UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Hornblende-rich, high grade metamorphic terranes in the southernmost Sierra Nevada, California, and implications for crustal depths and batholith roots

by

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Open-File Report 83-465

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

Menlo Park, California

1983

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ABSTRACT

The southernmost Sierra Nevada widely exposes hornblende-rich, gneissic to granoblastic, amphibolite- to granulite-grade, metamorphic rocks and associated magmatic rocks, all of mid-Cretaceous age. Locally, red garnet, in part in euhedral crystals as large as 10 cm, as well as strongly pleochroic hypersthene, characterize these rocks. These hornblende-rich rocks dominate the north slopes of the southern tail of the Sierra Nevada, but are also present as inclusion masses of various sizes in the dominantly granitic terrane to the northeast.

The mafic, hornblende-rich rocks reflect a deeper crustal level than the dominantly granitic terrane to the northeast based on: 1) "index" minerals (presence of hypersthene, coarse garnet, and brown hornblende; 2) textures (considerable ambivalence of whether individual samples are metamorphic or magmatic, 3) metamorphic grade (at least local granulite facies); and 4) the presence of migmatite, and the evidence of local melting and mobilization. These rocks may be exposures of the upper part of the root zone and metamorphic substrate of the Sierra Nevada batholith. Xenoliths of gneiss, amphibolite, and granulite from sub-batholithic levels, that have been transported upward and preserved in volcanic rocks in the central Sierra Nevada, are similar to some exposed rocks of the southernmost Sierra Nevada.

Hypersthene-bearing granulite and tonalite, as well as distinctive granofels of mid-Cretaceous age, are exposed in the western part of the Santa Lucia Range (some 300 km to the northwest across the San Andreas fault). These rocks have much in common with some of the metamorphic and magmatic rocks in the southernmost Sierra Nevada, suggesting that the two areas record similar metamorphic conditions and crustal depth. Mid-Cretaceous hypersthene granulite is rare, which makes correlation of the Santa Lucia Range and the southernmost Sierra Nevada seem attractive. Nevertheless, possibly significant petrographic and rock distribution differences between the two areas (particularly the relative abundances of carbonate rocks and amphibolite) dictate caution in suggesting the two terranes were once contiguous.

INTRODUCTION

The basement of the southernmost Sierra Nevada (fig. 1) consists mostly of discrete granitic plutons that intrude dominantly metasedimentary rocks that are variously calcareous, siliceous, and pelitic (fig. 2). The southernmost Sierra Nevada in this regard resembles much of the rest of Sierra Nevada batholith. A conspicuous difference in the south, however, is the widespread occurrence of hornblende-rich gneissic and granoblastic rocks (fig. 3), many of them bearing hypersthene and coarse red garnet. These mafic metamorphic rocks are of higher grade and of greater depth of formation than are the metamorphic rocks in most of the Sierra Nevada batholith. These granitic, mafic metamorphic, and other rocks of the southernmost Sierra Nevada may be typical of the complexes that lie beneath the presently exposed "normal" batholithic rocks in much of the rest of the batholith, which has been eroded to a more shallow depth.

The structural pattern throughout most of the Sierra Nevada batholith has a dominantly north to northwest grain that is shown by the elongation of the batholith itself, by primary foliation and elongation of individual plutons, and by pronounced elongation of included metamorphic rocks. By contrast, the southernmost Sierra Nevada (particularly the Sierran tail) has a strong easterly to northeasterly structural grain. The rather abrupt change in structural grain may be original feature of the batholith, or a reflection of some later structural contortion, but it is not a simple oroclinal bend.

Parallel with the anomalously easterly grain are the Garlock fault, with demonstrated left lateral strike slip offset of some 50 to 60 km (Smith, 1962; Smith and Ketner, 1970), and the Pastoria fault, which also may have strike slip fault offset. These two faults juxtapose a hornblende-rich, high-grade metamorphic terrane on the north against a granitic terrane on the south that probably represents much shallower crustal depths, and may record as much as 10 to 20 km of north-side-up vertical movement.

Large, elongate slivers (horses) of relatively low-grade schist that contain chlorite and albitic plagioclase are found along both the Garlock and Pastoria faults. These schist bodies, physically similar to the Rand Schist (Hulin, 1925) that is exposed about 50 km northeast of Mojave, are exotic to the southernmost Sierra Nevada by virtue of their lithology and metamorphic grade. The Rand Schist is generally considered to be part of the widespread Pelona-Orocopia Schist terrane that in almost all of its outcrop areas is structurally overlain by high-grade metamorphic rocks (Haxel and Dillon, 1978). Such a relationship between schist and high-grade metamorphic rocks is not as evident in the southernmost Sierra, but the eastern end of the westernmost Rand Schist sliver (fig. 2) does appear to plunge beneath the mafic rocks of the San Emigdio-Tehachapi terrane (Ross, 1981). The significance of these Rand slivers, and what they mean in terms of movement of the Garlock and Pastoria faults, hinges on the still controversial question of what was the original distribution pattern of the Rand-Pelona-Orocopia Schists. But at the least, these exotic schist slivers emphasize that the Garlock and Pastoria faults are a significant crustal break and represents more than a simple zone of lateral movement.

This report is an outgrowth of several years of study by the U.S. Geological Survey of the southernmost Sierra Nevada aimed at understanding the basement framework and structural setting of major faults of diverse styles that converge there, and whose movement has not only disrupted, but presumably severed and removed parts of the Sierra Nevada batholith to points yet unknown. Data summarized here are limited to the hornblende-rich terranes and the plots of figures 4 and 5 show only specific samples that I have identified and studied. A preliminary version of the geologic map of the area of figure 2 with some explanatory text has been published (Ross, 1980), and a more detailed description of the geology of that area with an updated map is now being processed for publication (Ross, in press).

HORNBLENDE-RICH TERRANES

A group of presumably related masses that are rich in hornblende, commonly gneissic, and that locally bear distinctive red garnet and hypersthene, are perhaps the most distinctive basement rocks of the southernmost Sierra Nevada (fig. 3). By far the largest mass, the San Emigdio-Tehachapi terrane, stretches across the entire length of the Sierra tail. Many smaller bodies, with in part similar lithologies and locally much mixed with granitic material, are scattered through the outcrop area of the tonalite of Bear Valley Springs. Other similar masses are "strung along" the Garlock fault. Another mafic body, the Hoffman mass, is immersed in granodiorite and granite, much removed from the other mafic bodies. Following the discussion of the character and lithology of each mafic body, there are a few notes on mafic rocks south of the Garlock fault, in and closely associated with the Bean Canyon Formation. Discussion of these rocks (not shown on figure 3) is included to sound a note of caution that not all of the hornblende-rich rocks in this region are necessarily related.

San Emigdio-Tehachapi Mafic Terrane

Along the entire length of the Sierra Nevada tail, a conspicuous belt of dominantly mafic and gneissic to granoblastic rocks underlies an area of almost 300 km^2 (fig. 3). In part, these rocks are in fault contact with adjacent distinctly different terranes, in part the mafic rocks are overlapped by Tertiary sedimentary rocks and alluvium, and at the west and to the northeast the mafic terrane is intruded by younger granitic rocks.

Individual map units are difficult to sort out of this mafic terrane. Earlier work by Wiese (1950) subdivided part of this terrane into gabbro, diorite, and gneiss. In my reconnaissance study I could only locally map distinct mafic and felsic masses. The overall character of these rocks is metamorphic and gneissic, but there are local areas where the mafic rocks are relatively massive and homogeneous. These locally massive and homogeneous rocks could be intrusive and derived from magma, but they could as well be the result of local melting and mobilization of the high-grade metamorphic rocks.

The characterizing rock types of the mafic terrane are granulite, amphibolite and diorite-tonalite, gneiss, and unquestionably metasedimentary rocks (impure quartzite and calc-hornfels). Gradation and intermixing of these rock types is common and they cannot everywhere be separated by reconnaissance mapping. Figures 4A, B, C locate the samples I have studied. Petrographic (thin section) notes on selected samples of these rocks can be found in Ross (1983). The rock types are characterized as follows:

Granulite is a massive, medium-grained hypersthene-bearing rock with granoblastic texture. The dominant minerals are intermediate plagioclase and green to brown [1/] hornblende. Lesser, but varying amounts of quartz and biotite are present, but not in all specimens.

Granofels is much like granulite, but without hypersthene. It generally has significant amounts of quartz and biotite and is also characterized by red garnet and coarse shiny flakes of graphite.

Amphibolite is a dark massive rock composed almost exclusively of intermediate plagioclase and green to brown hornblende. Coarse red garnet is locally conspicuous.

[1/] Here, and throughout the report, the colors of hornblende and biotite refer to pleochroic colors in thin section. These two minerals are almost invariably black in hand specimens.

Diorite-tonalite represents a broad gradational category between unquestionably metamorphic amphibolite and unquestionably magmatic tonalite. These rocks are generally homogeneous, massive and have a xenomorphic granular texture. Quartz (as much as 20 percent) is present, and hornblende is characteristically markedly in excess of biotite, but biotite can comprise as much as 15 percent of the rock.

Gneiss (fig. 4C) comprises all the strongly foliated gradations of granofels (felsic quartzofeldspathic gneiss) and amphibolite (amphibolitic to tonalitic gneiss). The conspicuous presence of a gneissic fabric throughout the mafic terrane has led me to interpret much of the magmatic-looking diorite-tonalite as local melt spots in a metamorphic terrane.

Impure Quartzite is composed of a granoblastic mat of quartz with small amounts of, mostly, feldspar and mica. Pale pink garnet is locally conspicuous. With increase in "impurities" theses rock grade to granofels, and with increase in foliation, to felsic quartzofeldspathic gneiss.

Calc-hornfels is a rare constituent as fine-grained gray green layers. Some layers are composed of plagioclase, clinopyroxene, and less pale green amphibole. Other layers are more siliceous with varying amounts of quartz, plagioclase, clinopyroxene, and epidote.

In addition to these latter two lithologies that are obviously metasedimentary, much of the felsic quartzofeldspathic gneiss and some of the granofels is probably also metasedimentary. K-feldspar and discrete muscovite crystals are common locally, (fig. 4E), particularly in the felsic gneiss, and suggest pelitic sedimentary parent material. Discrete epidote also suggests calcareous admixtures in rocks other than the obvious calc-hornfels layers. Although only epidote occurrences that were not obviously secondary are plotted on fig. 4E, some or all of the epidote could indeed be a retrograde product. Metasedimentary rocks (of continental(?) derivation) are a significant fraction of the mafic terrane, but the more abundant rocks, dominated by hornblende, are most probably meta-igneous. Scattered initial strontium values in these rocks, in the range of 0.0703 to 0.704, suggest their derivation from oceanic crust.

A striking feature of the mafic terrane is the widespread occurrence of haloed crystals of red garnet as large as 10 cm across, many of which are euhedral (fig. 4D). Microprobe determinations from a number of the garnets (Ross, in press) indicate general compositional uniformity with the following appoximate end-member molecule composition:

Almandine	63 percent
Pyrope	21 percent
Grossularite	10 percent
Spessartite	4 percent
Andradite	2 percent
	100 percent

The garnet is found mostly in the fine-to medium-grained amphibolite and granofels, but some of the most spectacular garnets are in float boulders of diorite-tonalite that were first described by Murdoch (1939). Garnet is a common metamorphic mineral and occurs through a wide range of environments, but red garnets, and particularly 8 to 10 cm dodecahedrons in a fine grained amphibolite, bespeak a "high-grade" and probably relatively deep environment.

I have not seen both red garnet and hypersthene in the same thin section, but have seen both minerals in the same rock type and relatively closely associated in the field. I feel fairly confident that this mineral pair exists in equilibrium, at least locally in the mafic terranes. Sharry (1981) noted one sample with coexisting red garnet and orthopyroxene in the Tunis Creek area.

Live Oak

The Live Oak mafic body, covering about 6 km^2, was mapped as "gabbro and gabbro-diorite, including olivine norite" by Dibblee and Chesterman (1953). They noted gradational contacts with the surrounding tonalite, and found the contact difficult to map. Near the east side of the Live Oak body, I mapped hypersthene-bearing tonalite that contained gneissic streaks and patches.

The mafic body is undoubtedly igneous, at least in part, for it contains patches of strongly retrograded olivine norite. Nevertheless, the presence of fine-to medium-grained plagioclase amphibolite, hornblende-rich tonalite, and gneissic remnants in the surrounding tonalite, suggest metamorphic lithologies similar to the major types of the San Emigdio-Tehachapi terrane. Particularly noteworthy is the tonalitic outcrop, about 3 km east of the Live Oak body, in highway road cuts where the outcrop is at least 50 percent dark, elongate gneissic streaks and lenses. Just north of the Live Oak mafic body, a large dark inclusion mass in the tonalite was found to be composed chiefly of pale brown hornblende and labradorite. Most likely this is a fragment of amphibolite from the Live Oak body.

Breckenridge

Small remnants of strongly retrograded olivine gabbro-norite are exposed along the Breckenridge Road about 6 km ESE of the Live Oak body (Mt. Adelaide 7-1/2' quadrangle). The mafic rocks are remnants in an intrusion breccia of tonalite and fine-grained felsic granitic rock. The remnant mafic patches contain no dark gneiss, no amphibolite, or any other rock type that would tie them directly to the dark amphibolitic gneiss terrane of the San Emigdio-Tehachapi Mountains. They do have the mineralogy and texture to suggest that they are correlative with part of the Live Oak body.

The mafic rocks have gabbroic to granoblastic (polygonal) textures and are dominated by well-twinned fresh labradorite and colorless to pale green amphibole. Studded through the samples are pleochroic (pink to green) lamellar twinned orthopyroxene, as well as olivine that is altered along curving fractures. Some of the orthopyroxene appears to have schiller inclusions. Most olivine and orthopyroxene grains are surrounded by reaction rims of amphibole with vermicular intergrowths of green spinel. In addition, scattered grains of green spinel and opaque minerals are present. It is the mineralogy and texture in general, and the conspicuous vermicular green spinel in particular, that suggest a correlation with the Live Oak body.

