

GEOLOGY AND MINERAL RESOURCES OF THE SIERRA ESTRELLA, MARICOPA COUNTY, ARIZONA

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INTRODUCTION

This report includes a geologic map (1:50,000 scale), description of rock units, and description of mineral deposits that were prepared as part of a Master of Science thesis project at Arizona State University in Tempe, Arizona. Preparation of this report included research of previous geologic work and geologic mapping. Mapping was done directly on a topographic base map at a scale of 1:24,000 and aerial photos were used as a field mapping aid. Field work was conducted between September 12, 1991 and May 1, 1992.

The Sierra Estrella is a northwest-trending mountain range consisting of a single compact ridge that is 38 km in length, and 5 to 7 km wide. The base of the range varies in elevation from 559 m above sea level near the confluence of the Gila and Salt Rivers in the north, to 788 m near the Gila River Indian Reservation boundary in the south. The highest elevations in the Sierra Estrella are an unnamed peak at 1375 m in the north-central part of the range and Montezuma Peak at 1323 m. This study covers approximately 165 km² of the Sierra Estrella. Approximately one-quarter of the study area lies within the boundaries of the Gila River Indian Reservation, and it was necessary to obtain a permit from the Gila River Indian Community Council to visit this area. The topography is extremely rugged and irregular, making the area accessible only on foot. However several unimproved dirt roads do extend to the base of the range on the east and west sides.

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PREVIOUS WORK

Early investigations of the Sierra Estrella consisted primarily of reconnaissance mapping and basic rock identification (Darton, 1925; Bryan, 1925; Darton, 1933). Bryan (1925) identified a Precambrian gneiss that comprised the bulk of the Sierra Estrella, with later intrusion of Mesozoic(?) granitoid rocks. The next generation of workers (Wilson et al., 1957; Wilson and Moore, 1959; Wilson, 1969; Wilson et al., 1969) expanded upon earlier work and identified the bulk of the range as Precambrian gneiss with minor amounts of Precambrian schist, and several small granitic plutons of Precambrian, Mesozoic, and Tertiary-Cretaceous(?) age. Paleozoic biotite K-Ar and Precambrian Rb-Sr dates were yielded by the southernmost granite (Pushkar and Damon, 1974) which refutes Wilson (1969) who believed the granite to be Mesozoic in age. The most recent work includes mapping of the northern Sierra Estrella (Sommer, 1982), which identified nine map units of various gneissic and granitic rocks. In addition, a helicopter traverse of the range (Spencer et al., 1985) and wilderness study area reports (Korzeb, 1988; Keith, 1989) have examined small portions of the study area in detail.

ROCK UNIT DESCRIPTIONS

Twelve map units were identified within the Sierra Estrella, as well as three rock units that are too areally restricted to show on the map (dikes and pegmatites). Each rock unit is described separately, and where appropriate broken down into subunits. Organization and relative ages of units are based on lithology and field relationships.

Young Quaternary Alluvium (Qy)

These deposits are of inferred latest Quaternary age (Holocene), and include channels and low terraces of small drainages, young alluvial fans, and broad terraces of major drainages. Surfaces are usually underlain by well sorted sand and silt with occasional gravel. Minimal soil development is characteristic. Surface clasts generally lack a dark coat of desert varnish. These units are shallowly dissected (<3 meters) by active channels.

Middle Quaternary Alluvium (Qm)

These deposits are of inferred early to middle Pleistocene age. Deposits are composed of well sorted sand, silt, and gravel. Sparse cobbles and boulders up to a meter in diameter are also present within these deposits. These surfaces are moderately dissected (3-6 meters) by active channels. Surface clasts are moderate to darkly varnished. Some soils are locally developed. This unit is most commonly well cemented by caliche.

Pegmatites

Numerous Tertiary pegmatitic dikes crop out in the Sierra Estrella. The pegmatites are abundant in all units except the Montezuma Granite, where they occur locally in the margins of the pluton. Intrusion of the pegmatites is both discordant along major fractures and concordant along foliation planes. The pegmatites range in thickness from 5 cm to 4 m, and are commonly approximately 100 m long. Several exceptionally thick pegmatites are up to 2 km long. Orientation of pegmatite dikes is roughly northwest-southeast and steeply dipping.

Compositionally the pegmatites consist of massive milky white quartz (65%-90%), large K-feldspar crystals up to 10 cm in diameter (10%-30%), and sericitized plagioclase (0%-25%). Locally the pegmatites contain several distinctive accessory minerals. Pegmatites in the pelitic schist and gneiss unit often contain numerous rounded red garnets up to 4 cm in diameter and books of muscovite and biotite up to 20 cm in diameter and 10 cm thick. Sparse crystals of light green beryl and black tourmaline are present in the pegmatites of the pelitic schist and gneiss unit. Pegmatites of the granitic and granitic gneiss units commonly contain chrysocolla staining and magnetite grains up to 4 cm in diameter.

Country rock adjacent to the pegmatite dikes is altered over a zone extending 1-10 meters from the edge of the dike. In the pelitic schist and gneiss unit the alteration is usually to a biotite, chlorite or muscovite schist. In the granitic rocks the alteration is to a granitic gneiss that is enriched in magnetite and sparse copper oxides.

Aplitic Dikes

Tertiary dikes of white fine- to medium-grained sugary textured aplite are found in abundance in all units except the Montezuma Granite, where they are sparse in the margins of the pluton. Intrusion of the aplite dikes is both discordant along major fractures and concordant along foliation planes. The

aprites range in thickness from 1-5 meters, are 100 meters to 2 kilometers long, and trend roughly northwest-southeast.

Composition of the aplite dikes is quartz (38%), plagioclase (33%), and alkali feldspar (29%). accessory minerals include secondary epidote and magnetite. Country rock is altered over a zone extending 1-10 meters from the edge of the aplite dikes. In the pelitic schist and gneiss unit the alteration is usually to a biotite, chlorite or muscovite schist. In the granitic rocks the alteration is to a granitic gneiss that is enriched in magnetite and occasionally copper oxides.

Mafic Dikes

Northwest-trending, medium-grained, grey-green to dark black dikes that is fine- to medium-grained cross-cut all units of Precambrian age throughout the range. Intrusion is discordant with local crystalloblastic foliation and contacts with the surrounding country rock are sharp and well defined. All dikes lack a strong foliation and seem to post-date deformation. The mafic dikes seem to be passively emplaced as indicated by the undeformed nature of foliation adjacent to the dikes and a general lack of drag folds.

The dikes can be divided into two populations. The small dike group consists of dikes 1-3 meters in width, 25 meters to 1 kilometer in length, and dipping 70° to 90° to the southwest. These dikes are typically fine grained and have compositions ranging from basaltic to amphibolitic.

The large dike group is generally 3-6 meters in width, 1/2 to 5 kilometers in length, and dipping 40° to 60° to the southwest. The aphanitic margins of these dikes grade into a medium to coarse grained interior of amphibole-pyroxene gabbro that consists of plagioclase (30-65%), pyroxene and amphibole (25-45%), quartz (0-5%), clinopyroxene (0-5%), and olivine (0-1%) with minor chlorite, muscovite, and magnetite. These large dikes also contain subophitic zones with pyroxene crystals up to 5 cm in length. These diabase dikes are similar in composition, intrusive style, and general appearance to the 1100-Ma diabase intrusions of the Gibson Creek complex, Apache Group and Troy Quartzite.

Montezuma Granite (pEgr)

The Montezuma Granite crops out in the southern portion of the Sierra Estrella. This monzogranitic pluton is medium grained and nonporphyritic at its margins, but grades over a short distance to coarse grained and porphyritic towards the center. This unit is light tan in color on weathered surfaces and a light grey on fresh surfaces. The mode of this compositionally homogeneous granite, estimated from stained slabs and thin sections, is quartz (32%), alkali feldspar (31%), plagioclase (30%), and biotite (7%). The corresponding ternary plot indicates that this unit is a monzogranite. Accessory minerals include muscovite, sphene, zircon, magnetite, and allanite. Sparse epidote and chlorite were noted as secondary alteration. A distinctive characteristic of this rock is the presence of a scattered (5%), large rectangular alkali-feldspar phenocrysts, the largest of which are well zoned and up to 6 cm in length. Plagioclase and quartz grains are equigranular in size, ranging from 2-4 mm.

