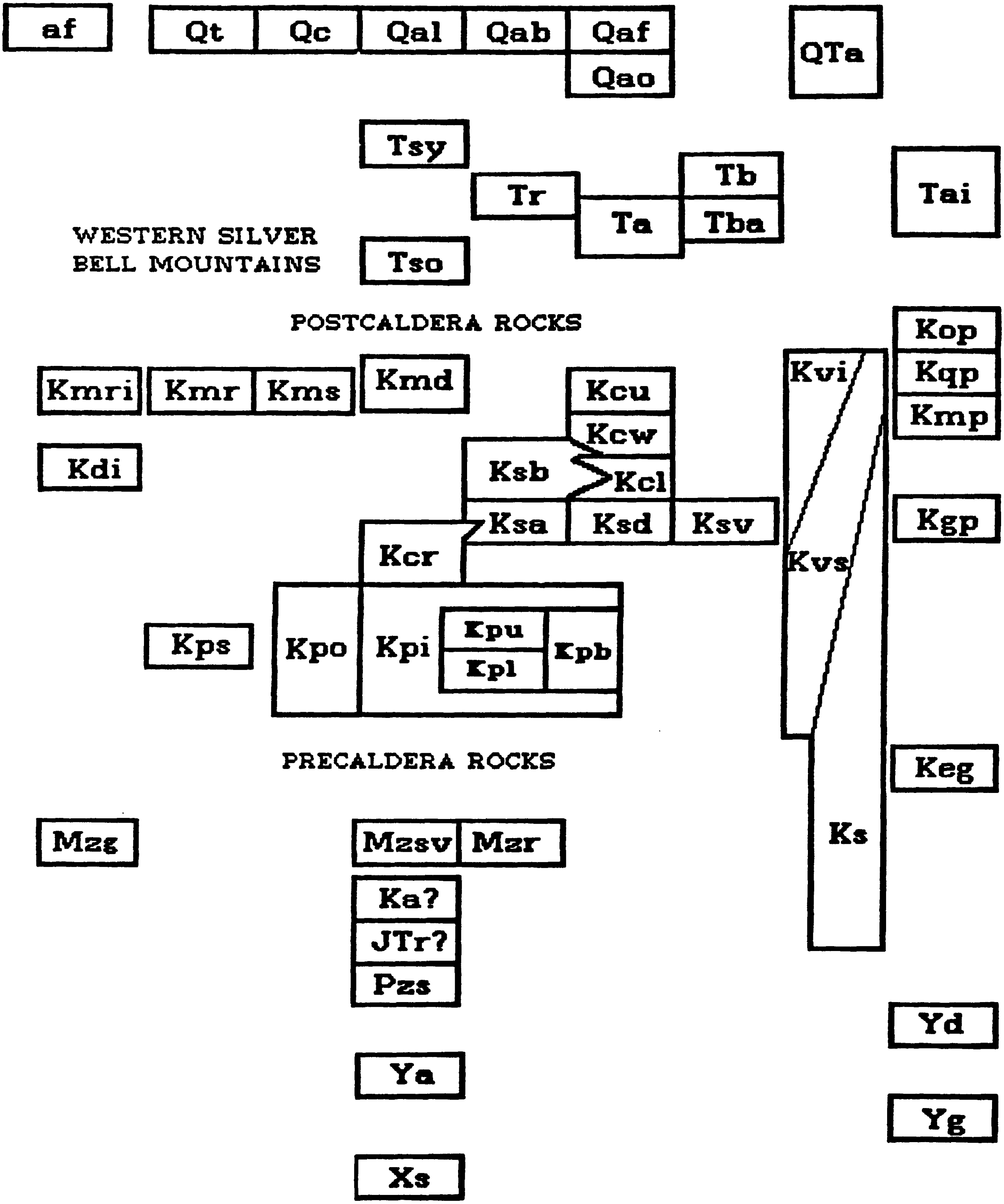
Streckeisen, A., 1976, To each plutonic rock its proper name: Earth Science Reviews, v. 12, p. 1-33.

Watson, B.N., 1964, Structure and petrology of the eastern portion of the Silver Bell Mountains, Pima County, Arizona [Ph.D. dissertation]: Tucson, University of Arizona, 168 p.

Watson, B.N., 1965, Areal geology of area east of Oxide pit: (Unpublished ASARCO, Inc. map)

Watson, B.N., 1968, Intrusive volcanic phenomena in southern Arizona, in Titley, S.R., ed., Southern Arizona Guidebook III: Arizona Geological Society, Tucson, Arizona, p. 147153.

Correlation of Map Units



MAP SYMBOLS

Contact--Dashed where approximate because covered by artificial fill (based on compilation by Galey and Henrickson, 1976).