Sams and others (1983) report "layers of deformed mafic-ultramafic cumulates" in the San Emigdio-Tehachapi terrane. This strengthens the suggestion that the Breckenridge as well as the Live Oak body may be related to the San Emigdio-Tehachapi terrane.

Pampa

A few kilometers south of the Live Oak body is a thin mafic body about 6 km long that was also described as "gabbro" by Dibblee and Chesterman (1953). I have examined this body only cursorily, and only at its two ends. Particularly noteworthy near the northeast end of the body is a hypersthene-bearing tonalite composed of fresh well-twinned plagioclase (about An_{50}), abundant coarse anhedral quartz, reddish brown biotite, pleochroic hypersthene, and less common olive brown hornblende. Most hypersthene has a "clean" contact with plagioclase, with only rare thin amphibole reaction rims. Associated with the tonalite is retrograded gabbro with blocky fresh subhedral plagioclase (about An_{50}) and abundant pale green to pale olive brown, generally acicular amphibole aggregates. Some amphibole cores contain skeletal clinopyroxene and some acicular amphibole masses are pseudomorphs, probably of pyroxene. Large crystals of reddish brown biotite, interstitial quartz, and aggregates of pale green chlorite make up the rest of the rock. Also present is a fine-grained granoblastic rock composed of clinopyroxene, olive brown hornblende, and plagioclase. Some hornblende aggregates to 3 mm long suggest pseudomorphs of phenocrysts and a possible volcanic protolith.

One of my samples from the southwest part of the Pampa body is composed almost entirely of fibrous amphibole and chlorite, and could be a strongly retrograded ultramafic rock. More common are probable gabbroic rocks, in part retrograded, and composed chiefly of labradorite and pale green to pale brown hornblende with included skeletal clinopyroxene. The physical resemblance of these rocks to specimens in the San Emigdio-Tehachapi mafic terrane is enough to raise suspicions that, at least in part, the Pampa rocks are metamorphic amphibolite, rather than magmatic gabbro.

Most distinctive, and probably most abundant, in the southwestern part of the Pampa mafic body is hypersthene-hornblende tonalite. This rock has a decided granitic texture with subhedral well-twinned plagioclase (about An_{50}): 50 to 60 percent, quartz: 5 to 10 percent, pale brown hornblende: 15 to 30 percent, hypersthene: 10 to 20 percent, reddish brown biotite: 5 percent, and opaque grains: $\sim$1 percent. Some of the hypersthene is sharply in contact with plagioclase, but most has an amphibole reaction rim. One specimen contains both clinopyroxene and hypersthene, but has bright olive green hornblende and dark brown biotite, interference colors typical of normal granitic rocks (particularly tonalite) in this region. This rock has characteristics of both metamorphic granulite (two pyroxenes) and magmatic tonalite (green hornblende and brown biotite). The choice is not obvious, but the dilemma does emphasize that the Pampa body is not merely a gabbro inclusion in the surrounding tonalite.

Walker

Dibblee and Chesterman (1953) mapped a small body of "hornblendite and other ultra-basic rocks" just west of Walker Basin, and noted the presence of hornblende-rich gneiss. I made a very cursory investigation of the south end of this inclusion and collected and studied some highly retrograde ultramafic (?) rock that is now composed of a decussate mat of pale green to colorless, acicular to blocky amphibole, and lesser pale green chlorite with dull gray interference colors. Local coarse hornblende remnants that have hints of pale brown color, contain well-alined bladed purplish inclusions (schiller-like?). I also noted quartzite and biotite quartzofeldspathic gneiss. Float boulders at the foot of the slope just east of the ultramafic (?) body and presumably from it are described in my field notes as "hornblende gabbro-diorite---

hornblende-rich inclusion of dark gneissic complex." The Walker body thus has some similarity to the San Emigdio-Tehachapi terrane.

Caliente

South and west of Caliente, several square kilometers of mafic plutonic rocks are notably rich in hornblende. The Caliente rocks appear to be a large mafic enclave much mixed with, and intruded by, younger granitic rocks.

The most common rock type is hornblende-rich gabbro to tonalite that consists chiefly of well twinned andesine to labradorite and light to moderate olive green hornblende. Much of the hornblende is in aggregates that are in part composed of acicular, pale green crystals. Clinopyroxene skeletal crystals form cores of some hornblendes. Strongly pleochroic deep brown to reddish brown biotite is common in the tonalite, but absent in the more mafic rocks. Some associated fine grained amphibolite may be metavolcanic.

Several small bodies of ultramafic rock, enclosed in the Caliente rocks, are dominantly hornblende, but locally contain altered remnants of olivine and orthopyroxene. In places hornblende-rich gabbro intrudes the ultramafic rock and forms an intrusion breccia. This feature is well developed in a large road cut on the north side of Highway 58 about 4.5 km west of the junction with Highway 223 to Arvin (Bena 7-1/2 minute quadrangle).

The most distinctive and widespread ultramafic rock is coarse, knobby-weathering and contains subhedral hornblende crystals as long as 2 cm set in a fine grained groundmass of hornblende, clinopyroxene, and lesser labradorite. The hornblende is pale brown in thin section. Less common are patches of coarse-grained rock dominated by pale green hornblende that has abundant bladed opaque inclusions (schiller-like). These hornblende crystals enclose many small crystals of highly altered and fractured olivine. Less common are lamellar twinned orthopyroxene and green spinel. Perhaps these rocks are retrograded remnants of peridotite(?) bodies now immersed in a gabbroic and tonalitic matrix.

Gneissic streaks, patches, and lenses are common in the Caliente terrane. Felsic gneiss, very reminiscent of some of the gneiss in the San Emigdio-Tehachapi terrane is exposed in a road cut on the Caliente-Bodfish road about 2 km west of the intersection with the Bealville Road (Bena 7-1/2' quadrangle). Dark hornblende-rich gneiss that is even more reminiscent of the San Emigdio-Tehachapi terrane is exposed along Highway 58 near the previously described intrusion breccia and also on the grassy slopes to the southeast. The first report of these rocks was by Dibblee and Chesterman (1953) who noted "layers of banded hornblende-biotite gneiss made up of layers rich in hornblende alternating with layers containing less."

Comanche

A small mafic body, a few hundred meters across, is included in tonalite on the north side of Horsethief Flat on the Comanche Point Road (Bear Mountain 7-1/2' quadrangle). I mapped the body as "hornblende gabbro" and noted considerable grain size variation in the outcrop. Thin section study revealed fresh well-twinned labradorite and pale green hornblende in large crystals, as well as in aggregates. One fine-grained sample has a granoblastic texture and is composed of a mat of cleanly twinned zoned labradorite, olive brown hornblende, hypersthene, and abundant opaque grains. The hypersthene has clean sharp boundaries with adjacent hornblende and plagioclase grains. Here is yet another example of a mafic rock that has some suggestion that it is a magmatic rock (cleanly twinned and zoned plagioclase), but the overall texture and mineralogy points to a high grade (granulite) metamorphic rock.

Along the Comanche Point Road just west of Horsethief Flat (near the transmission line) the tonalite is darker and contains numerous dark inclusions and amphibole-rich clots. The one inclusion sample studied has a granoblastic to polygonal texture and is composed of labradorite, brown to pale green hornblende, common opaque grains and minor reddish brown biotite. Strongly pleochroic hypersthene is common as cores of hornblende crystals. Generally pale green to colorless hornblende forms a "bleached" zone between brown hornblende and hypersthene. The two different colored hornblendes are in optical continuity, however, so this is not a standard reaction rim. Also, several hypersthene grains are in sharp, clean contact with brown hornblende. I suggest these inclusions west of Horsethief Flat are analogous to the much larger inclusion swarm of the Loop area.

Cummings

A thin disrupted arcuate belt of mafic rocks extends for some 10 km east and southeast of Cummings Valley. Petrographic notes for selected samples are presented in Ross (1983) for this belt that is not easily visited because of access restrictions. In the field these rocks were variously referred to as diorite, hybrid rock, gabbro, and dirty, dark tonalite. It soon became apparent that hypersthene was a common characterizing accessory. A recent (1982) careful reexamination of petrographic notes and thin sections made it clear that there are two rather distinct hypersthene-bearing rock types in this belt.

The smaller northern body and the south part of the larger body are characterized by mafic, medium grained granoblastic to gneissic rocks that are composed dominantly of sharply twinned and somewhat zoned labradorite and pale brown to olive brown hornblende. Reddish brown biotite and quartz are present in small amounts in some samples. Strongly pleochroic hypersthene in fresh, clean anhedral crystals is common and some specimens in addition contain clinopyroxene. In part the hypersthene has sharp unaltered boundaries with hornblende and labradorite, but in other samples, clear to pale green, somewhat acicular, amphibole forms a cushioning reaction rim around the hypersthene. Almost certainly these rocks are hypersthene granulites similar to other granulites in the San Emigdio-Tehachapi terrane, particularly in the Tunis Creek area.

In rather strong contrast, specimens from the northern part of the larger southern mass consist of a hypautomorphic granular combination of andesine, abundant quartz (10 to 20 percent), olive green (granitic) hornblende in excess of brown to reddish brown biotite. Accessory hypersthene (as much as 7 percent) generally has sharp unaltered grain boundaries with adjacent minerals. The mineralogy and texture of these rocks indicate that they are magmatic tonalite.

Loop Inclusion Swarm

Ovoid mafic inclusions up to a few tens of cm in maximum dimension are packed together in a tonalite matrix over an elliptical area (about 1 x 4 km) in, and southeast of, the "Loop" on the Southern Pacific Railroad line (Keene 7-1/2' quadrangle). As much as 75 to 90 percent of individual outcrops are composed of inclusion material. Although the inclusions have the appearance of "typical" hornblendic Sierran inclusions, and are rarely foliated, the two inclusions that I selected as typical both contain hypersthene.

One sample consists of a granoblastic or polygonal mat of fresh twinned labradorite (55 percent), light to moderate olive brown hornblende (35 percent), pink to green pleochroic hypersthene (9 percent), and metallic opaque grains (1 percent). The hypersthene seems in equilibrium as it forms clean sharp contacts against hornblende and plagioclase with no reaction zones. The other sample is somewhat coarser grained and xenomorphic granular or granoblastic. It likewise is dominated by fresh well-twinned plagioclase of about An_{50} (50 percent) and olive green hornblende (30 percent). Brown biotite (10 percent), quartz (5 percent), pleochroic hypersthene (5 percent), and scattered opaque grains are also present. Both of these inclusion samples are similar to the hypersthene granulite of the Tunis Creek area.

Two specimens in 4 km^2 are hardly an exhaustive sample, but they do suggest affinity with the other mafic, metamorphic terranes of the region, particularly the San Emigdio-Tehachapi terrane. Perhaps the Loop body is a somewhat dismembered equivalent of the Cummings belt?

A hypersthene granulite specimen from streaky inclusion and schlieren material in uppermost Tejon Creek (figure 4A) is a very similar to the granulite samples from the Loop swarm. The matrix rock in Tejon Creek is foliated hornblende-rich tonalite that is similar to the hornblende-rich rock that dominates the Caliente terrane.

Tweedy

The Tweedy mafic body is engulfed by granodiorite about 5 km north of Tehachapi. It only covers about 1/5 km^2 and in my short examination I could not determine its relation with the surrounding granitic rocks. In field notes I described the rock as "coarse knobby hornblende gabbro." Specimens range from fine- to coarse-grained and consist of twinned, in part subhedral plagioclase (about An_{50}): 40 percent, pale olive hornblende: 40 percent, clinopyroxene: 20 percent, abundant coarse sphene and traces of quartz and K-feldspar. From the texture and mineralogy of the specimens alone, this body could be either plagioclase amphibolite or gabbro. Just southwest of the mafic body there are streaky gneissic layers in the granodiorite and coarse red garnet in crystals as large as 3 cm across. These gneissic rocks and the coarse garnets are remiscent of some amphibolitic gneiss in the San Emigdio-Tehachapi Mountains.

Mountain Park

The lower mountain slopes just south of Tehachapi Valley (Tehachapi South 7-1/2' quadrangle) expose about 6 km^2 of cataclastic felsic gneiss in a northwest-trending belt. The gneiss is composed mostly of plagioclase, quartz, reddish brown biotite, and lesser garnet. Layers of nearly pure to impure quartzite are present; one contains abundant sillimanite. Other layers are mica schist with abundant red brown biotite, and muscovite. Marble lenses are also present.

The larger (gneissic) Mountain Park mass has the overall appearance of the felsic gneiss of the San Emigdio-Tehachapi terrane, but also has some affinities (sillimanite, mica schist, marble) with the metasedimentary rocks to the north and east. The smaller eastern body is even more enigmatic. It contains significant amounts of marble and calc-hornfels, as well as quartzite. But it also contains plagioclase amphibolite composed of plagioclase (about An_{50}) and olive brown hornblende, liberally sprinkled with opaque grains. In this rock are also coarse, poikilitic red garnets with bleached haloes. In short, a rock that is typical of the San Emigdio-Tehachapi terrane to the west.

It is not clear to me why there is an apparent association of gneiss and garnetiferous amphibolite with marble-bearing metasedimentary layers here in the Mountain Park bodies. Perhaps the gneiss and amphibolite are inclusions in the tonalite that surrounds the Mountain Park bodies, and the whole tonalite package intrudes the marble-bearing metasedimentary rocks. This is possible, but considering the abundance of marble-bearing metasedimentary layers on all sides of the two Mountain Park pendants, it seems like special pleading.

The Mountan Park rocks are along a transition zone between largely marble-free metamorphic rocks to the west and a relatively marble-rich metamorphic terrane to the northeast. Marble associated with felsic gneiss and garnetiferous amphibolite to the east in slivers in the Garlock fault (Cameron area) might be analogous to the Mountain Park rocks. In addition to the lithologic change, this may be a transitional zone between the higher grade (granulite) rocks to the west and the sillimanite-bearing metamorphic rocks of somewhat lower grade to the northeast.