This pluton is typical of 1400 Ma granites in the region in terms of intrusive style, texture, gamma radiation levels, and rock composition. Xenoliths and a weak foliation are sparse in this pluton near the margins. The Montezuma Granite represents the youngest episode of Precambrian plutonism in the Sierra Estrella range.

Quartz Diorite/Tonalite (pEdt)

This dark-grey to light-grey massive quartz diorite/tonalite is found on the slopes south of Montezuma Peak in the Sierra Estrella. This pluton is medium grained on its margins and coarser grained towards

the center. Locally this unit has a weak foliation near the contact with other units. Weathered outcrops are a mottled black and brown color. Most outcrops are irregular, deeply weathered, and surrounded by large piles of grus. The mode, estimated from stained slabs and thin sections, is quartz (15-24%), plagioclase (70-75%), and biotite (6-10%). The corresponding ternary plot indicates that this rock ranges from a quartz diorite to a tonalite. Equigranular plagioclase and quartz grains range in size from 2-4 mm while biotite grains average 1 mm. The principle mafic constituent is biotite, although minor amounts of hornblende have been noted in some samples. Accessory minerals include muscovite, magnetite, ilmenite, allanite, sphene, zircon, and secondary epidote.

The pluton intrudes the micaceous schist and gneiss unit to the north, forming an injection zone up to 1/2 km wide. Numerous xenoliths of pelitic, calc-silicate, amphibolite, and granitic gneisses are found in this injection zone. However, xenoliths are found with less abundance through the entire unit. Most xenoliths are extensively folded and indicate a deformation event prior to intrusion. Xenoliths range in diameter from a few centimeters to large bodies tens of meters across. The larger bodies are less common and may be roof pendants. Average xenolith diameter is 10-35 cm. The abundance of xenoliths in the injection zone indicates shallow emplacement (8-17 km or shallower) in a brittle country rock, and that stoping was the main mechanism of magma emplacement.

White Granite (pEwg)

This equigranular leucogranite is fine- to medium-grained and strongly peraluminous. Compositionally this unit is a true granite. Estimated mode from hand samples and thin sections is quartz (30%), plagioclase (35%), orthoclase (25%), and garnet (1-5%) with minor muscovite, magnetite, apatite, sphene, and zircon. Average grain size is 1-3 mm. This unit is flow foliated and may be syntectonic to the regional Proterozoic deformation. Numerous xenoliths (up to more than 15m in diameter) of the surrounding units are incorporated into the margins of the white granite and contain a linear "entrainment flow" alignment. This unit was only found on the west-central side of the range in a large cluster of adjoined sheet-like intrusions. This rock may be equivalent to the Cotton Center Granite of the nearby Maricopa Mountains based on similar composition, weathering style, and deformation characteristics.

Foliated Alkali-Feldspar Granite (pEkg)

The Precambrian Foliated Alkali-Feldspar Granite is a suite of variably foliated granitic to granodioritic plutonic rocks that are medium to coarse grained and grey to pinkish-grey on fresh surfaces. Exposure is predominantly in the central part of the map area. The rock varies from a highly deformed, well foliated augen gneiss to an almost undeformed homogeneous granite-granodiorite. Weathered outcrops form spalling, spheroidally weathered tan to brown boulders that are surrounded by grus-covered slopes. This unit produces a lighter color soil than the surrounding migmatitic gneiss. This unit intrudes the older migmatitic gneiss and was probably emplaced during a period of intense deformation.

The compositional mode, estimated from hand samples and thin sections, is quartz (38-28%), alkali-feldspar (30-20%), plagioclase (35-29%), biotite (8-15%), and muscovite (<1%). Accessory minerals include allanite, apatite, sphene, hornblende, secondary epidote, and magnetite. A distinctive characteristic of this unit is a scattering (5-10%) of alkali-feldspar phenocrysts that are 0.5-7 cm in diameter, although small regions at the center of the plutons lack the phenocrysts. Where present, the phenocrysts are rectangular with slightly rounded corners in the less deformed exposures; and rounded to lenticular augen in the highly deformed outcrops. This unit contains numerous inclusions of the surrounding Migmatitic Gneiss and Amphibole Gneiss. These inclusions occur as thin, elongate sheets up to 10 meters in length. Local small, rounded xenoliths up to 1/2 meter in diameter are also present.

This unit is quite similar to the Komatke Granite of the adjacent South Mountains in lithology,

weathering style, deformation style, gamma radiation levels, and general appearance. Both rock units are on strike with each other across the Gila River valley.

Mafic Intrusions (p€mi)

The Precambrian Mafic Intrusions crop out in two locations in the northwest part of the map area. This dark green to black rock consists of plagioclase (35-45%), actinolite (25-35%), magnetite (5-10%), epidote (10%), biotite (5-10%), and chlorite (0-5%), with minor clay minerals. Relict crystal structures indicate that the fibrous actinolite replaced primary olivine or pyroxene. The entire unit has undergone extreme retrogressive alteration. Mineralogy indicates a gabbro may have been the protolith.

This unit has a high specific gravity and forms low, rounded outcrops of deeply weathered rock. A weak foliation exists throughout the entire unit, with localized areas of intensely altered and foliated rock. These areas have a strong phyllitic foliation and have undergone extensive clay alteration.

Old Granitic Gneiss (p€og)

The Old Granitic Gneiss is strongly foliated to massive. Weathered outcrops are low, blocky, and dark grey to dark brown due to desert varnish. Fresh surfaces are light- to dark-grey. This Precambrian unit is discordantly cut by numerous small bodies of Amphibolite Gneiss. Composition of the Old Granitic Gneiss is plagioclase (30-40%), alkali-feldspar (2--35%), quartz (15-25%), biotite (5-15%), and retrogressive muscovite (0-3%). Accessory minerals include chlorite, magnetite, sphene, and secondary epidote. Protolith is uncertain due to the high metamorphic grade and a general lack of relict features, but may be plutonic based on mineral compositions and weak mineral textures observed.

This unit seems to have intruded the migmatitic gneiss in places. The local severity of deformation and structural relationships indicate this unit was emplaced before regional deformation. The contacts between the Migmatitic Gneiss and the Old Granitic Gneiss are consistently difficult to accurately locate, as the two units grade into each other over a distance of 50-100 meters, and most original contact relations have been obliterated. Occasional bodies of swirled and migmatized Old Granitic Gneiss also exist within the Migmatitic Gneiss unit, which adds to difficulties in separating the two units.

Migmatitic Gneiss (p€mg)

The Precambrian Migmatitic Gneiss is an undifferentiated unit mainly composed of interlayered migmatitic rock with minor Quartzofeldspathic Gneiss, Old Granitic Gneiss, Amphibole Gneiss, Marble, and Biotite-Muscovite Schist and Gneiss. This unit usually forms serrated ridges of dark colored jagged rock in the central and northern portion of the map area. The weathered surfaces are thickly coated with desert varnish. Layering within the unit ranges from 1 cm to greater than 10 meters. This unit has a well defined crystalloblastic foliation imparted by compositional layering and alignment of micas. Small scale folds and other structures < 1m across are locally common.

The Migmatitic Gneiss contains thin layers of other major units seen elsewhere in the range and bodies of the Amphibole Gneiss and the Marble units that are large enough to show on the map. The Amphibole Gneiss and Marble units are only found within the Migmatitic Gneiss.