Fault--Dashed where approximately located; dotted where concealed or intruded by plutonic rocks; queried where inferred. Bar and ball on downthrown side. Dip tick indicates measured dip and strike of fault. Triangles indicate fault-line scarp.

Fault zone (filled by gouge)--

Fault-vein--

Ring-fault zone--Dashed where approximately located.

Strike and dip of bedding--

55 Inclined

Vertical

Horizontal

85 Overturned

40 Fold axis and plunge of fold

Strike and dip of pumice compaction foliation in tuffs

43 Inclined

Vertical

12 36 Lineated tuff; lineation in the plane of foliation

Strike and dip of flow layering in volcanic rocks

Inclined

Vertical

Open-pit boundary

Thickness contour (800 feet) of Quaternary-Tertiary alluvial fill--based on gravity model of Oppenhemimer and Sumner (1980).

Exploratory drillhole

Figure 1: Sources of compiled geologic mapping

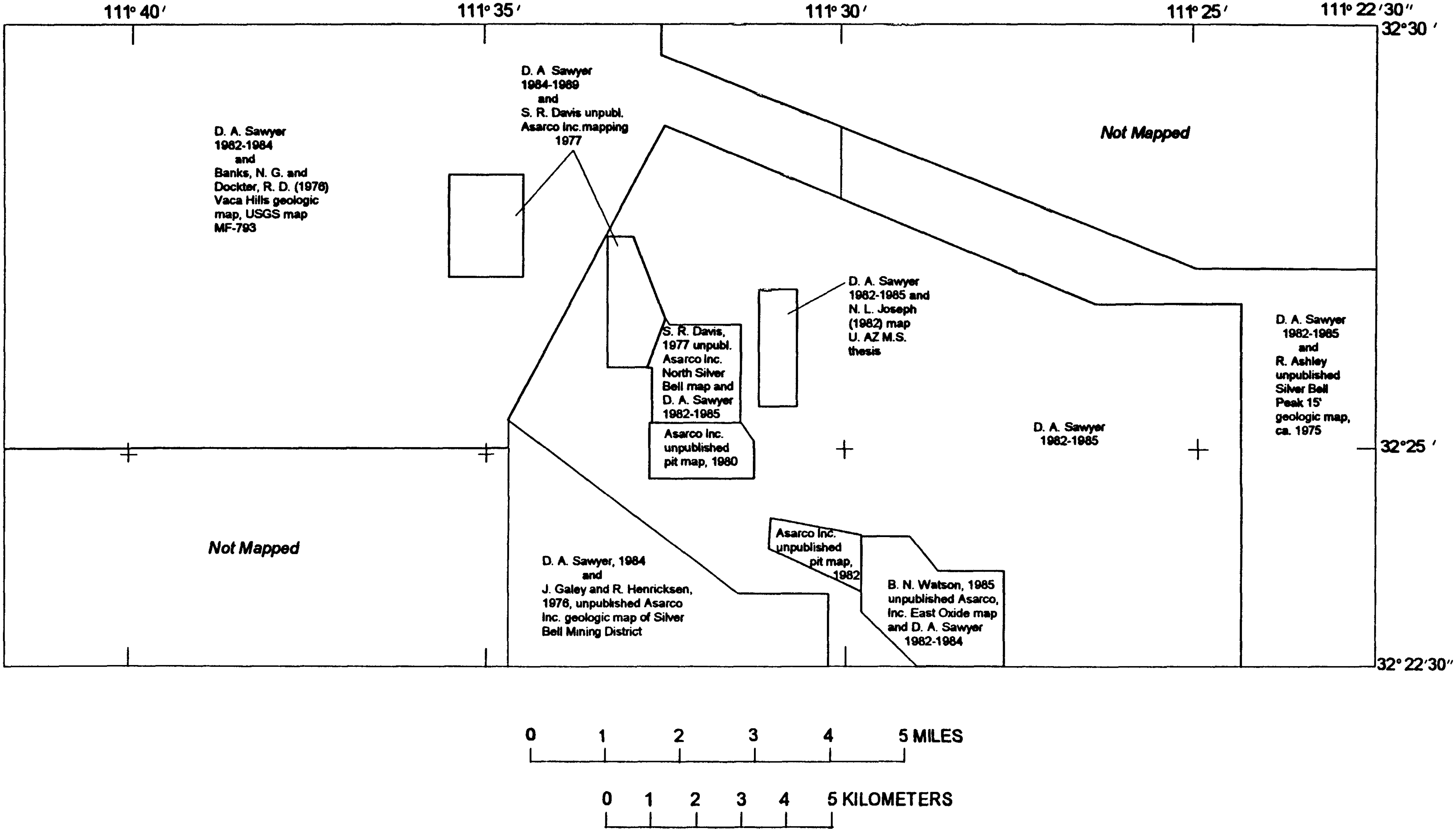
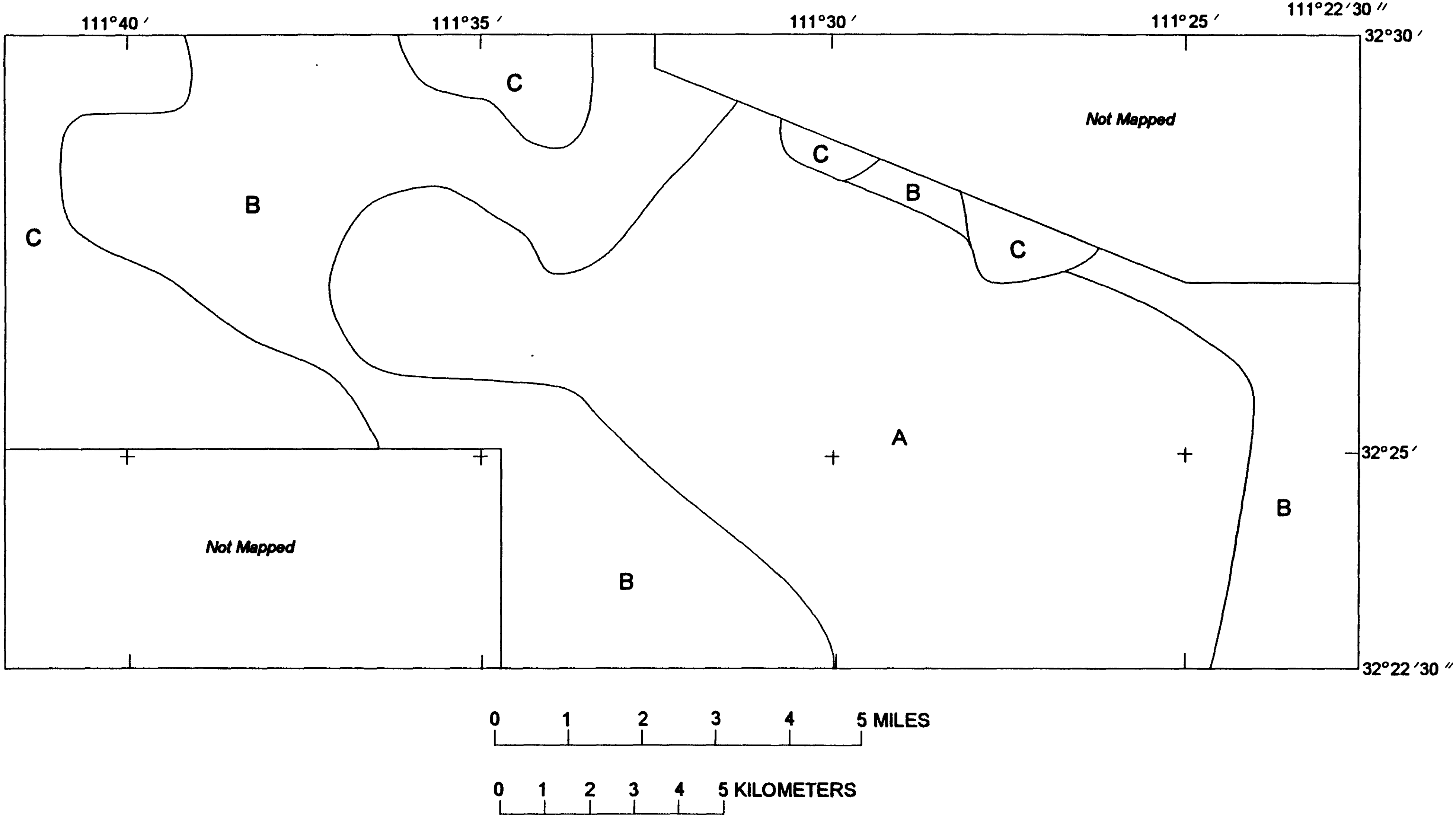


Figure 2: Index of geologic mapping reliability



A: Mapped by D. A. Sawyer, S. R. Davis, or B. N. Watson at scales > 1:24,000; contacts and faults located > 95% confidence; extensive laboratory chemistry and petrography.

B: Reconnaisance geologic mapping by D. A. Sawyer, N. G. Banks, R. D. Dockter, or R. Ashley at 1:24,000; extensive field checking, some laboratory chemistry and petrography; includes all Quatemary deposits and Galey and Henricksen, 1976.

C: Reconnaisance geologic mapping at scales smaller than 1:24,000; modified from N. G. Banks and R. D. Dockter (1976) or R. Ashley (unpublished data), sparse field checking, no laboratory follow-up.