Cameron

Various slices and slivers of mafic rocks are strung out along the Garlock fault east from Cameron Canyon eastward for more than 20 km from Cameron Canyon (about 12 km southeast of Tehachapi). The mafic slivers are abruptly terminated on the south against the southern strand of the Garlock fault. The north contact of the largest (westernmost) mafic sliver "retreats" up canyons in the mountain front, suggesting a low angle (thrust?) contact with granitic rocks to the north. The more easterly mafic slivers are intertwined with granitic rocks along anastomosing faults. Weathering, alteration, and shearing along the mountain front here greatly hinder determination of rock relations.

Fortunately, the westernmost fault sliver is relatively coherent and well exposed in several canyons, and mafic rocks are readily visible in parts of the eastern slivers. Dark amphibolite, in which pale green amphibole aggregates with brown cores generally exceed plagioclase, is the most conspicuous rock type. These rocks contain abundant opaque grains. Interstitial quartz is commonly cataclastically deformed. Cataclasis and retrograde metamorphism to various degrees is widespread in these rocks. Much of the amphibolite has a strong gneissic fabric.

Coarse haloed red garnet is abundant and widespread. A spectacular exhibit of garnets, as large as 10 cm is in Waterfall Canyon (on the north side of Highway 58, about 3 km east of Cameron, Monolith 7-1/2' quadrangle). Microprobe determinations on two garnets (Ross, in press) indicate the following approximate end-member molecule composition:

Almandine	52 percent
Pyrope	27 percent
Grossularite	17 percent
Spessartite	2 percent
Andradite	2 percent
	100

These garnets look identical to those of the San Emigdio-Tehachapi terrane (page 5), but they are lower in almandine and higher in pyrope and grossularite. The presence of carbonate rocks in the Cameron slivers and their virtual absence in the San Emigdio-Tehachapi terrane, may account for the garnet differences.

Felsic gneiss containing abundant quartz, plagioclase, and lesser K-feldspar, olive to reddish brown biotite, and minor olive hornblende, is relatively abundant, and commonly strongly cataclastically deformed. Marble is also relatively common locally. In the easternmost slivers, marble appears to be interlayered with garnetiferous amphibolite. Ted Antonioli (personal commun., 1980) made a detailed study of the Cameron slivers and noted a dark garnetiferous gneiss "facies" as well as a marble-bearing felsic gneiss "facies." The felsic gneiss Antonioli noted is similar to the felsic (quartzofeldspathic) gneiss of the San Emigdio-Tehachapi mafic terrane. The garnetiferous dark plagioclase amphibolite and gneiss of the Cameron slivers are virtually identical to much of the San Emigdio-Tehachapi mafic terrane.

In the course of his work in the Cameron slivers Antonioli mapped a small body of peridotite. If the peridotite belongs to the mafic terrane, which its location suggests, I think it is a very important discovery. Sams and others (1983) report the presence of ultramafic rocks within the main San Emgidio-Tehachapi mafic terrane, and scraps of ultramafic rock are known from the possibly related Live Oak, Pampa, Caliente, and Eagle Rest Peak bodies. The Cameron peridotite thus helps tie this area to several of the other mafic areas.

Cinco

A small body of mafic rocks is exposed at the base of the mountain front directly west of Cinco on Highway 14. The mafic rocks are most likely a sliver in the Garlock fault zone, but the relations were not clear to me during a short visit to the outcrops. Samsell (1962), first noted these rocks and described several rock types, including hornblende-andesine gneiss.

In my short field visit I noted diorite, dark and light-colored gneiss, augen gneiss, fine-grained diorite (amphibolite) with coarse haloed red garnets to 5 cm across, and some marble. The garnet-bearing amphibolite and the gneissic rocks at Cinco are strikingly reminiscent of some of the major rock types of the San Emigdio-Tehachapi terrane.

Petrographic examination revealed that the dark "diorite" was plagioclase amphibolite that is dominated by well-twinned plagioclase (about An_{50}) and dark greenish hornblende with distinctly brown cores that occurs in aggregates or in discrete crystals. Opaque grains are abundant, as is coarse garnet. Minor quartz is present and cataclasis is common. The gneissic rocks, composed of various amounts of plagioclase, quartz, epidote, and abundant pale green hornblende, are commonly cataclastic augen to flaser gneiss. Some of the green hornblende in the gneiss has brown cores. Strongly retrograde amphibolite and gneiss are present in this body with strongly seriticized plagioclase, and hornblende completely replaced by epidote and chlorite.

The Cinco, and the previously described Cameron mafic rocks, are both structurally isolated in the complex Garlock fault zone. I have previously speculated (Ross, 1980) that these rocks were originally parts of the San Emigdio-Tehachapi mafic terrane that have been separated by lateral movement on the fault. Though definite lithologic correlatives of the San Emigdio-Tehachapi terrane, these mafic fragments may reflect uplift along the Garlock fault of parts of widely distributed mafic basement rather than lateral fault transport of pieces of the more limited San Emigdio-Tehachapi terrane.

Hoffman

Along and north of Hoffman Canyon (about 8 km northwest of Cinco) mafic rocks covering about 50 km^2 are much intruded by younger granitic rocks. Samsell (1962) first noted the presence of abundant schistose and gneissose xenoliths in this area. Early in my reconnaissance studies of the southernmost Sierra Nevada in 1978 I was surprised by the presence of these anomalously dark rocks well east of the "quartz diorite line of Moore (1959)" in an area where the metamorphic rocks are generally marble-rich metasedimentary pendants and inclusions. At that time I noted amphibolite, hornblende-rich "diorite" and gneiss, and suggested that these dark rocks were correlative with the dark amphibolitic gneiss of the San Emigdio-Tehachapi Mountains (Ross, in press).

Recent (1982) reexamination of all the thin sections from the Hoffman Canyon body reinforced my earlier suggestions of similarity with the San Emigdio-Tehachapi dark terrane, but my overall impression is that the Hoffman rocks may be of somewhat lower metamorphic grade. Most common in the Hoffman mafic rocks is amphibolite (in part quartz-bearing) composed of well-twinned andesine-labradorite, moderate green to olive hornblende, and abundant opaque grains. These rocks grade to gneissic rocks of similar mineralogy. Also present is quartzofeldspathic gneiss composed of andesine, brown biotite, and quartz.

Biotite is present, but much less common than hornblende in the amphibolite and dark gneiss and is brown to reddish brown. Clinopyroxene is present, but scattered in the dark rocks. Only one occurrence of coarse haloed red garnet was observed near the west end of the Hoffman mafic mass.

The overall appearance and general mineral content of these dark rocks are strongly compatible with the San Emigdio-Tehachapi terrane. However, in the Hoffman mass coarse haloed garnet is rare, orthopyroxene is apparently absent and clinopyroxene is scattered. Hornblende is green (rarely brown) and biotite is mostly brown to reddish brown. Plagioclase is perhaps less calcic than in the San Emigdio-Tehachapi rocks.

The Hoffman mafic mass (fig. 2, 3) is isolated from the other mafic bodies and is immersed in a granite-granodiorite terrane whose initial $^{87}Sr/^{86}Sr$ ratios of 0.707 to 0.708 (Kistler and Peterman, 1978) indicate intrusion through Precambrian continental basement. Thus the Hoffman mafic rocks, with oceanic (?) affinities, are out of place and seem to call for lateral and/or vertical displacement from kindred mafic rocks of the region. Large masses of mafic rock in a similar(?) setting are shown as "Mesozoic basic intrusive rocks" on the Bakersfield sheet of the Geologic Map of California (Smith, 1965). These rocks, some 40 to 60 km north of the Hoffman body, are the Summit gabbro of Miller and Webb (1940). Brief descriptions of these rocks suggest much lithologic variety. These rocks need to be investigated to see if they have mafic metamorphic affinities and any similarity to the Hoffman mafic rocks.

Eagle Rest Peak

This mass, which is separated from the basement rocks of the Sierran tail by Tertiary sedimentary rocks, covers about 25 km^2 and includes gabbro, pyroxenite, and metavolcanic rocks. About half of the outcrop area consists of gabbro and lesser pyroxenite. Coarse-grained anorthositic gabbro is common and consists of calcic plagioclase (labradorite-bytownite), pale green amphibole, clinopyroxene, minor orthopyroxene, and opaque grains. The pyroxenite is a partly serpentinized mix of clinopyroxene and orthopyroxene. Hornblende quartz diorite-gabbro is about one half plagioclase (andesine to labradorite), about one third green hornblende, one quarter quartz, and also contains minor biotite and metallic opaque grains.

The presumed wall rock of these gabbroic rocks is mafic fine- to coarse-grained metavolcanic rock with local diabasic texture. These wallrocks, dominantly composed of intermediate plagioclase and pale green hornblende, and are now amphibolite.

It is problematical if the Eagle Rest Peak mafic rocks are related to the rest of the exposed mafic rocks in the southernmost Sierra Nevada. There are dark plagioclase amphibolites in the San Emigdio-Tehachapi terrane that resemble some rocks at Eagle Rest Peak, but dark plagioclase amphibolite is not a very distinctive rock for correlation. I have seen no counterparts of either the coarse-grained anorthositic gabbro or the hornblende-quartz gabbro in other basement outcrops of the southernmost Sierra Nevada. The Eagle Rest Peak body may be a fragment of either the Kings River ophiolite (Saleeby, 1978) or the Coast Range ophiolite (Bailey and Blake, 1974) and structurally separate from the basement rocks of the Sierra Nevada tail.

Igneous rocks in (and associated with) the Bean Canyon Formation

Mafic rocks, referred to collectively as "hornblende diorite and gabbro" by Dibblee (1967), are scattered through the basement terrane south of the Garlock fault. Similarly named rocks north of the Garlock fault are in large part suspect of being hornblende-rich metamorphic rocks. It thus seems worthwhile to briefly summarize the data I have on these mafic rocks, as well as the hornblende-bearing rocks of the Bean Canyon Formation.

A much altered and retrograded ultramafic rock, rich in colorless acicular amphibole that is studded with olivine, is exposed in Bean Canyon (fig. 2). G. A. Davis (written commun., 1977) suggested that this serpentinized peridotite is a fragment of disrupted ophiolite. West of Cottonwood Creek (fig. 2) another possible ultramafic remnant is even more altered, and is now a mat of hornblende and epidote, with traces of plagioclase and biotite. East of Cottonwood Creek, a remnant of truly intrusive gabbro was found in a mixed area of largely contaminated granodiorite. The gabbro contains abundant pale brown to colorless, in part euhedral, hornblende crystals as large as 3 mm. Also present are somewhat smaller, but also in part euhedral, clinopyroxene crystals, plagioclase (about An_{50}), and minor K-feldspar. These are the only localities south of the Garlock fault where I have noted unequivocal mafic and ultramafic magmatic rocks. Some areas previously mapped as hornblende diorite and gabbro have proved to be largely dark (contaminated?) granodiorite, but I have not examined all the previously noted mafic rocks, and some may be gabbro.

Metavolcanic rocks are a minor component of the Bean Canyon Formation along its entire outcrop belt. Most are readily recognizable in thin section by the preservation of phenocrysts (or pyroclasts) of plagioclase as large as 4 mm, and less commonly of quartz. Aggregates of brown biotite and green hornblende also mimic former larger crystals in some layers. All of these metavolcanic rocks now have a dense hornfelsic matrix. Original compositions range from rhyolite or quartz latite to andesite or basalt. Some of these metavolcanic rocks are rich in hornblende and are now amphibolites, but all are fine-grained and none bear resemblance to the coarser, high-grade metamorphic rocks north of the Garlock fault.

DISTRIBUTION OF CERTAIN MINERALS AND OTHER FEATURES

The following discussion, keyed to index maps (fig. 5), focuses on the distribution of some minerals in the southernmost Sierra Nevada that may have value as indicators of metamorphic grade or crustal depth or both. Also included is a discussion of the locally abundant pegmatite and other felsic dikes.

Hypersthene [1]

Hypersthene in distinctly pleochroic (pink to green) fresh grains occurs in three settings in the southernmost Sierra Nevada (fig. 5A). First, some hypersthene is in undoubted granoblastic, high-grade metamorphic rocks. In part, these rocks are somewhat retrograde and the hypersthene has a pale amphibole reaction rim against plagioclase and dark-colored primary hornblende. In other samples, fresh hypersthene has clean sharp contacts with both hornblende and plagioclase, suggestive of preservation of a high-grade (granulite) equilibrium assemblage. Second, hypersthene also occurs as remnants in undoubted retrograded gabbro and ultramafic magmatic rocks. Third, hypersthene occurs in rocks that look magmatic. Much of the hypersthene in these rocks is fresh and in sharp contact with adjacent minerals, or with only a thin reaction rim of pale amphibole. In the Cummings belt the hypersthene is in tonalitic rocks that are closely associated with granulite. The hypersthene occurrences near the north edge of the map area (in the Pampa body and near the Live Oak body) look much like the hypersthene in the tonalite in the Cummings belt, but the setting suggests that the hypersthene here may be inherited from nearby mafic and ultramafic plutonic rocks. Hurlbut (1933) attributed the presence of hypersthene and augite in mafic inclusions in the southern California batholith to contamination from gabbro.

I have been repeatedly perplexed by tonalitic rocks that have magmatic character (sharply twinned and zoned plagioclase and hypautomorphic texture) but that contain fresh hypersthene in equilibrium with adjacent hornblende and plagioclase crystals. These rocks have seemed to me to be transitional between magmatic tonalite and metamorphic granulite. Warren Hamilton (written commun., 1983) has suggested that the hypersthene tonalites are magmatic rocks that have crystallized under granulite facies conditions, and that hypersthene tonalite reflects crystallization under conditions of lower water content, and higher pressure and temperature relative to the shallower normal granitic rocks of the Sierra Nevada batholith. On the other hand, Saleeby (1977) and Saleeby and Sharp (1980) have discussed hypersthene-bearing tonalites from the west side of the central Sierra Nevada batholith (Durrell, 1940; Macdonald, 1941) as part of a suture-filling suite of rocks ranging from cumulate olivine gabbro to biotite -hornblende tonalite. To my knowledge, no coarse amphibolitic gneiss or hypersthene-bearing granulitic rocks have been reported from the area Saleeby (1977) discussed. It is well to note here that the tonalite of Bear Valley Springs, which is in a transitional position between oceanic and continental crust, based on initial strontium data, could well be a tonalitic end-member of Saleeby's suture-filling suite. Two things set the southernmost Sierra Nevada rocks apart from the more northern areas; 1) is the close association of hypersthene-bearing magmatic tonalite and unequivocal hypersthene granulite (for example, in the Cummings belt); and 2) inclusions of gneiss, granulite, and associated rocks are found throughout the outcrop area of the tonalite of Bear Valley Springs.