The migmatitic sub-unit is light- to dark-grey on fresh surfaces. Modal composition varies locally, but usually is one-third quartz and two-thirds feldspar. Muscovite, biotite, hornblende, secondary epidote, and magnetite comprise less than 10% of the total rock. This fine to medium grained unit has local sheet-like intrusions of the Foliated Alkali-Feldspar Granite up to 5 meters in diameter. The migmatite has layering that is usually swirled and intensely deformed; the most intensely deformed areas are adjacent to intrusions of the Foliated Alkali-Feldspar Granite. Some areas, especially in the northern

portion of the map area, have very well developed layering that may represent relict bedding. The protolith of the migmatite sub-unit is uncertain due to the high metamorphic grade and a general lack of relict features, but may be sedimentary based on the highly variable mineral compositions.

Amphibole Gneiss (pEag) -- The Amphibole Gneiss sub-unit of the Migmatitic Gneiss is composed of interlayered amphibolite, massive quartz, and minor biotite-muscovite schist and gneiss. This unit is typically concordant with the foliation of the surrounding Migmatitic Gneiss, but is locally discordant. Layers of the subunits are typically approximately 1/2 to 2 meters thick. Mapped areas of this rock unit are simply the larger bodies of Amphibole Gneiss within the undifferentiated Migmatitic Gneiss unit.

The amphibolite is grey to black on both fresh and weathered surfaces, and is fine grained. Composition is hornblende (45-90%), plagioclase (5-35%), quartz (0-20%) and biotite (0-10%). Accessory minerals include minor chlorite, actinolite, apatite, magnetite, and zircon. Hornblende is usually subhedral and 1-5mm in length. Parallel alignment of hornblende and biotite define foliation. Layers within the amphibolite are 1-10 cm thick and remarkably homogeneous along the strike of foliation. This sub-unit weathers to produce a rich black sand and flat, low grus-covered outcrops.

Massive quartz is coarse grained with no visible accessory minerals. White to light-grey in color, these layers of quartz within the amphibolite are massive and homogeneous. Layers of this subunit are typically 1/2 to 2 meters thick. The massive quartz is more resistant than the surrounding amphibolite and forms ridges up to 2 meters high. Composition is quartz (70-90%), alkali feldspar (5-15%), and plagioclase (5-15%).

Minor Micaceous Schist and Gneiss are also associated with this unit at its contacts with the surrounding Migmatitic Gneiss. The amphibolite and massive quartz probably represent metamorphosed mafic intrusions in the form of sills and quartz veins.

Marble (pEmb) -- The Marble sub-unit of the Migmatitic Gneiss is a light-tan to brown on both weathered and fresh surfaces, and is fine to medium grained. These marbles and associated calcareous rocks exhibits compositional banding on the scale of 1-5 cm and form layers up to 30 meters thick. Weathered surfaces have a distinctive "elephant skin texture" that highlights compositional banding. The marble is impure, containing quartz (0-20%) and alkali feldspar (0-5%) in addition to calcite and dolomite. Accessory minerals within the marble and associated calcareous rocks include minor garnet, epidote, muscovite, subhedral sphene, diopside, and tremolite. Soils surrounding these outcrops tend to be very well cemented with caliche. Only a few exposures of this unit were large enough to be mapped, and many smaller outcrops of the rock exist within the Migmatitic Gneiss unit.

Micaceous Schist and Gneiss (pEms)

The Micaceous Schist and Gneiss unit is broken up into two sub-units. This rock may be part of the Pinal Supergroup based on lithology, weathering style, and deformation style. Pinal schist is normally a greenschist-grade rock of uniform lithology, but metamorphic grade can be locally elevated to amphibolite-grade near batholiths (e.g., The Table Top and Javelina Mountains near the Maricopa batholith). The lithologic uniformity of the Micaceous Schist and Gneiss also links it to the Pinal Schist, which is uniform over large regions.

Quartzofeldspathic Schist and Gneiss -- This massive fine grained rock is light- to dark-grey in color and varies locally from a gneiss to a schistose gneiss. Parallel orientation of micas defines schistosity, while gneissic layering is defined by both gradational changes in mineralogy and small fine- to coarse-grained veins of quartz and feldspar. The veins are abundant through most of the unit, run parallel to foliation, have sharp contacts with the country rock, and range from

1/2 to 4 cm thick. Ptygmatic folds are present in these pegmatitic to aplitic veins. Modal composition is quartz (30-35%), feldspar (40-60%), biotite (8-20%), and muscovite (0-5%) with minor epidote, magnetite, zircon, and ilmenite. This unit rarely has strong layering on the order of 1-10 cm, and more commonly is homogeneous and massive with weak to nonexistent layering. Protolith for these rocks is most likely a muddy arkose sandstone.

Biotite-Muscovite Schist and Gneiss -- These pelitic schists and gneisses are composed mainly of plagioclase (30-40%), quartz (15-40%), biotite (5-20%), and muscovite (2-15%). Almandine garnet is commonly present in the pelitic rocks (1-20%) and usually forms rounded porphyroblastic grains up to 1.7 cm in diameter. Sillimanite is the only aluminum silicate present in the pelites, and it occurs in two varieties. The first variety occurs as fibrous needles up to 0.7 mm long, while the second generation of sillimanite occurs as coarse-grained mats of various sizes. A few samples have a high (2-10%) carbonate content and exhibit a "pitted" texture on weathered surfaces. Accessory minerals include apatite, zircon, alkali-feldspar, tourmaline, and magnetite. Minor amounts of the secondary minerals epidote, sericite, and chlorite are also present.

Foliation in these pelites is defined by the long axis of quartz and feldspar, and the parallel alignment of the micas and sillimanite needles. In the pelitic gneiss the segregation of mafic minerals and quartz+plagioclase imparts gneissic banding.

Based on the assemblage of minerals present, the protolith of the pelitic schists and gneisses is inferred to be a shale or sandy mudstone with scattered carbonates.

ECONOMIC GEOLOGY

Nonmetallic Resources

Sand and Gravel.— Young Quaternary sands and gravels (Qy in Fig. 1) are by far the most abundant commercial resource. These reserves are present in washes and as surrounding overbank deposits. These deposits have been historically exploited on a very small scale as a construction aggregate and as landscaping material. However the overall abundance of similar types of deposits within the greater Phoenix area and transportation costs make this resource of limited value for local construction only. The areas of middle alluvium (Qm in Fig. 1) are not suitable for sand and gravel extraction as these deposits are well cemented by caliche with depth.

Quartz.— Many pegmatites in the Sierra Estrella are a source of very pure quartz. This quartz may be suitable for use as smelter flux, roofing granules, and landscaping material. However, like most deposits within the Sierra Estrella, the problem of expensive transport from the rugged range to market makes this commodity marginally profitable at best.

Dimension Stone.— The Montezuma Granite in the southern Sierra Estrella is well suited for use as a decorative dimension stone. This hard, unaltered, and attractive stone has an appealing light pink to tan color. This stone may also have use as rip-rap. Since this resource is located adjacent to a well maintained dirt road it may be profitable as potential quarry sites can be easily reached. The local demand for this product and market price would be the overriding factors determining profitability.

Feldspar.— The occurrence of large feldspar masses in the pegmatites of the Sierra Estrella may also be of commercial interest. Feldspar is used in mild abrasives, high-temperature ceramic production, and the manufacture of vitrified products. The small tonnages available and the difficult accessibility of the deposits make production of this resource a currently unfavorable venture.

Mica.— Commercial grade mica is found within the pegmatites and metamorphic rocks of the Sierra Estrella. These deposits have been worked in the past with marginal success (Krasen et al, 1982). The

pegmatites contain muscovite books up to 20 cm square and 10 cm thick. This mica splits well but up to 50% is bent, twinned, and contains magnetite grains that make it unsuitable for use as sheet mica. Though this mica is unsuitable for sheet mica, it can be used as a source of flake mica. Flake mica is ground to a mesh size of 80 to 325 and is used in the manufacture of cements, drilling mud, reflective paint, welding rods, and asphalt shingles. Muscovite schist surrounding the pegmatites is also a good source of flake mica. Analysis of the schist (Wilson, 1969) indicated that the rock is composed of up to 21.8 percent muscovite. Current commercial grade mining of flake mica is usually of rock that is > 50 percent mica.

Overall, the pegmatitic mica is to sporadic in occurrence and the schist is of too low a grade to warrant mining at 1991 prices (Table 1). There have been historical efforts to produce mica at two locations within the Sierra Estrella none-the-less, as well as several mica prospects (Table 2).

Beryl.- Beryl crystals up to 10 cm in diameter and 26 cm long have been found within the pegmatites of the Sierra Estrella. These light green beryl crystals are rare and only found within a few of the larger pegmatites. Beryl is a source of beryllium which is used in some ceramics, electronics, metal alloys, and nuclear reactors to moderate neutrons. Because of the scarcity of beryl within the pegmatites and the current low demand for beryllium, these deposits have little prospect for development.

Garnet.- Red euhedral garnets up to 4 cm in diameter and anhedral garnet masses up to 10 cm in diameter are found within pegmatites of the Sierra Estrella. Garnets are also found scattered through some of the pelitic rocks. Garnet is a popular semi-precious stone, but the garnets of the Sierra Estrella are not of gem quality due to numerous mineral inclusions. Garnet also has industrial uses as an abrasive agent. The garnet however is not found in abundance to compete with other larger and more accessible deposits that currently supply the limited market.

Tourmaline.- Black tourmaline crystals up to 4 cm in diameter and over 30 cm in length comprise up to 2 percent of some pegmatites within the Sierra Estrella. This tourmaline is not of gem quality, but may be considered a potential resource if it is found to possess favorable piezo-electric properties. The tourmaline is hard, and cuts and polishes well. There is unfortunately no current domestic market for tourmaline that is of less than gem quality.

Metallic Resources

Copper.- All observed copper within the Sierra Estrella occurs as copper oxides within the pegmatites and surrounding countryrock. Copper values range up to 8,950 parts per million (ppm) (Keith et al, 1989) but only in small discontinuous lenticular bodies in the pegmatites. As a result, the copper contained within the pegmatites would be costly to exploit. When this consideration is combined with the low tonnages of ore present, the Sierra Estrella presents itself as an unfavorable prospect for copper production.

Gold and Silver.- Pegmatites of the Sierra Estrella contain an average of 15 to 40 parts per billion (ppb) gold with one pegmatite reportedly containing up to 23 parts per million (ppm) gold and 13.5 (ppm) silver (Korzeb, 1988). While most of the pegmatites are not presently an economically feasible source of gold or silver, they do provide a good source for gold placer deposits.

Since 1980 there have been over 75 placer claims located in the alluvium on the western side of the Sierra Estrella. These claims have not been worked beyond a few exploration trenches (as of 1991). Gold in these placers reportedly averages 0.1 oz/st (Sevenmile Mining Association, Tempe, Arizona, oral communication, 1987).

MINING HISTORY

The proximity of early transcontinental travel routes indicate that the Sierra Estrella was probably explored and prospected prior to 1868. In 1868 the U.S. Land Office noted that several partially developed copper mines were located in T. 3 S., R. 2 E. In 1920 there were nine lode claims filed for the same township and range (U.S. Mineral Surveys No. 3657 and 3658) which indicated development was restricted to a small stope, discovery cuts, and a few shallow pits. No other records were found that discuss mining activity in the Sierra Estrella prior to 1920. Descriptions of other undated workings and workings postdating 1920 are given in the site descriptions. The Estrella mineral district, which includes mines near Montezuma Peak, has recorded production of 2,000 lbs of copper and minor gold and silver in 1937 (Keith et al., 1983). This district includes mines #11, #12, and #13 (Figure 2) and recorded production was probably from the Sunrise Mine (#13 in Figure 2).

SITE DESCRIPTIONS

The following section describes in detail the workings and geology of the major prospect diggings in Table 2. Location of these sites is denoted on Fig. 2 by the corresponding ID number from Table 2. Additional information on some sites is available on file at the Arizona Department of Mines and Mineral Resources under the appropriate AZMILS number.

#4 Unknown 3 Prospects

AZMILS I.D. #: 456a County: Maricopa
Township: 3 S Range: 1 E Section: 2 Quarter: SE

Site Description:

3 prospect pits, each 1x2 meters by 3 meters deep are located in two 1/2 meter wide pegmatitic dikes of approx. 20 meter length. The pegmatites discordantly intrude a fine-grained early proterozoic quartz + feldspar + biotite + muscovite gneiss with locally schistose areas. Crystalloblastic foliation is 030°, 48° SE. The countryrock is homogeneous for hundreds of meters surrounding the site, and is believed to have a muddy quartzofeldspathic sandstone protolith. The pegmatites strike north and dip 75° W. No signs of recent activity were seen.

Economic Mineralization:

The pegmatite contains quartz + feldspar + biotite + muscovite + garnet. Small amounts of chrysocolla and possibly other copper oxides stain the surrounding gneiss to about a 1 meter radius of the pegmatite. Highest concentration of copper oxides is within the quartz of the pegmatite. Small irregular shaped bodies (< 1 cm diameter) of pure chrysocolla were also noted within the quartz.

#5 Unknown 3 Prospects

AZMILS I.D. #: 456b County: Maricopa
Township: 3 S Range: 1 E Section: 2 Quarter: NW

Site Description:

In addition to the 3 pits shown on the Montezuma Peak Quadrangle, 4 other pits were located. Pits are all 1x2 meter openings that vary from 1/2 to 2 meters depth. Pits are centered on 2 pegmatites (098°, 32° NE and 101°, 19° NE) that discordantly intrude a fine-grained early proterozoic quartz + feldspar + biotite + muscovite gneiss with locally schistose areas. Crystalloblastic foliation is 130°, 40° SW. The countryrock is homogeneous for hundreds of meters surrounding the site, and is believed to have a muddy quartzofeldspathic sandstone protolith.

Economic Mineralization:

The pegmatite contains quartz + feldspar + biotite + muscovite + garnet + tourmaline. No copper

mineralization was noted, but abundant 4x4x1 cm books of muscovite are present. Books are often flawed and contain opaque (magnetite?) inclusions.

#6 Crusher Mica Quarry

AZMILS I.D. #: 457 County: Maricopa
Township: 3 S Range: 1 E Section: 2 Quarter: NW

Site Description:

Five additional pits and a trench not shown on the Montezuma Peak Quadrangle were located. Pits are all 1x2 meter openings that vary from 1/2 to 2 meters depth. The trench is 4 meters long and 1/2 meter deep by 1 meter wide. 3 pits and the trench are centered on 2 pegmatites trending 003°, 85°E and 005°, 88°E. An epidotized fault plane (007°, 42° W) extends through the saddle, 1 pegmatite, and a pit. Pegmatites discordantly intrude a fine-grained early proterozoic quartz + feldspar + biotite + muscovite gneiss with locally schistose areas. Crystalloblastic foliation ranges from 173°, 42° NW to 138°, 12° SE. The countryrock is homogeneous for hundreds of meters surrounding the site, and is believed to have a muddy quartzofeldspathic sandstone protolith. The Crusher mica quarry shows no signs of recent activity. A road leads up to the old loading dock where there are the remains of an old loading bin, crusher, and screen sieves. A 1 meter pile of crushed and sieved mica remains at this location. Three terraces, 3 shallow 1x1x1 meter pits, and 2 large cuts (3x4x2 meters and 7x3x2 meters) comprise the quarry. Last production seems to have been in the late 1950's (Krasen et al, 1982).