Hypersthene in tonalite can originate in different geologic environments, and in the southernmost Sierra Nevada the choice is not everywhere obvious.

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[1] I use the term hypersthene, with the recognition that some could as well be bronzite.

Perhaps the two origins of the magmatic hypersthene just mentioned can be somewhat melded together. A suture-filling transitional tonalite could bring up and include fragments of deeper batholithic root rocks. Thus the local hypersthene-bearing spots in the tonalite of Bear Valley Springs reflect its deeper origin, whereas most of this possibly suture-filling rock now reflects a somewhat higher crustal level.

Hypersthene is spread over what seems to be a north-trending belt encompassing the eastern part of the San Emigdio-Tehachapi terrane and several of the mafic patches engulfed in the tonalite of Bear Valley Springs (fig. 5A). I have identified hypersthene in only 25 thin sections of the several hundred that have been examined of presumably suitable host rocks (mafic rocks, metamorphic rocks, and tonalite). Hypersthene is easily identifiable in thin section, and golden brown hypersthene crystals can generally be identified in hand specimens after a little practice. Thus hypersthene is not apt to be overlooked, and its relative sparseness in the southernmost Sierra Nevada is probably real. Some caution should be exercised in extrapolating from this sparse hypersthene occurrence to conclusions about metamorphic grade for the entire area.

Brown Hornblende

Hornblende that is pleochroic in various shades of light brown to olive brown is widespread in the amphibolite and mafic gneiss of the San Emigdio-Tehachapi terrane and in the closely related Cameron and Cinco areas (fig. 5B). Brown hornblende is also common in and near the Caliente, Pampa, and Live Oak mafic bodies north of the White Wolf fault. In part these occurrences are from retrograded mafic and ultramafic plutonic rocks, but brown hornblende is also found in definitely metamorphic amphibolite in these same areas. In addition, there are scattered occurrences of olive brown hornblende in normal granitic rocks.

By contrast, the typical hornblende color in thin section of granitic rocks of the southernmost Sierra Nevada is bright green, grassy green, or olive green. Such green hornblende also occurs in the San Emigdio-Tehachapi mafic belt, particularly in a broad transition zone with the tonalite of Bear Valley Springs.

Brown hornblende in metamorphic rocks is generally an index to relatively high-grade conditions, as suggested by the following references. Howie (1955) noted that hornblende in the granulite facies of the charnockitic rocks of Madras, India has a characteristic olive-brown color. Greenish brown or brown hornblende is associated with only the highest grade zone in a region of progressive regional metamorphism in the central Abukuma Plateau, Japan (Shido and Miyashiro, 1959). Eskola (1952) observed that in Lapland, common green hornblende is a reliable criterion of the amphibolite facies and is in contrast to the typical greenish brown hornblende of the lower granulite facies. Hamilton (1981) cites brown hornblende as a useful "index mineral" for the lower granulite facies. These data suggest that the wider distribution of brown hornblende (fig. 5B) relative to hypersthene (fig. 5A), particularly west into the Sierra Nevada tail, suggests a more extensive area of granulite facies metamorphism in the San Emigdio-Tehachapi terrane than the distribution of hypersthene-bearing samples alone would indicate.

Reddish Brown Biotite

Reddish brown biotite is widespread in the granodiorite of Lebec south of the Pastoria fault (fig. 5C), and less common but widespread, in the presumably correlative granodiorite of Gato-Montes to the east. Elsewhere in the granitic terrane, only scattered specimens have distinctive reddish brown biotite. Throughout the granitic terrane (except for the Lebec body) dark brown to opaque interference colors are characteristic of biotite. Most of the biotite in granofels and felsic gneiss of the San Emigdio-Tehachapi terrane is distinctly reddish brown. It thus appears that reddish brown biotite is common in both granitic and biotite-bearing metamorphic rocks in the Sierra Nevada tail, but rare elsewhere.

Reddish brown biotite is generally an indication of relatively high TiO_2 content (Deer and others, 1965). Engel and Engel (1960) have noted a systematic color change from greenish brown through reddish brown to deep reddish black, and a corresponding increase in TiO_2 content, with increasing regional metamorphism in the Adirondack Mountains, New York. John (1981) has recorded the presence of reddish brown biotite with "higher Ti contents in higher grade assemblages" in pelitic metamorphic rocks at the northern end of the Gabilan Range, California. He further noted that all the prograde mineral assemblages are above the second sillimanite isograd of Evans and Guidotti (1966). Warren Hamilton (personal commun., 1982) suggested that red biotite in a metamorphic rock indicates highest amphibolite and granulite facies (at or higher than the "second sillimanite isograd"), and that red biotite contains half as much combined water as ordinary green and brown biotite, which restricts red biotite to high-grade rocks.

Reddish brown biotite in metamorphic rocks thus appears to be a good index mineral for fairly high-grade conditions. Reddish brown biotite in granitic rocks probably means at least a relatively high TiO_2 content, and where abundant, as in the granodiorite of Lebec (fig. 5C), may reflect some unuusual (deep?) environment.

Muscovite

Occurrences of discrete, relatively coarse muscovite crystals in granitic rocks are plotted on figure 5D . Ocurrences of definitely secondary white mica are not plotted. Nevertheless one person's clean discrete primary muscovite crystal is, to someone else, a coarsely reconstituted secondary muscovite crystal. Most of the units in which I have found coarse, discrete muscovite also contain at least some hornblende and sphene, but not necessarily in the same sample. Also at most 1 percent of coarse muscovite is present in any one sample.

Coarse, discrete crystals of muscovite are relatively widespread in the granodiorite of Lebec, but are limited to one small area in the presumably correlative granodiorite of Gato-Montes. North of the Pastoria and Garlock faults, coarse muscovite is sparse, but there is a "relative concentration" in the northeast part of the map area.

Normative corundum is commonly cited as a clue to peraluminous, muscovite-bearing rocks. As much as 2 to 2.5 percent of normative corundum is present in some chemical analyses of granitic rocks of the southernmost Sierra Nevada. Uncertainties in analytical values of alkalis, lime, and alumina suggest that such amounts of normative corundum are unreliable guides to primary muscovite. Whether primary or secondary, I have been repeatedly impressed by the coarse discrete flakes of muscovite and the clean interlayers of muscovite and biotite in these rocks. These are not simple alteration products. If they are indeed secondary, they at least represent considerable reconstitution of material that to me suggests something hotter, deeper, and/or higher grade than typical deuteric or hydrothermal late granitic processes that produce the normal sericitic alteration.

I would suggest that the relative abundance of coarse muscovite in the granodiorite of Lebec, coupled with the abundant reddish brown biotite in the same unit, may be significant. Perhaps the granitic rocks in the Sierra tail south of the Pastoria fault zone reflect a somewhat deeper crustal level than the similar-looking granodiorite and granite bodies to the north and east.

Miller and Bradfish (1980) refer to experimental work of Luth and others (1964) and Day (1973) which suggest that "ideal muscovite" should not be stable in granitic rocks at pressures of less than about 3 kb. Primary muscovite would thus seem to suggest crustal depths of at least 10 km. Miller and Bradfish (1980) further point out, however, that plutonic muscovite is "nonideal" in composition and may have a larger stability field and may be stable at lower pressures and shallower crustal depths. Thus even if muscovite in granitic rocks is primary, there is still some question of what it means in terms of crustal depth. Nevertheless, one observation remains--primary-looking muscovite appears to be more common in the southernmost Sierra Nevada than in the rest of the batholith.

Sillimanite and Andalusite

Sillimanite both as coarse prismatic crystals and in fibrolite bundles is common and widespread (fig. 5E) in the metasedimentary rocks included in the granodiorite of Lebec (south of the Pastoria fault). Sillimanite is also widespread north of the Garlock fault in a number of metasedimentary pendants. Note that sillimanite is particularly abundant immediately north of the San Emigdio-Tehachapi mafic terrane.

Andalusite is much less widespread and is only abundant in the Pampa Schist (north-central part of the map area), where it occurs in coarse conspicuous crystals that are in part chiastolitic. Coarse andalusite is also locally abundant in dark metasedimentary layers in the Bean Canyon Formation, south of the Garlock fault. In part the more limited occurrence of andalusite may be a compositional control. Black, dense hornfelsic rocks that seem to be the perfect host for andalusite (and particularly chiastolite) are generally limited to the Pampa and Bean Canyon units.

The occurrences of sillimanite and andalusite are mutually exclusive, except near the north part of the map area where the two aluminosilicates are closely associated in the Pampa Schist.

Noteworthy is the absence of sillimanite in the San Emigdio-Tehachapi mafic terrane, and the abundance of sillimanite just north of the limits of the mafic terrane. This is not solely a compositional control, as some of the biotite-bearing granofels in the mafic terrane is compositionally very similar to sillimanite-bearing layers in the metasedimentary rocks to the north.

The Mountain Park terrane, south of Tehachapi, contains sillimanite-bearing layers, marble, and mica schist, but also plagioclase amphibolite with labradorite and brown hornblende that contains coarse poikilitic red garnet with bleached haloes. Possibly this is a transition between an area where sillimanite is stable to the north and a higher grade(?) terrane to the south and west where it is not stable. A similar possible transition zone is suspected along the margin of the San Emigdio-Tehachapi terrane, just south of the Comanche body, where sillimanite is common, and associated with coarse, haloed red garnet.

Present distribution of the aluminosilicates indicates that sillimanite and andalusite occur together near the north margin of the map area (there is some replacement of andalusite by sillimanite). To the south is a broad belt where sillimanite alone is present, then rather abruptly sillimanite disappears and is not found in the San Emigdio-Tehachapi mafic terrane. Crude "isograds" could be drawn to reflect these associations, but as the data are sparse I will leave the placement of such boundaries to the discretion of individual readers.

Note that the granodiorite of Lebec (fig. 5E) has abundant sillimanite in its included metamorphic rocks, whereas the presumably correlative granodiorite of Gato-Montes (Ross, in press) contains no sillimanite and only andalusite in its pendant rocks. Here once again the Lebec unit is "different" from its granite and granodiorite relatives and neighbors!

Holdaway (1971) has stated that: "The Al_2SiO_5 phase diagram is perhaps the most studied and least well defined silicate phase diagram." This pretty well sums up the long-term uncertainty about the stability fields of andalusite and sillimanite and what their presence or coexistence means in terms of P-T conditions, and hence, crustal depth. A review of aluminum silicate polymorphs (Ribbe, 1980) has cited Holdaway (1971) and Richardson and others (1969) as the most current and reliable experimental phase diagrams for the aluminosilicates and their elusive triple point. Holdaway (1971) place the triple point at 3.76 ± 0.30 kb and $501° \pm 20°C$. He further pointed out that the formation of andalusite indicates a depth of cover of less than 13 km. Richardson and others (1969) on the other hand placed the triple point at 5.5 kb and 622°C., which would increase the crustal depth where andalusite could occur. Warren Hamilton (written commun., 1983) suggested that andalusite alone equates to a crustal depth of formation of no more than 7 to 8 km, andalusite and sillimanite coexist at depths of 8 to 13 km, and sillimanite alone points to formation depths of 15 to 18 km.

Prehnite

Prehnite occurs as lozenges in biotite crystals and thin secondary veinlets in both granitic and metamorphic rocks (fig. 5F). Most of the prehnite is in the San Emigdio-Tehachapi terrane and the related Cameron, Cinco, and Hoffman mafic terranes. Prehnite is most common in a dark tonalite near the west end of the San Emigdio-Tehachapi terrane. The prehnite is definitely secondary, but shows no evidence of local derivation (as for example, from the alteration of plagioclase or mafic minerals).

Perhaps significantly, prehnite appears to be almost exclusively localized in a zone within a few kilometers of the Garlock and Pastoria fault zones. It is tempting to speculate that the prehnite may have leaked up along the Garlock and Pastoria fault zones.

Ross (1976d) described much more abundant prehnite veins and lozenges in the western Santa Lucia Range (fig. 1) that appear to be concentrated near the

San Gregorio-Hosgri fault zone. The prehnite here is also not a locally derived alteration product and may have leaked up along a fault zone. The source of the prehnite is unknown, but Ross (1976d) speculated that it may be a precipitate of metamorphic fluids (Barnes, 1970; White and others, 1973) derived from the metamorphism of underlying graywacke.

Prehnite, hosted largely by granulite and related rocks and concentrated near major fault zones, both in the southernmost Sierra Nevada and the Santa Lucia Range, may be more than just coincidence. Relatively high-grade metamorphic rocks and mafic plutonic and metamorphic rocks also host prehnite in Norway (Field and Rodwell, 1967), Germany (Maggetti, 1972), Sweden (Zeck, 1971), and Ireland (Hall, 1965). Could generation of secondary, late, but definitely introduced prehnite in mafic and high-grade rocks, be a clue to some special P-T or chemical conditions that are depth indicators?

Epidote and Allanite

Discrete, but anhedral, coarse crystals of epidote that look primary are a sparse accessory mineral in a few granitic rock samples in the southernmost Sierra Nevada. Euhedral allanite in rich chocolate brown crystals as long as 2 mm is also widely scattered and commonly rimmed with epidote. Deer and others (1965) observed that this is a common association in granitic rocks. Allanite, which has a distinctive reddish tint, is particularly abundant in the granodiorite of Lebec, where it favors samples that also contain reddish brown biotite.