Economic Mineralization:

The pits and trench on the pegmatite contains quartz + feldspar + biotite + muscovite + garnet + tourmaline. No copper mineralization was noted, but abundant 4x4x1 cm books of muscovite are present. Books are often flawed and contain opaque (magnetite?) inclusions. The crusher quarry production seems to have been centered around zones of coarse mica schist that are 3+ meters wide. The mica flakes tend to comprise 25% + of the rock in this zone, and flakes average 1-2 cm in diameter. Flakes tend to be irregularly shaped, flawed, and crumpled.

#7 Unknown-2 prospects

AZMILS I.D. #: 458 County: Maricopa
Township: 3 S Range: 1 E Section: 12 Quarter: SW

Site Description:

Field visit to site revealed 2 prospect pits in a stream drainage. Pits are within 2 meters of each other and have been partially filled in with sandy stream sediment. Pit dimensions are 1 1/2 by 2 meters, and 1 meter deep. Original pit depths are unknown due to stream sediment infilling. Pits are centered on a concordantly intruded quartz + feldspar pegmatite 1 1/2 meters wide, 10+ meters in length, and striking 005° and dipping 32° SE. The surrounding countryrock is a fine-grained early proterozoic quartz + feldspar + biotite + muscovite gneiss with locally schistose areas. Foliation is 008°, 31° SE. The countryrock is homogeneous for hundreds of meters surrounding the site, and is believed to have a muddy quartzofeldspathic sandstone protolith.

Economic Mineralization:

Small amounts of chrysocolla and possibly other copper oxides stain the surrounding gneiss to about a 1 meter radius of the pegmatite. Highest concentration of copper oxides is within the quartz of the pegmatite. Small irregular shaped bodies (1-3 cm diameter) of pure chrysocolla were also noted within the quartz.

#9 MacKenzie

AZMILS I.D. #: 686 County: Maricopa

Township: 2 S Range: 1 E Section: 33 Quarter: E

Site Description:

Field visit to site revealed numerous prospect pits that been mostly filled in with sandy sediment. Pits are centered on a discordantly intruded quartz + feldspar pegmatites 1/2 to 1/4 meter wide, 5+ meters in length, and striking 064° and dipping approx 80° NW. The surrounding countryrock is a fine-grained early proterozoic quartz + feldspar + biotite + muscovite gneiss with locally schistose areas. Crystalloblastic foliation is 042°, 75° NW. The countryrock is homogeneous for hundreds of meters surrounding the site, and is believed to have a muddy quartzofeldspathic sandstone protolith. The countryrock is altered approximately 2+ meters from either side of the pegmatite. Average pit dimensions are 1 1/2 by 2 meters, and 1 meter deep. The exceptions are two pits in the saddle that are 1x1x3 meters deep. Original pit depths are unknown due to sediment infilling. Small piles and scattered samples of chrysocolla stained quartz are located around the pits.

Economic Mineralization:

Most pits contain small amounts of chrysocolla and possibly other copper oxides that stain the surrounding altered countryrock to about a 1 meter radius of the pegmatite. Highest concentration of copper oxides is within the quartz of the pegmatite. Small irregular shaped bodies (1-3 cm diameter) of pure chrysocolla were also noted within the quartz. One location has copper oxide mineralization that is 5-6% of the rock, and composed of small irregular shaped bodies (3-6 cm diameter) of pure chrysocolla disseminated throughout a zone for 1/2 meter surrounding the pegmatite.

#10 Butterfly Mt. mica deposit

AZMILS I.D. #: 248 County: Pinal
Township: 2 S Range: 2 E Section: 19 Quarter: SW

Site Description:

A prospect shaft (shown as an adit on the Montezuma Peak quadrangle topographic sheet) extends about 8-9 meters into a pegmatitic dike. The pegmatite discordantly intrudes a fine-grained early proterozoic quartz + feldspar + biotite + muscovite gneiss with locally schistose areas. Crystalloblastic foliation is 012°, 29° SE. The countryrock is homogeneous for hundreds of meters surrounding the site, and is believed to have a muddy quartzofeldspathic sandstone protolith. The pegmatite strikes 135°, 75° SW and is approximately 2 meters wide at the shaft. The pegmatite lenses out 11 meters to the southeast and 17 meters to the northwest of the shaft.

Economic Mineralization:

The pegmatite contains quartz + feldspar + biotite + muscovite + garnet. The books of biotite are small and sparse, while the muscovite books are up to 10 cm long by 8 cm wide, by 5 cm thick. The books of muscovite are irregular shaped, flawed, and fairly plentiful in a zone 1/2 meter wide adjacent to the footwall. Garnets are less than 1 cm in diameter, grossular to spess. In composition, and highly fractured and retrogressively metamorphosed.

#13 Sunrise Claim

AZMILS I.D. #: 249c County: Pinal
Township: 3 S Range: 2 E Section: 6 Quarter: SE

Site Description:

Field visit to site revealed the remains of a small hand-made aerial tram. The rusted cables and rotted poles of the tram extend along the trail from the former loading bin to the mine site. Ore samples were found in abundance at the old loading bin and all along the tram route. At the mine site a prospect pit measuring 2x2x1 meters and an adit 2 meters high and 2 meters wide extends inward approximately 18 meters. The adit was driven into the hanging wall zone of a discordantly intruded quartz pegmatite that is 3 meters wide, 25+ meters in length, striking 134°, and dipping 48° SW. At the back of the adit the

pegmatite narrows to 30 cm. No recent work on the adit was evident, and the entrance was partially collapsed. The pegmatite is coarsely crystalline, vitreous, colorless to white, brecciated body. The surrounding countryrock is a fine-grained early proterozoic quartz + feldspar + biotite + muscovite gneiss with locally schistose areas. Foliation is 058°, 34° SE. The countryrock is homogeneous for hundreds of meters surrounding the site, and is believed to have a muddy quartzofeldspathic sandstone protolith.

Site History and Economic Mineralization

The site was apparently active prior to 1868, based on a U.S. Land Office report of that year which states that "Several copper mines, as yet but partially developed" were located at the site (See also AZMILS I.D. # 249a, 249b, 250b, and 250c). In 1920 a lode claim was surveyed at the site, but not patented. The same claim was resurveyed in 1922. Both surveys were performed by the Sacaton Copper Company. In April of 1963 an investigation of the site revealed no recent improvements to the site. The same study yielded ore samples from the back of the adit which assayed as follows:

3% Copper

0.22 Ounce per ton Gold

0.35 Ounce per ton Silver

Small amounts of chrysocolla and possibly other copper oxides stain the surrounding gneiss to about a 1 meter radius of the pegmatite. Highest concentration of copper oxides is within the hanging wall of the quartz pegmatite. Small irregular shaped bodies (1-5 cm diameter) of pure chrysocolla, limonite, and hematite were also noted within the quartz.

#14 Sunset Claim

AZMILS I.D. #: 250a

County: Pinal

Township: 3 S

Range: 2 E

Section: 20

Quarter: NE

Site Description:

Field visit to site revealed evidence of possible minor excavations that are centered on several discordantly intruded quartz + feldspar pegmatites 1/2-1 meter wide, 10+ meters in length, and striking N-S and dipping SE. The surrounding 1.6 billion year old quartz diorite countryrock is altered approximately 15+ meters from either side of the pegmatites. Small pieces of chrysocolla are located in small scattered piles in this area.

Economic Mineralization:

Small amounts of chrysocolla and possibly other copper oxides stain the surrounding altered quartz diorite up to a 1 meter radius of the pegmatite. Highest concentration of copper oxides is within the quartz of the pegmatite. Small irregular shaped bodies (1-3 cm diameter) of pure chrysocolla were also noted within the quartz.

#15 Little Minnie Claim

AZMILS I.D. #: 250b

County: Pinal

Township: 3 S

Range: 2 E

Section: 17

Quarter: SE

Site Description:

Field visit to site revealed a prospect pit that been mostly filled in with sandy sediment. Pit is centered on a concordantly intruded quartz + feldspar pegmatite 1/2 meter wide, 5+ meters in length, and striking 007° and dipping approx 50° SE. The surrounding 1.6 billion-year-old quartz diorite country rock is altered approximately 15+ meters from either side of the pegmatite. Pit dimensions are 1 1/2 by 2 meters, and 1 meter deep. Original pit depth is unknown due to sediment infilling. A small pile and scattered samples of chrysocolla stained quartz are located around the pit.