E-an Zen and Jane Hammarstrom, (written commun., 1982) note that magmatic epidote has been found in a number of localities in the western Cordillera. They suggest that these magmatic epidote-bearing granitic rocks, that appear to occur on the inboard margins of accreted terranes from northern California to southeastern Alaska, may be high-pressure facies of typical calc-alkaline granitic rocks. Thus magmatic epidote may be another indicator of deeper crustal levels.

Aplite-alaskite-pegmatite Dikes

Coarse-grained pegmatite dikes and commonly associated alaskite and aplite dikes are widespread and common in the southernmost Sierra Nevada. Swarms of dikes were impressive enough to be mapped by Dibblee and Chesterman (1953), both east and west of the Caliente mafic terrane and also in and near the Pampa body. Conspicuous pegmatite dike swarms were also mapped by Dibblee and Warne (1970) in and near the Loop inclusion swarm, and in a large area west of the Comanche mafic rocks.

In my field investigations, I found no additional dike swarms comparable to the five just mentioned. Felsic dike material is notably abundant south of the Garlock fault, locally conspicuous in some felsic gneiss of the San Emigdio-Tehachapi terrane, and widespread and locally impressive throughout the granitic rocks to the north.

In the swarms, pegmatite dikes are up to 10 to 20 m thick and some can be traced for more than a kilometer. Most, however, are no thicker than 1 to 2 m and are much shorter. Only rare dikes are composite. Feldspar and quartz alone make up most dikes, but locally coarse muscovite and/or biotite, and distinctive black tourmaline are present. Some of the dikes in the felsic gneiss contain small amounts of pink to garnet.

My impression is that pegmatite and other felsic dikes are much more abundant in the southernmost Sierra Nevada than in areas of the central Sierra Nevada and Inyo-White Mountains that I have studied. However, Bateman and others (1963), Bateman (1965), and Moore (1963) note locally impressive dikes and swarms of pegmatite and related felsic rocks in the central Sierra Nevada. Hamilton (1981) noted that pegmatite sheets and veins are particularly abundant in middle crust granitic terranes (below depths recorded by exposed granitic rocks of the central Sierra Nevada batholith). Pegmatite abundance alone is no compelling argument for deeper exposed crustal levels in the southernmost Sierra Nevada, but coupled with the other indicators previously discussed, certainly supports such a view.

COMPARISON AND CONTRAST TO HYPERSTHENE-BEARING ROCKS IN THE SANTA LUCIA RANGE

Hypersthene-bearing granitic and metamorphic rocks (Compton, 1960, 1966; Ross, 1976a, b, c) in the western Santa Lucia Range (across the San Andreas fault and about 300 km to the northwest near Monterey, California) naturally invite a comparison with the hypersthene-bearing rocks of the southernmost Sierra Nevada. Granitic rocks, showing about the same radiometric age as the metamorphic rocks they intrude, have the same middle Cretaceous age in both areas. J. H. Chen (personal commun., 1980, cited by Hamilton, 1981) indicates a U-Pb radiometric age of middle Cretaceous on both granulitic metamorphism and associated granitic rocks in the western Santa Lucia Range. Sams and others (1983) report 99 m.y. concordant zircon ages on the tonalite of Bear Valley Springs and concordant zircon ages in the 100 to 115 m.y. range for samples of the hornblende-rich gneiss in the southernmost Sierra Nevada.

Hypersthene-bearing tonalite in the Santa Lucia Range has a somewhat lower quartz content than "normal" tonalite, hornblende that is markedly in excess of biotite, and only traces of K-feldspar (Ross, 1976a, b). Thus in mineral content and general appearance the hypersthene-bearing tonalite of the Santa Lucia Range is similar to some hypersthene-bearing rocks of the southernmost Sierra Nevada.

Based on field work and petrography in both areas, I am even more impressed by the similarities of some of the high-grade metamorphic rocks of the two areas--particularly quartz-bearing granofels and impure quartzite. These rocks have a clean, fresh granoblastic texture, and contain abundant reddish brown biotite, conspicuous coarse shiny flakes of graphite, and brown hornblende. Red garnet is also characteristic of both terranes. Also worthy of note is the absence of sillimanite, both in the belt of rocks containing granofelsic rocks in the western Santa Lucia Range and in the southernmost Sierra Nevada.

Amphibolite is locally abundant in the Santa Lucia Range, but it is commonly in relatively thin interbeds with marble and calc-hornfels. I have interpreted much of the amphibolite in the Santa Lucia Range as metasedimentary. This is in marked contrast to the extensive massive to gneissic amphibolite in the San Emigdio-Tehachapi that I suggest is dominantly or exclusively meta-igneous. The granofelsic belt in the Santa Lucia Range is strikingly rich in marble relative to the rest of the metamorphic terrane of the Range (Ross, 1976a). This is a complete reversal of the pattern in the southernmost Sierra Nevada where the high-grade San Emigdio-Tehachapi terrane has only rare and local calcareous material, and the metasedimentary rocks to the north and east are rich in marble.

In my earlier work in the Santa Lucia Range, I suggested that: "Most of the metamorphic rocks appear to be high in the amphibolite facies and contain widely distributed sillimanite and red garnet. West of the Palo Colorado-Coast Ridge fault zone, sillimanite is absent, but hypersthene and coarse red garnet are found both in the gneiss and in associated "charnockitic" plutonic rocks, suggesting that, at least locally, the granulite facies (Compton, 1960, 1966) was reached (Ross, 1976a)." Based on my more recent work in the southernmost Sierra Nevada, I suspect both Compton and I were conservative in assigning rocks to the granulite facies in the Santa Lucia Range. The almost mutually exclusive occurrence of sillimanite and orthopyroxene (Ross, 1976c, fig. 4) is so similar to the relation in the southernmost Sierra Nevada (fig. 5E) that I now suspect that these rocks in the western Santa Lucia Range with limited hypersthene, but abundant granofels, are largely a granulite-grade terrane. The extensive sillimanite-garnet gneissic and schistose terrane to the east that encompasses the rest of the Santa Lucia Range and the Gabilan Range seems to be largely of amphibolite grade. Compton (1960) noted that granulite facies rocks "occur here and there in the central part" (of the Santa Lucia Range) within the area of dominantly sillimanite-bearing, amphibolite-grade metamorphic rocks. Another notable enclave in the amphibolite-grade terrane is found in the central Gabilan Range (Ross, 1976c). Here, in a largely marble and mica schist pendant, is a "layer" of spotted amphibolite that is dominated by polygonal plagioclase (about An_{45-50}) and light to moderate olive brown hornblende. Present in the rock are conspicuous crystals of pink-green pleochroic hypersthene and less clinopyroxene in fresh crystals, both of which are in sharp contact with adjacent plagioclase and hornblende. Abundant metallic opaque grains and minor quartz are also present. This rock is almost certainly a hypersthene-granulite.

In summary, both the western Santa Lucia Range and the Sierra Nevada tail contain strikingly similar hypersthene granulite, hypersthene-bearing tonalite, and distinctive granofels. Both areas are bounded on the east by vast granitic terranes containing sillimanite-bearing, amphibolite-grade metamorphic rocks in which there are enclaves of granulite-facies rocks. Thus the metamorphic environment of the two areas is strikingly similar. Lithologic dissimilarities, such as form and protolith of amphibolitic rocks and the distribution of calcareous rocks, leave the question of correlation tantalizing, but moot. Correlation would be more acceptable if the metamorphic grade distribution in the Santa Lucia-Gabilan and southernmost Sierra Nevada terranes were "mirror images" of each other. The fact that the metamorphic grade decreases to the northeast in both terranes is a serious obstacle to their original juxtaposition.

The presence of the schist of Sierra de Salinas in the Santa Lucia Range also provides a possible analogy to the southernmost Sierra Nevada. The schist of Sierra de Salinas is a possible correlative of the Rand-Pelona-Orocopia Schist terrane (Ross, 1976d). Throughout southern California, these schists are characteristically in structural contact with high-grade metamorphic rocks. The Sierra de Salinas is largely isolated from the high-grade gneissic and granulitic (?) rocks that are exposed in the main part of the Santa Lucia Range. Migmatitic rocks with red garnet, however, are in fault contact with the schist at the north end of the Sierra de Salinas, but the relations are not clear, due to poor exposures and limited study. Granitic rocks intrude the schist of Sierra de Salinas at the southern end of the Sierra de Salinas and in the Gabilan Range. This is atypical of the Rand-Pelona-Orocopia terrane, but felsic granitic rocks presumably intrude the westernmost Rand Schist sliver in the southernmost Sierra Nevada.

The near juxtaposition of a block of possible Rand-Pelona-Orocopia Schist (anomalous to the Salinian block) and hypersthene-bearing tonalitic and metamorphic rocks, which contain abundant red garnet, makes it tempting to propose the same structural setting for the Santa Lucia Range as for the other areas of the Rand-Pelona-Orocopia Schist (including the southernmost Sierra Nevada?).

METAMORPHIC GRADE

The hornblende-rich mafic terranes of the southernmost Sierra Nevada, based on their mineralogy, have aspects of both upper amphibolite and lower granulite grade metamorphism. Unquestioned hypersthene granulite facies rocks are present in the southernmost Sierra Nevada, and are particularly well developed in the Tunis Creek area (fig. 4A). Granofels that may or may not reflect granulite facies conditions is more widespread. The absence of sillimanite throughout the San Emigdio-Tehachapi mafic terrane may reflect metamorphic conditions higher than amphibolite grade, in which sillimanite is no longer stable, for that entire mafic terrane.

Widespread hypersthene, brown hornblende, and coarse red garnet in the mafic terranes suggest relatively deep and high-grade (granulite) metamorphic conditions. Yet brown biotite, muscovite, and K-feldspar (fig. 4E) are rather common in the San Emigdio-Tehachapi terrane away from the Tunis Creek hot spot, green hornblende in discrete primary crystals is also widespread, and many of the mafic rocks do not contain pyroxene, all of which points to amphibolite grade conditions.

Problems of "grade assignment" in high-grade metamorphic terranes are widespread. Turner and Verhoogen (1951) noted that in many classic granulite terranes where the paragenesis of the granulite facies is clearly recognizable, it is to some extent obscured by the presence of considerable hornblende or biotite. They cite, as an example, the famous Lewisian area of Scotland, where regions of normal amphibolite facies are associated with minor rocks with the granulite pair diopside-hypersthene. Buddington (1939) observed "characters of both amphibolite and granulite facies" in high-grade rocks of the Grenville Series of the Adirondack Complex. He interpreted the association of supposedly unstable biotite and hornblende in the granulite facies to indicate: 1) disequilibrium (retrograde metamorphism), 2) transitional conditions between granulite and amphibolite facies, or 3) insufficient water for all the iron or magnesia to be accommodated by the hydrous minerals biotite and hornblende. This latter concept of "dry spots" is essentially what Compton (1960) postulated to explain the hypersthene-bearing rocks of the western Santa Lucia Range.

In the southernmost Sierra Nevada, retrograde metamorphism of the mafic metamorphic rocks, most recognizable in the pale green "actinolitic" amphibole, is widespread and locally impressive. Nevertheless, much of the plagioclase amphibolite is surprisingly fresh and does not look like retrograded pyroxene rock. The concept of local "dry spots" is somewhat more difficult to evaluate, from my data, but it is certainly a valid possibility to explain local granulite in a largely amphibolitic terrane. From my own observations and the petrographic study of the rocks of the southernmost Sierra Nevada, I would favor concept (2) of Buddington (1939) "transitional conditions between granulite and amphibolitic facies." A not unreasonable extrapolation from the distribution of the granulite-grade indicators (hypersthene, brown hornblende, red biotite, coarse red garnet), discussed in this report, would suggest a vast terrane of granulite facies rocks in the southernmost Sierra Nevada. On the other hand, one cannot ignore the presence of the amphibolite-grade indicators, green hornblende and brown biotite, and the absence of pyroxene and red garnet from large areas.

CRUSTAL LEVEL OF THE BASEMENT ROCKS OF THE SIERRA NEVADA

In a recent study, Sharry (1981, 1982) has reported that geobarometry and geothermometry of two-pyroxene granulite north of the Garlock fault suggests P-T conditions of 8.3 Kb and 740° C., which equates to a depth of about 30 km. Ghent and others (1977) suggest that migmatitic amphibolitic granulites in British Columbia may represent depths of as much as 25 km. The lithologies of some of their rocks are comparable to the mafic terranes of the southernmost Sierra Nevada.

Hamilton (1981), in describing migmatitic middle crust rocks in which metamorphic rocks dominate, noted that they represent a depth range from about 12 to 25 km. The shallower parts are in upper amphibolitic facies (and often include granitic rocks with primary muscovite) and the deeper parts are in lower granulite facies, characterized by orthopyroxene and brown hornblende. These two environments can be matched in the southernmost Sierra.

These scattered data suggest that maximum crustal depths on the order of 25 to 30 km may be represented by the mafic terranes of the southernmost Sierra Nevada. At these depths A. H. Lachenbruch (written commun., in Bateman and Eaton, 1967) has suggested that melting temperatures (630°) could develop. At least local melting and mobilization of the mafic basement rocks in the southernmost Sierra is suggested from diking and local homogeneous texture, as well as from the presence of cleanly twinned and somewhat zoned plagioclase. The commmon quandary of deciding in the field or even in thin section if a sample is metamorphic or magmatic also suggests at least near-melting conditions. Closely similar U-Pb radiometric ages of associated metamorphic and granitic rocks in the Sierran tail (Sams and others, 1983) also point to depths suitable for melting and equilibration of the metamorphic rocks.

By contrast, Bateman and Eaton (1967) suggest that present exposures in the central Sierra Nevada represent much shallower crustal depths of about 10 km. Other estimates of the crustal depth of present exposures elsewhere in the Sierra generally range from 5 to 15 km (Putnam and Alfors, 1965; Evernden and Kistler, 1960, Hietanen, 1973; Presnall and Bateman, 1973).