Economic Mineralization:

Small amounts of chrysocolla and possibly other copper oxides stain the surrounding altered quartz diorite to about a 1 meter radius of the pegmatite. Highest concentration of copper oxides is within the

quartz of the pegmatite. Small irregular shaped bodies (1-3 cm diameter) of pure chrysocolla were also noted within the quartz.

#16 La Cruz Claim

AZMILS I.D. #: 250c County: Pinal
Township: 3 S Range: 2 E Section: 17 Quarter: NE

Site Description:

Field visit to site revealed a prospect pit that has been partially filled in with sandy sediment. Pit is centered on a concordantly intruded quartz + feldspar pegmatite 1 meter wide, 10+ meters in length, and striking 008° and dipping 41° SE. The surrounding 1.6 billion-year-old quartz diorite country rock is altered approximately 15+ meters from either side of the pegmatite. Pit dimensions are 1.5 by 2 meters, and 1 meter deep. Original pit depth is unknown due to sediment infilling.

Economic Mineralization:

Small amounts of chrysocolla and possibly other copper oxides stain the surrounding altered quartz diorite to about a 1 meter radius of the pegmatite. Highest concentration of copper oxides is within the quartz of the pegmatite. Small irregular shaped bodies (1-3 cm diameter) of pure chrysocolla were also noted within the quartz.

#18 Unknown

AZMILS I.D. #: None County: Maricopa
Township: 1 S Range: 1 W Section: 27 Quarter: NE

Site Description:

2 prospect pits, each 1x2 meters by 3 meters deep are located in a 1/2 meter wide pegmatitic dike of approximately 20 meter length. The pegmatite discordantly intrudes a fine-grained early proterozoic quartz + feldspar + biotite + muscovite gneiss with locally schistose areas. Crystalloblastic foliation is 061°, 64° SE. The country rock is homogeneous for hundreds of meters surrounding the site, and is believed to have a muddy quartzofeldspathic sandstone protolith. The pegmatite strikes 004° and dips 77° W. No signs of recent activity were seen, but a pile of rotten timbers and a broken ladder into one of the pits remain.

Economic Mineralization:

The pegmatite contains quartz + feldspar + biotite + muscovite + garnet. Small amounts of chrysocolla and possibly other copper oxides stain the surrounding gneiss to about a 1 meter radius of the pegmatite. Highest concentration of copper oxides is within the quartz of the pegmatite. Small irregular shaped bodies (1-3 cm diameter) of pure chrysocolla were also noted within the quartz.

EROSIONAL SURFACES

Introduction

The southern portion of the Sierra Estrella contains a large, tabular, erosional surface that covers about 1 mi², as well as three smaller surfaces (Fig. 3). These surfaces are uncharacteristically flat compared to the overall topography of the range. Each surface is blanketed with 0.5 to 5+ m of poorly sorted and moderately stratified sand and gravel. Clasts are subangular to well rounded and up to 1 m in diameter. This alluvium is locally cemented by moderately to strongly developed caliche. Occasional monadnocks protrude through the alluvium. Each erosional surface dips slightly (0° to 10°) in the downstream direction of its main drainage. These erosional surfaces have apparently been exposed since their formation because they show no signs of past burial and can therefore be classified as epigene paleoforms (Twidale, 1985). The surfaces are defined and characterized by the following criteria.

Bedrock Weathering

The bedrock on the slopes of the Sierra Estrella is quite fresh and unweathered in most places. The bedrock on the ridge of the range and along the border of the erosional surfaces, however, exhibits deep and extreme weathering. The resulting contrast in weathering characteristics within the same rock units may indicate a difference in weathering history. The most probable explanation is that these areas have been exposed for drastically different periods of time.

Stream Incision

In general, it is expected that mature streams with high channel gradients are high-energy systems that will be deeply incised. Likewise, mature, low-energy, low-stream-gradient systems will not be incised as deeply. In the Sierra Estrella, however, the opposite was noted. The seasonal streams on the slopes of the range are broadly and shallowly incised and have high channel gradients of up to 45°. The streams of the erosional surfaces are deeply and steeply incised and slope only 1° to 20°. The streams on the slopes of the range appear quite young compared to the streams of the erosional surfaces. Based on these observations, it is possible that the stream channels in the erosional surfaces were established before Basin and Range faulting and uplift of the Sierra Estrella.

Clast Composition

The tabular erosional surfaces are characterized by well-rounded stream cobbles in the sediments that are not derived from local bedrock. These exotic clasts are too numerous (up to 5% of the sediment) and commonly too large (up to 0.75 m) to be human artifacts introduced to the range. Clast lithology ranges from local bedrock to andesite, rhyolite, porphyritic basalt, and red to purple quartzites.

Geologic History

The rocks of the Sierra Estrella were probably unroofed by movement along the South Mountains detachment fault between 25 and 15 Ma. After they were unroofed, the rocks were deeply beveled in certain areas by fluvial streams (Fig. 4). The resultant Tertiary topography included fairly steep mountains surrounding a gently rolling peneplain with a few scattered and well-rounded monadnocks. Uplift and disruption of this erosional system occurred with Basin and Range faulting about 15 to 7 Ma. Since that time, the Tertiary erosional surfaces have been stranded in the Sierra Estrella and have been only slightly modified.

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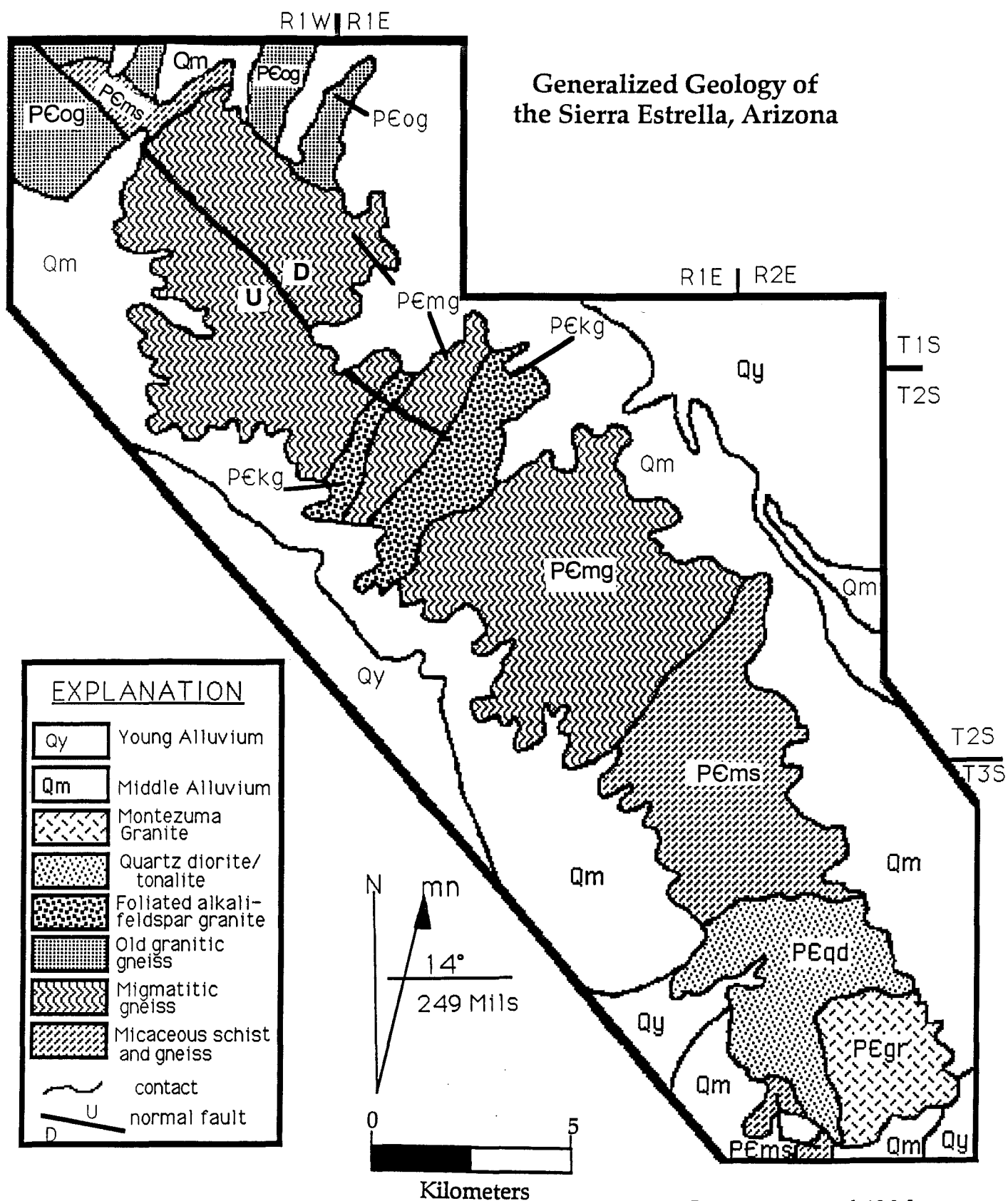