Hypersthene- and augite-bearing tonalite has been described along the western margin of the central Sierra Nevada batholith by Durrell (1940) and Macdonald (1941). These localities (fig. 1, locs. D and M) suggest possible analogy with the relatively high-grade and deep crustal conditions of the southernmost Sierra Nevada, as does the report of brown hornblende and hypersthene in hornblende gabbro by Durrell (1940). Considerable recent and detailed work in these areas (Saleeby, 1977; Mack and others, 1979; Saleeby and Sharp, 1980) indicates that these pyroxene tonalites are part of a suture-filling suite of rocks emplaced directly into a major suture zone between oceanic and continental crust. Sharp contacts, resolvable contact aureoles, and evidence of relatively rapid cooling of these rocks, argues against great emplacement depth (Saleeby and Sharp, 1980). None of the work along the western margin of the central Sierra has reported coarse gneiss or granulite-grade metamorphic rock, which is perhaps the best argument against deep crustal emplacement for those rocks. Examination of mafic inclusions in the pyroxene tonalites of the central Sierra, however, for evidence of deeper root rocks might prove fruitful.

Many years ago, near the east margin of the Sierra Nevada batholith in the Inyo Mountains (fig. 1, loc. R), I noted the occurrences of accessory orthopyroxene and abundant clinopyroxene in a dark granitic rock and coarse prismatic sillimanite in associated metasedimentary rocks (Ross, 1969). Now in the light of the southernmost Sierra Nevada data, these anomalous Inyo mineral occurrences take on possible significance as crustal depth indicators.

Clinopyroxene is particularly abundant in these dark granitic rocks (as much as 20 percent in part in subhedral to euhedral crystals), but coexisting orthopyroxene is relatively sparse. Coarse, prismatic sillimanite was found at three localities along the east base of the Inyo Mountains, and has been chemically analyzed by Dodge (1971). Coarse, prismatic sillimanite is virtually unknown from the metamorphic terranes of the central and northern Sierra Nevada, or elsewhere in the Inyo-White Mountains.

The dark granitic rocks of the Inyo Mountains are Jurassic, in contrast to the largely Middle Cretaceous age of the southern Sierra Nevada granitic rocks. Also Dunne and others (1978) consider the dark Inyo rocks to be part of an alkalic suite that is chemically and petrographically distinct from Sierran-type granitic rocks. The dark Inyo rocks are indeed anomalously high in K-feldspar (for such dark rocks) and are low in quartz compared to typical Sierran granitic rocks. The abundance of clinopyroxene is also atypical of Sierran granitic rocks.

Even if the orthopyroxene-clinopyroxene-bearing granitic rocks of the Inyo Mountains are from a different magmatic suite (and certainly they have a different age) from the granitic rocks of the southernmost Sierra Nevada, they suggest a relatively deep crustal level, perhaps comparable to that of much of the southernmost Sierra Nevada terrane.

The granodiorite of Lebec, the major granitic pluton south of the Pastoria fault in the Sierra Nevada tail (fig. 2), has the physical appearance of a shallow, upper crust, "normal" granitic rock similar to the extensive granite and granodiorite plutons to the north and east of the tail. Yet the granodiorite of Lebec has abundant reddish brown biotite (fig. 5C), widespread, coarse "primary" muscovite (fig. 5D), and coarse sillimanite is more abundant in associated metamorphic rocks (fig. 5E), than in metamorphic rocks associated with granodiorite and related granite plutons to the north and east. These mineral associations suggest that the Lebec mass represents a somewhat deeper crustal level than the other granitic plutons, and that the whole Sierra tail, not just the mafic terrane north of the Pastoria fault zone, is relatively deep. The crustal depth "differential" across the Pastoria fault may be less than that across the Garlock fault to the east, where Sharry (1982) has estimated a 30 km crustal depth north of the fault, and only a 10 km depth south of the fault. The presence of andalusite, and the absence of sillimanite in the metamorphic framework rocks south of the Garlock fault (fig. 5E), is compatible with a relatively shallow crustal depth south of that fault.

About 10 km west of Tehachapi, the tonalite of Bear Valley Springs includes a northwest-trending "pendant," about 15 km long, that is composed of calcareous, siliceous, and pelitic metasedimentary rocks (fig. 6). The pendant rocks and the enclosing tonalite are grossly similar to other areas of exposure of these widespread rock types. The contact between the metamorphic and tonalitic rocks, however, is a strongly foliated and deformed envelope of tonalite as thick as 2 km. In part the tonalite is intensely deformed to mylonite and even ultramylonite. The belt of deformed tonalite also contains felsic granitic rocks, gabbro, diorite (amphibolite?), gneiss, and hybrid-looking rocks. Most contacts between plutonic and metasedimentary rocks in the southernmost Sierra Nevada are relatively sharp and do not show such pronounced zones of shearing. Two areas of conspicuously sheared plutonic rock are present, however, further to the north. About 30 km north of Tehachapi, strongly deformed tonalite forms a belt as much as 1 km thick and several kilometers long, against metasedimentary rocks. About 10 km north-northwest of Tehachapi, a large oviod mass of felsic granitic rock, included in metasedimentary rock, is strongly deformed to augen gneiss. These two localities and some minor nearby local sheared rocks can most simply be explained as protoclastic deformation at the edge of a pluton. But this essentially north-trending zone of deformation, close to the quartz diorite line of Moore (1959), could also mark a zone of considerable difference in crustal depth between the deeper tonalites on the west and the shallower, younger, and more felsic granitic bodies on the east.

Just east of the sheared envelope (fig. 6) is the Loop inclusion swarm containing hypersthene granulite and the Mountain Park gneiss body, and just to the west is the Cummings belt of hypersthene granulite and hypersthene-bearing tonalite. In discussing the Mountain Park body, note has already been made of a possible transition between mafic rocks of deeper affinity with metasedimentary rocks of presumably less depth. Is the strongly deformed tonalite envelope evidence of protoclasis, but at considerable depth, based on the presence of both ultramylonite and nearby hypersthene granulite?

I have observed the coexistence of hypersthene and clinopyroxene (in the same thin section) locally in the Pampa and Cummings mafic terranes, but have not seen these two minerals together in the San Emigdio-Tehachapi terrane (based on the examination of about 150 thin sections). Sharry (1981), in a more detailed study of the eastern part of the San Emigdio-Tehachapi terrane, reported several occurrences of coexisting orthopyroxene and clinopyroxene. Sharry (1981, 1982) used this mineral pair in geothermometry and geobarometry calculations that suggested crustal cepths of formation of about 30 km. If these determinations are valid, it means that such crustal depths are also indicated for mafic terranes some distance north of the main San Emgidio-Tehachapi terrane.

THOUGHTS ON BATHOLITHIC "ROOTS

The mafic, largely metamorphic, terrane of the Sierran tail, representing crustal depths of as much as 30 km, may be an exposure of the root zone of the Sierra Nevada batholith, or a fragment of the substrate beneath the batholith.

In the central Sierra Nevada, Bateman (1979) has postulated a layer from 10 to 20 km deep in which settled mafic minerals and plagioclase are abundant. Below this level he envisions a thick layer of hornblende-bearing garnet pyroxene rocks down to the seismic Moho. The amphibolite and granulite-grade rocks that are exposed in the southernmost Sierra Nevada have at least some compositional compatibility with Bateman's suggestions for lower crustal rocks.

Barnes and others (1981) argued that the compositions of waters from a number of soda springs in the northern and central Sierra point to the presence of serpentinite (antigorite), metamorphosed marine sedimentary rock, and marble at depth in areas where the present outcrop is dominantly granitic. They further suggested that the metamorphosed marine clastic rocks may have had a mafic volcanic source. "Soda springs" sampled in the southernmost Sierra Nevada showed only shallow circulation of meteoric water and provided no hints of the basement composition (Ivan Barnes, personal commun., 1980). It is interesting to speculate, however, that the "metamorphosed marine clastic rocks of possible mafic volcanic source" might be similar to the hornblende-rich mafic rocks of the southernmost Sierra Nevada. Preliminary oxygen isotope studies on selected samaples of gneiss, amphibolite, and granulite from the San Emigdio-Tehachapi terrane show strong enrichment in ^{18}O, which points to a marine sedimentary protolith for these high-grade metamorphic rocks (Ivan Barnes, written commun., 1983).

The widespread tonalite of Bear Valley Springs has characteristics that suggest that it may also represent a relatively deep crustal level. The tonalite contains widespread and abundant ovoid mafic inclusions, which are in part amphibolite and even locally fresh hypersthene granulite. The tonalite locally contains hypersthene, which is fresh and in equilibrium with the rest of the rock. Abundant gneissic streaks and patches, dark schlieren, and some impressive mylonite zones are present in the tonalite. Hornblende and biotite are generally in anhedral, ragged crystals and clumpy intergrowths that give the rock a dirty, messy texture. The tonalite of Bear Valley Springs also appears to grade into, and be mixed with, rocks of the San Emigdio-Tehachapi terrane through a wide, indistinct contact zone. The tonalite has all the traits of a body that has been extensively granitized, ultrametamorphosed, and/or contaminated by a gneissic terrane. In other words, just the sort of plutonic body one might envision near the bottom of a batholithic terrane. In any event, the tonalite of Bear Valley Springs is markedly different from most of the rest of the plutons of the southernmost Sierra Nevada that look unequivocally clean and intrusive and suggests shallower crustal levels.

Scattered strontium data point to an oceanic crust environment for the mafic terrane and suggest its relationship with the tonalite of Bear Valley Springs. The following initial strontium values have been determained: mafic terrane, 0.703 to 0.704; tonalite of Bear Valley Springs, 0.7050 to 0.7055; and granite-granodiorite plutons to the northeast; 0.707 to 0.708. Kistler and Peterman (1978) indicate that the line of 0.706 initial strontium values marks the western limit of Precambrian continental crust. Thus both the mafic terrane and the tonalite of Bear Valley Springs have ocean affinities.

Evidence from the southernmost Sierra Nevada suggests that some, perhaps most, and maybe all of the mafic, ellipsoidal inclusions in the plutonic rocks of the entire batholith are remnants of a mafic root zone or metamorphic substrate. Typical-looking mafic inclusions, but with the mineral content of hypersthene granulite, are found in both the Loop and Comanche areas. A significant number of other mafic inclusions are amphibolite composed almost entirely of andesine-labradorite and olive green to olive brown hornblende. Other inclusions have in addition, small amounts of brown to reddish brown biotite and quartz--hornblende and plagioclase invariably dominate. These inclusion lithologies closely match the characterizing rocks of the San Emigdio-Tehachapi mafic terrane and the other widely scattered mafic scraps in the southernmost Sierra Nevada. I have seen no "inclusion-calving grounds," but it takes little imagination to extrapolate from the impressive Loop swarm to the mafic root or substrate of the Sierran tail.

Xenoliths of upper mantle and lower crust affinities have been recovered from trachyandesite that intrudes granodiorite in the central Sierra Nevada (Domenick and others, 1983). Some of the lower crust xenoliths appear to be similar to rocks that are presently exposed in the southernmost Sierra Nevada. One xenolith is a garnet granulite, composed principally of clinopyroxene, garnet, plagioclase, and orthopyroxene, and containing minor amounts of quartz, biotite, and hornblende. Domenick and others (1983) inferred that the granulite xenolith represents residua from a source that was partially melted to produce granodiorite. On a diagrammatic crustal cross section they note that the "point of origin" of the garnet granulite is at a crustal depth somewhat in excess of 30 km. The garnet granulite, with dominant clinopyroxene, probably is an upper granulite grade rock that represents a crustal level somewhat deeper than the exposed lower granulite grade rocks of the southernmost Sierra Nevada. I have not observed the mineral pair clinopyroxene-red garnet in the same thin section in the southernmost Sierra Nevada. Other xenoliths described by Domenick and others (1983), are amphibolite with minor biotite and hornblende hornfels composed principally of plagioclase and amphibole, with lesser orthopyroxene, biotite, and quartz. These xenoliths, shown diagrammatically to have come from depths of about 15 km appear to be similar to the two most characterizing lithologies of the mafic terranes of the southernmost Sierra Nevada. The hornblende hornfels has a mineral content much like the hypersthene granulite of the San Emigdio-Tehachapi terrane and may represent a somewhat deeper crustal level than the postulated 15 km. A sillimanite gneiss xenolith is also described that consists of plagioclase, biotite, garnet, and minor sillimanite and amphibole. Domenick and others (1983) suggest that this xenolith came from a depth of about 10 km. This amphibolite-grade xenolith is compatible with metasedimentary rocks in the broad area north of the San Emigdio-Tehachapi mafic terrane where sillimanite is the sole aluminosilicate (fig. 5E). The absence of quartz in this xenolith is, however, atypical of most southernmost Sierra sillimanite-bearing rocks.

The lucky chance preservation of xenoliths, coupled with the diligent observation required to spot them, provide a natural core through the crust and upper mantle, as Brooks and others (1980) have noted. Particularly fascinating to me is the general lithologic correlation between some of the xenoliths and the exposed basement of the southernmost Sierra Nevada. The upper part of the "sub-granitic crust of metamorphosed sedimentary and igneous rocks" inferred from the xenoliths by Domenick and others (1983), thus probably has an exposed counterpart at the southern end of the batholith.

Another batholith root zone analog may be preserved in the Santa Lucia Range (fig. 1). A general comparison of these rocks with the southernmost Sierra Nevada basement has already been made (p.23). Ross and McCulloch (1979) noted an extensive migmatitic-gneissic mixed zone in the Santa Lucia Range that might represent a batholithic root zone. They presented no data on P-T conditions, but the presence of both high amphibolite and low granulite grade rocks suggests depths comparable to those suggested for similar terranes by Sharry (1982), Hamilton (1981), and Ghent (1977)--depths on the order of 20 to 30 km. The Santa Lucia Range rocks have more quartzofeldspathic gneiss and less amphibolitic material than is found in the mafic "root" terrane of the southernmost Sierra Nevada. Suggestively the Santa Lucia basement is more "continental" and the southernmost Sierra basement is more "oceanic." Alternatively the Santa Lucia basement may be a somewhat more "reactive," and higher level in a root zone whereas the southernmost Sierra Nevada basement may represent a somewhat more "refractory" (and deeper?) part of a root zone.

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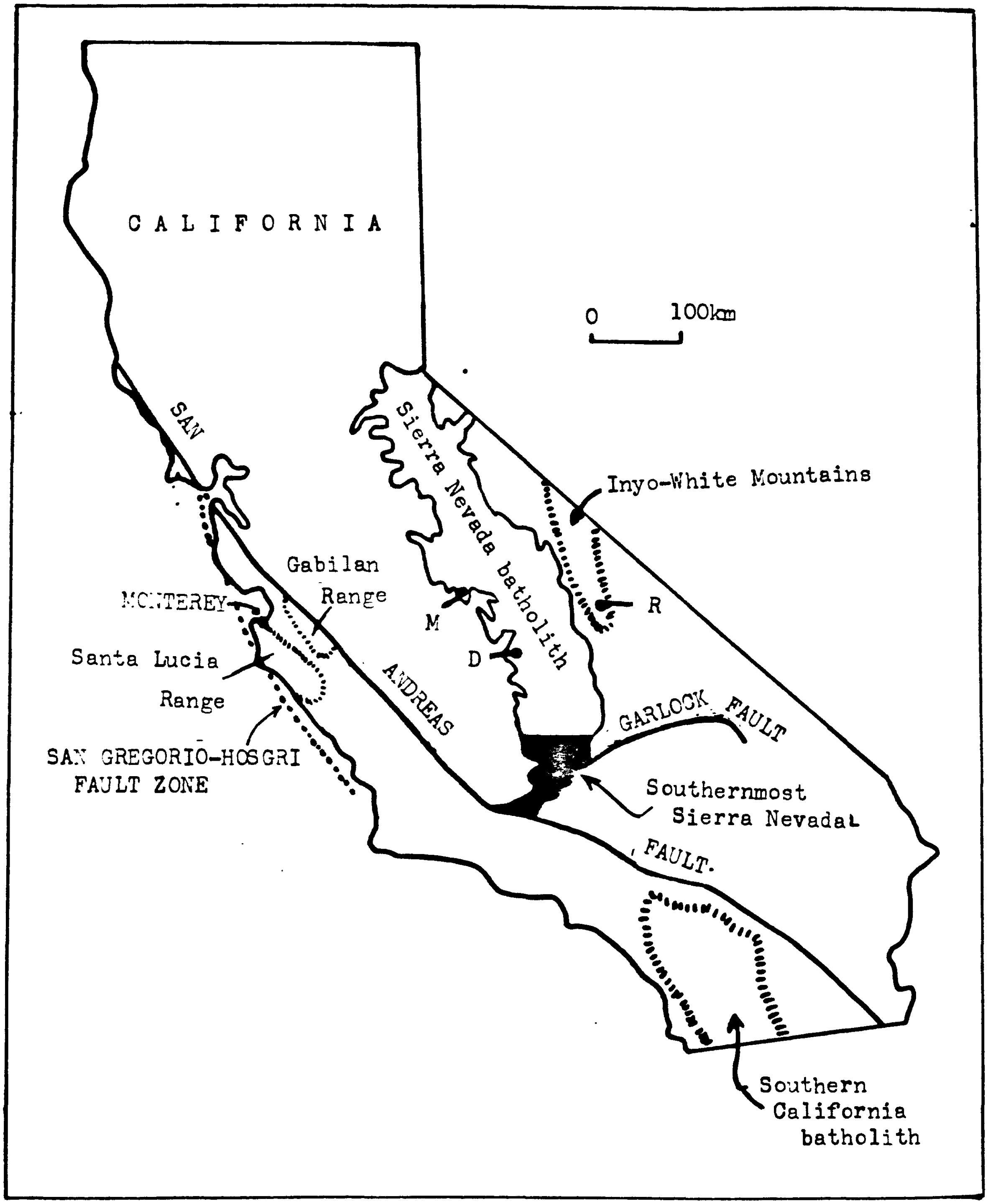

Figure 1. Index map showing location and setting of southernmost Sierra Nevada. Selected localities of pyroxene-bearing granitic rocks: D (Durrell, 1940), M (Macdonald, 1941), R (Ross, 1969).

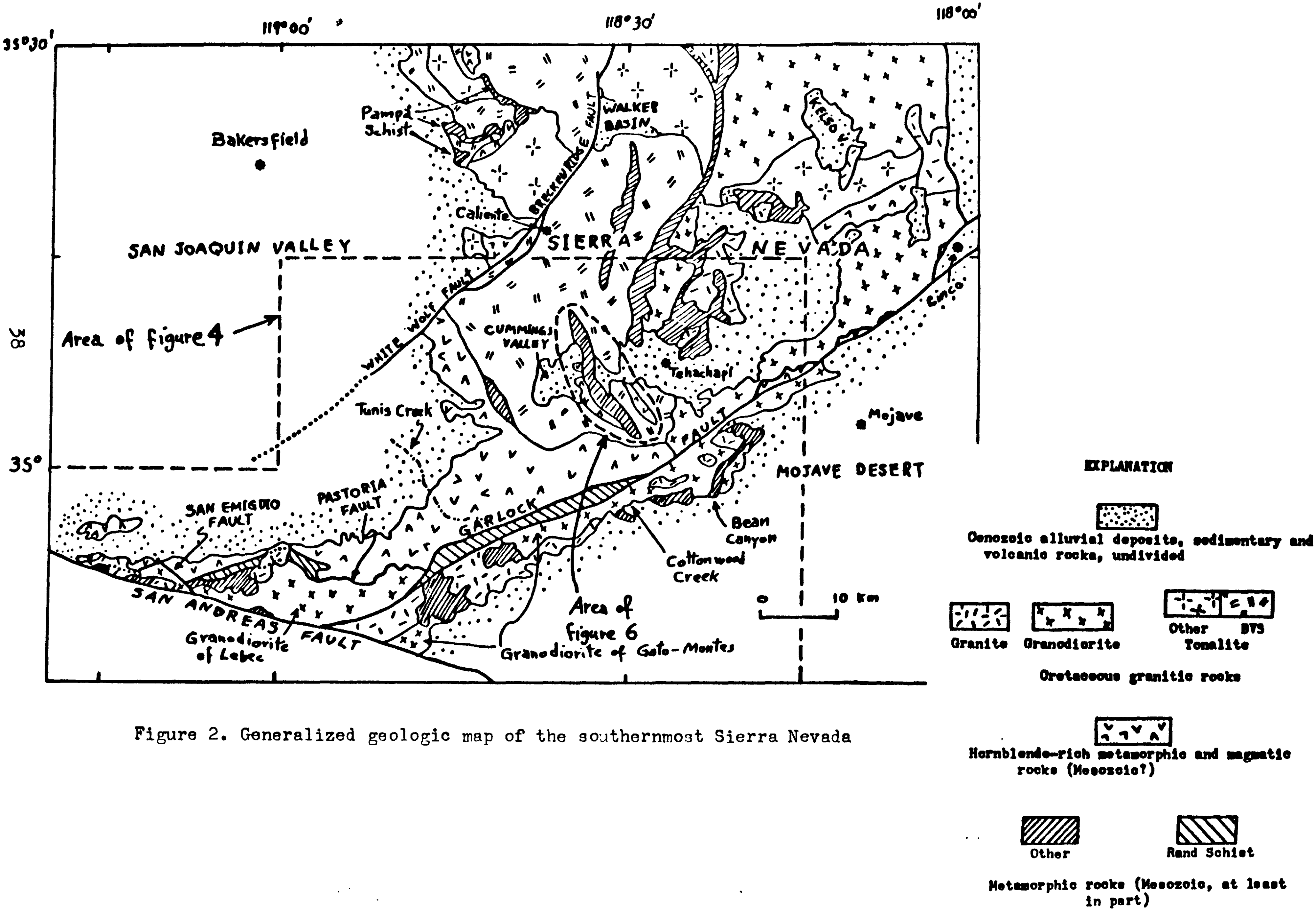

Figure 2. Generalized geologic map of the southernmost Sierra Nevada

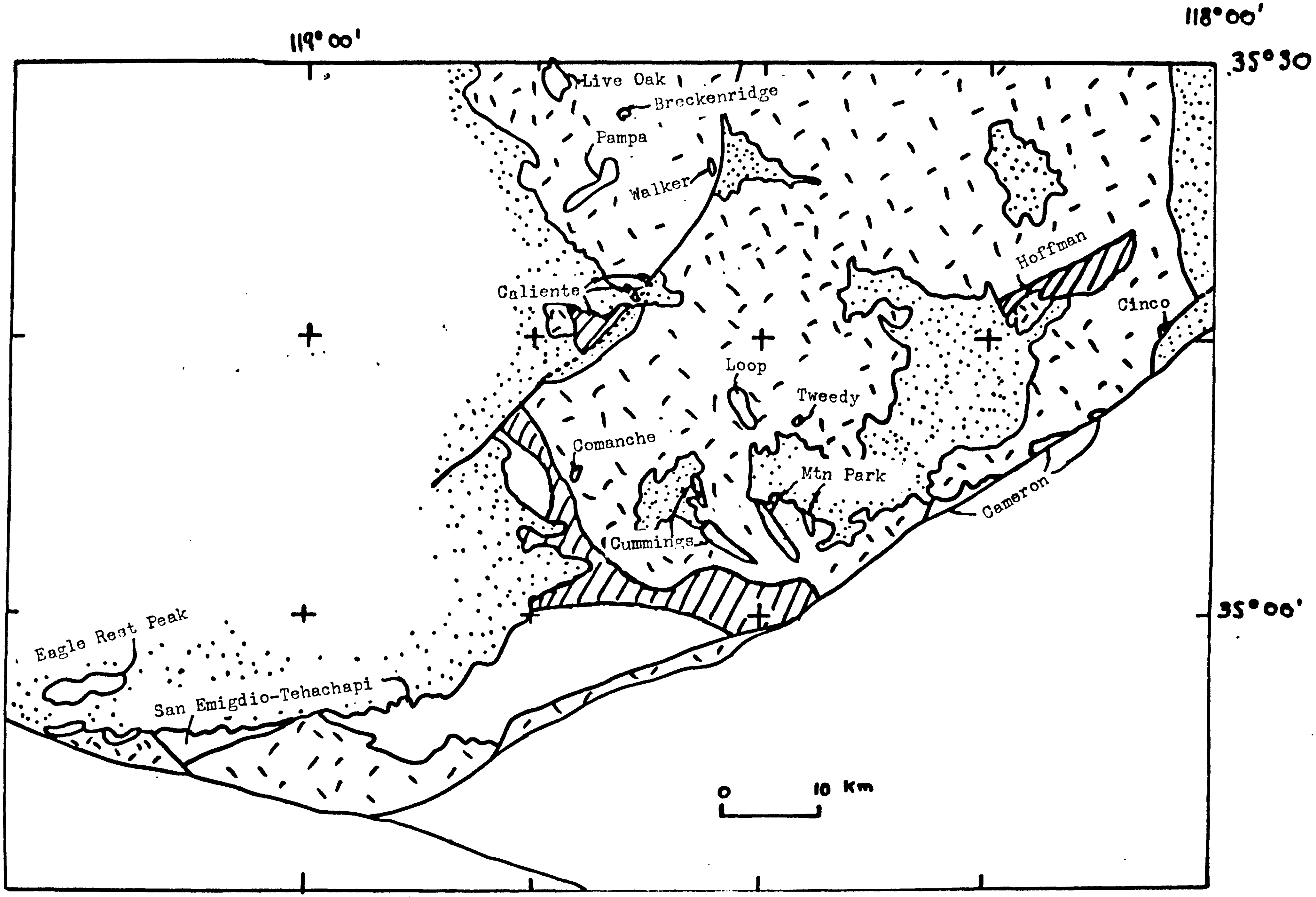

Figure 3. Location of hornblende-rich metamorphic and magmatic terranes, southernmost Sierra Nevada, California. (Cross-barred areas indicate hornblende-rich terranes that are extensively invaded by younger granitic rocks)

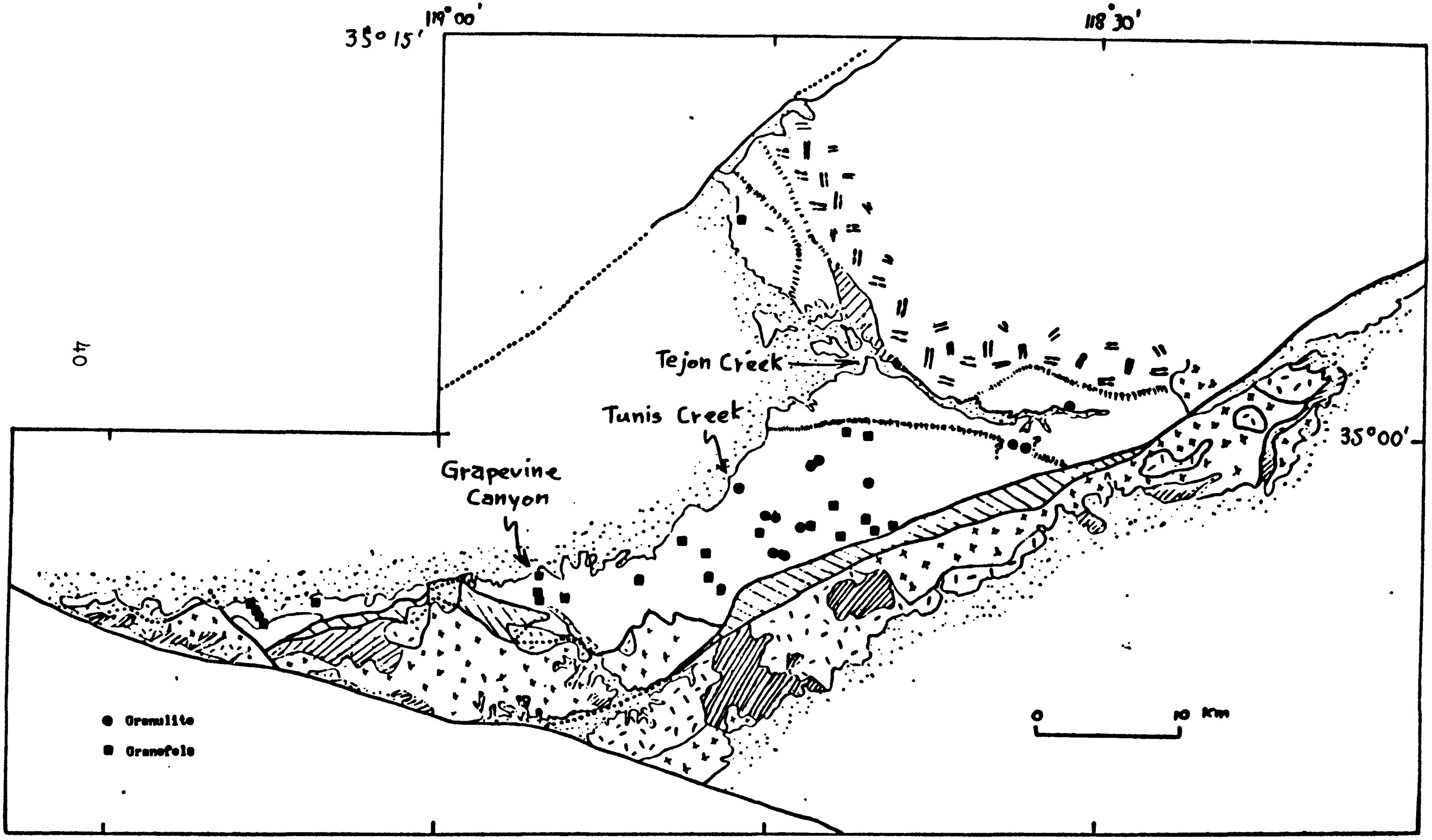

Figure 4 A. Generalized geologic setting of the San Emigdio-Tehachapi hornblende-rich terrane showing the location of samples of granulite and granofels.