Figure 1. Generalized Geologic Map of the Sierra Estrella, Arizona

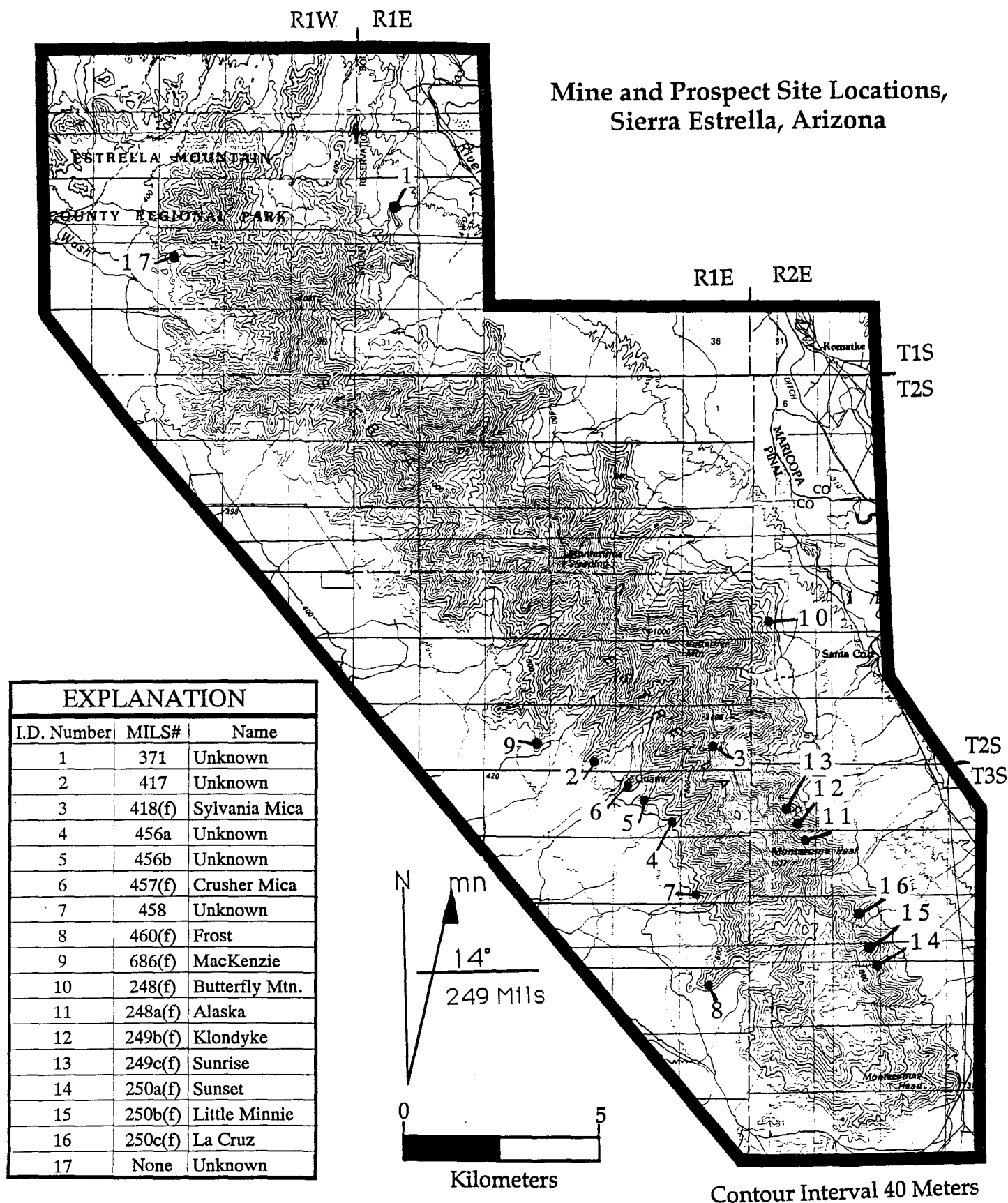


Figure 2. Mines and Prospect Site Locations of the Sierra Estrella, Arizona

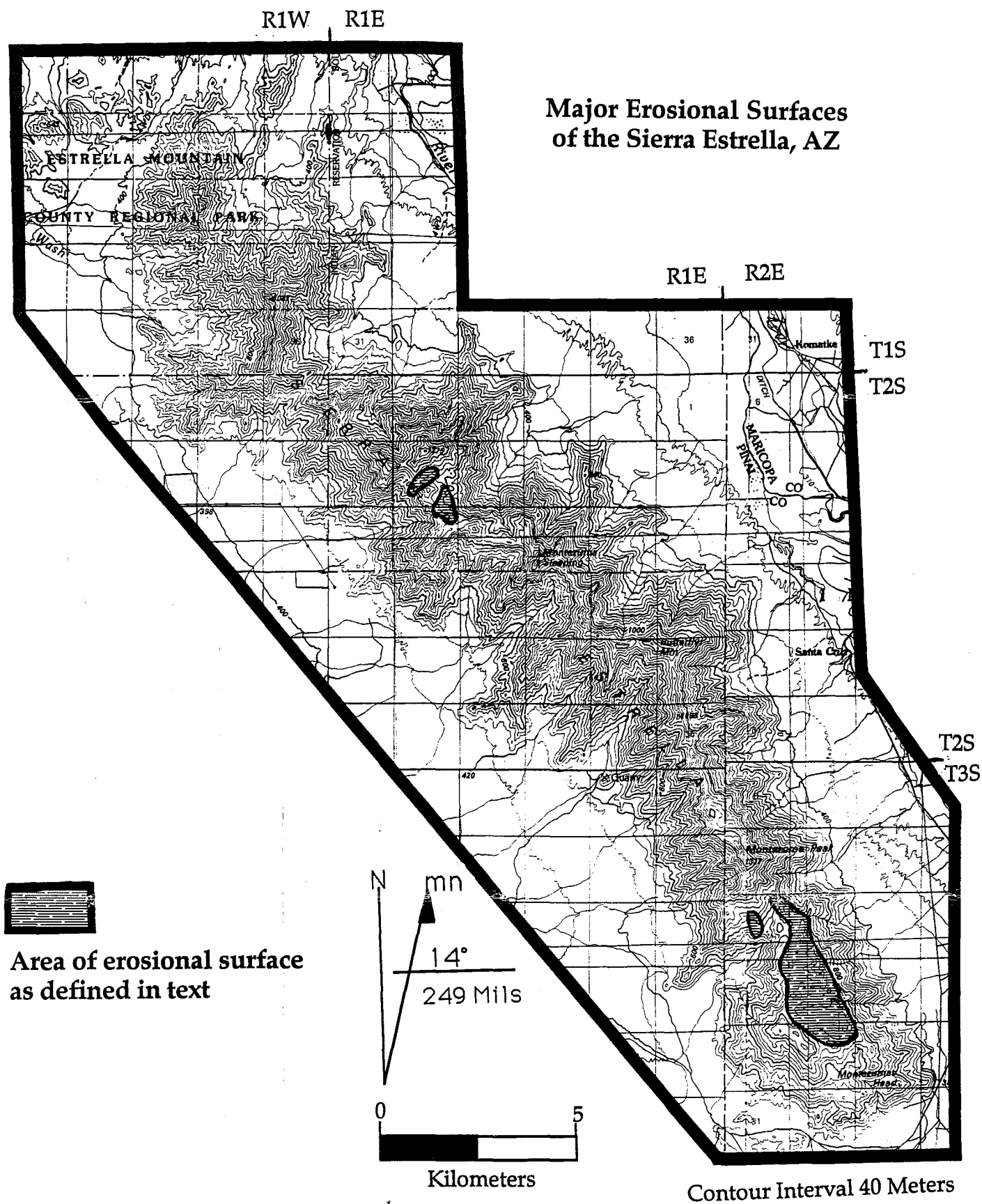


Figure 3. Location of Major Stranded Erosional Surfaces

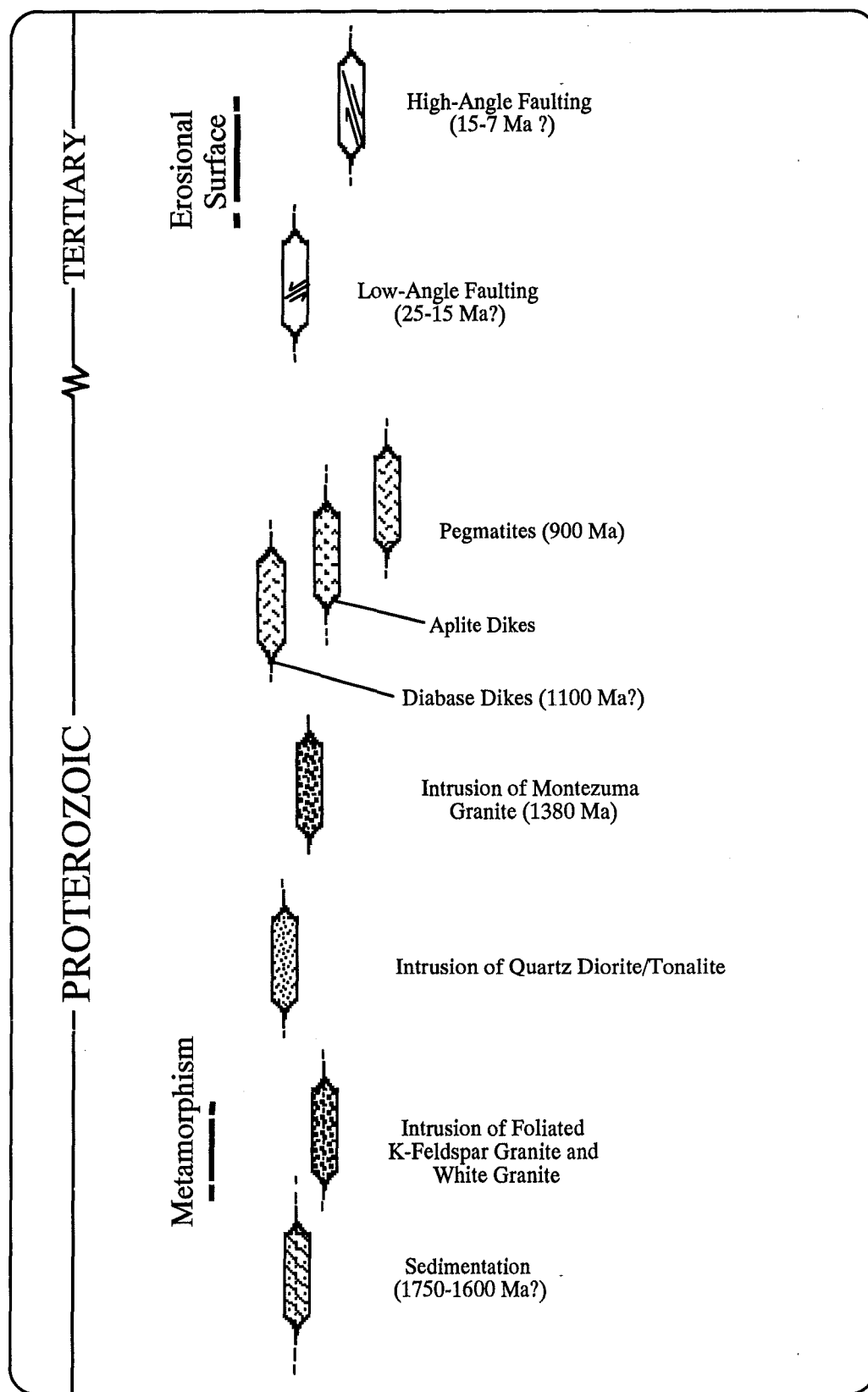


Figure 4. Schematic Chronology of Major Geologic Events in the Sierra Estrella, Arizona

Table 1. Commodity price average for 1991

Commodity	Price
Quartz	\$10-30 per ton
Feldspar	\$50-80 per ton
Mica	\$40-70 per ton
Gold	\$362 per ounce
Silver	\$4.03 per ounce
Copper	\$1.05 per lb.
Beryl	\$60-90 per stu
Garnet	\$195-255 per ton
Dimension Stone	\$20-60 per ton

Table 2. Mines and prospects of the Sierra Estrella, Arizona

[AZMILS- Arizona Mineral Industry Location System]

I.D. #	AZMILS	Name	Workings	County	Twn. Shp.	Rng.	Sec.	Qtr.	Minerals or Commodities
1	371	Unknown	Prospect and Adit	Maricopa	1S	1E	19	NE	Cu, Mica
2	417	Unknown	Prospects	Maricopa	2S	1E	34	SE	Cu
3	418	Sylvania Mica	Prospect	Maricopa	2S	1E	36	C	Gold, Cu, Feldspar, Mica
4	456A	Unknown	Prospects	Maricopa	3S	1E	2	SE	Mica
5	456B	Unknown	Prospects	Maricopa	3S	1E	2	NW	Cu
6	457	Crusher Mica	20x10x8ft cut	Maricopa	3S	1E	2	NW	Mica, Qtz, Tourmaline
7	458	Unknown	Prospects	Maricopa	3S	1E	12	SW	Cu
8	460	Frost	Prospects	Maricopa	3S	1E	24	C	Mica, Cu, Qtz, Feldspar, Beryl, Tourmaline
9	686	MacKenzie	Prospects	Maricopa	2S	1E	33	SE	Cu, Mica
10	248	Butterfly Mtn.	Prospect, Adit	Pinal	2S	2E	19	SW	Mica, Qtz
11	248A	Alaska	Prospects	Pinal	3S	2E	7	NE	Cu
12	249B	Klondyke	Prospects	Pinal	3S	2E	6	SE	Cu
13	249C	Sunrise	Adit, Prospect	Pinal	3S	2E	6	SE	Cu, gold, silver
14	250A	Sunset	Prospects	Pinal	3S	2E	20	NE	Cu
15	250B	Little Minnie	Prospects	Pinal	3S	2E	17	SE	Cu
16	250C	La Cruz	Prospects	Pinal	3S	2E	17	NE	Cu
17	None	Unknown	Prospects	Maricopa	1S	1W	27	NE	Cu