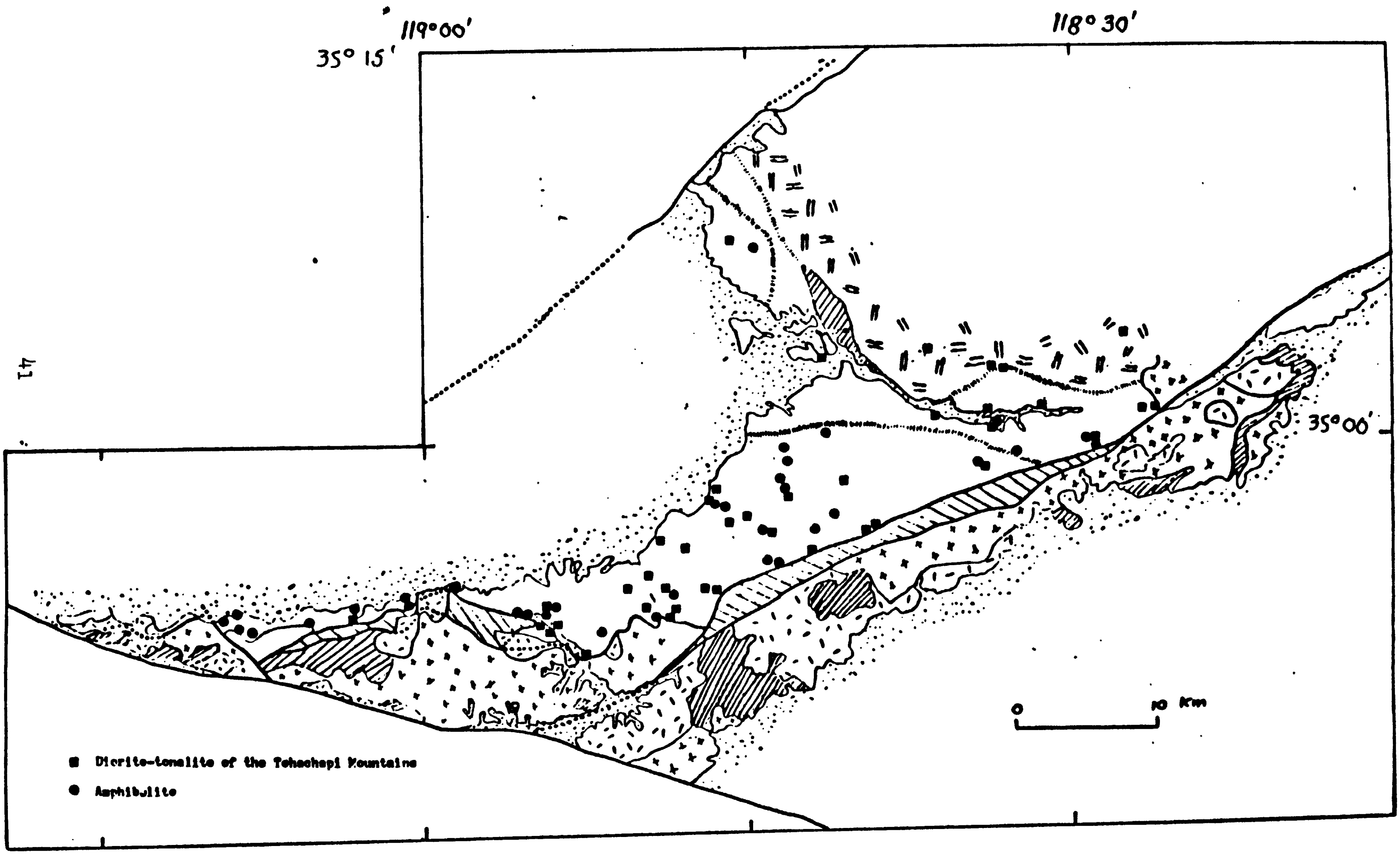

Figure 4 B. Generalized geologic setting of the San Emigdio-Tehachapi hornblende-rich terrane showing the location of samples of diorite-tonalite of the Tehachapi Mountains and amphibolite.

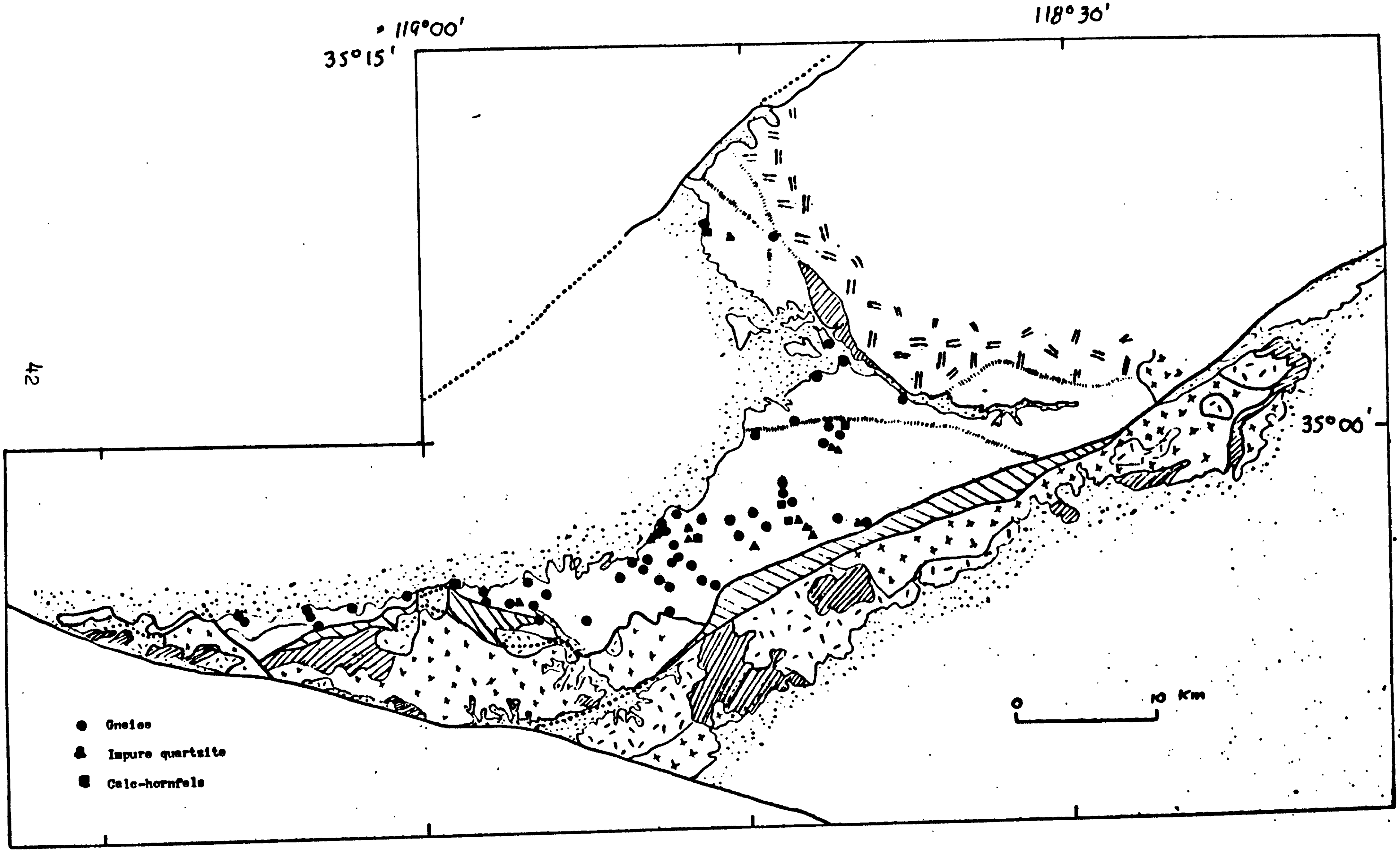

Figure 4 C. Generalized geologic setting of the San Emigdio-Tehachapi hornblende-rich terrane showing the location of samples of gneiss, impure quartzite, and calc-hornfels.

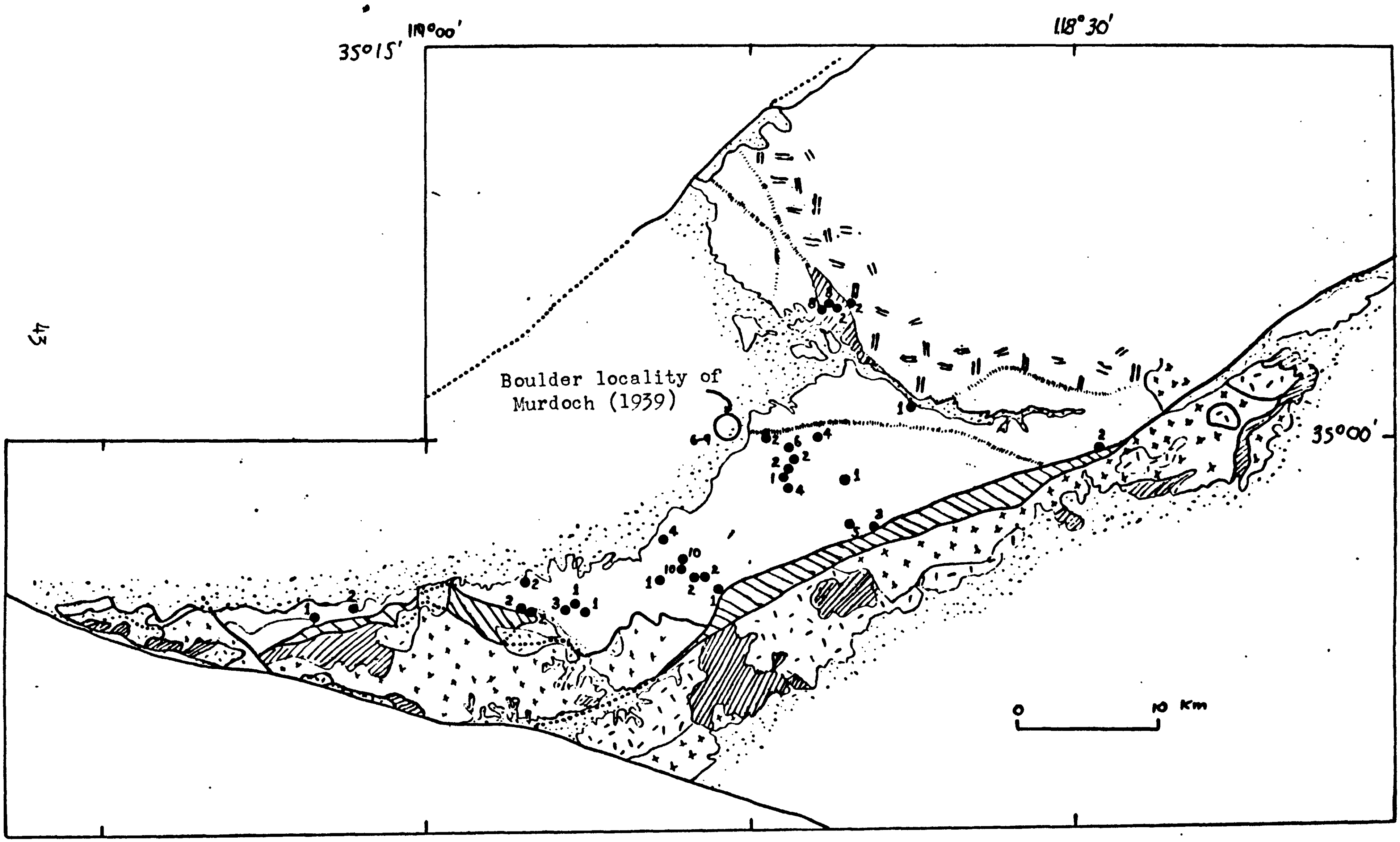

Figure 4 D. Generalized geologic setting of the San Emigdio-Tehachapi hornblende-rich terrane showing the location of samples containing coarse, red, haloed garnet (maximum size shown in cm).

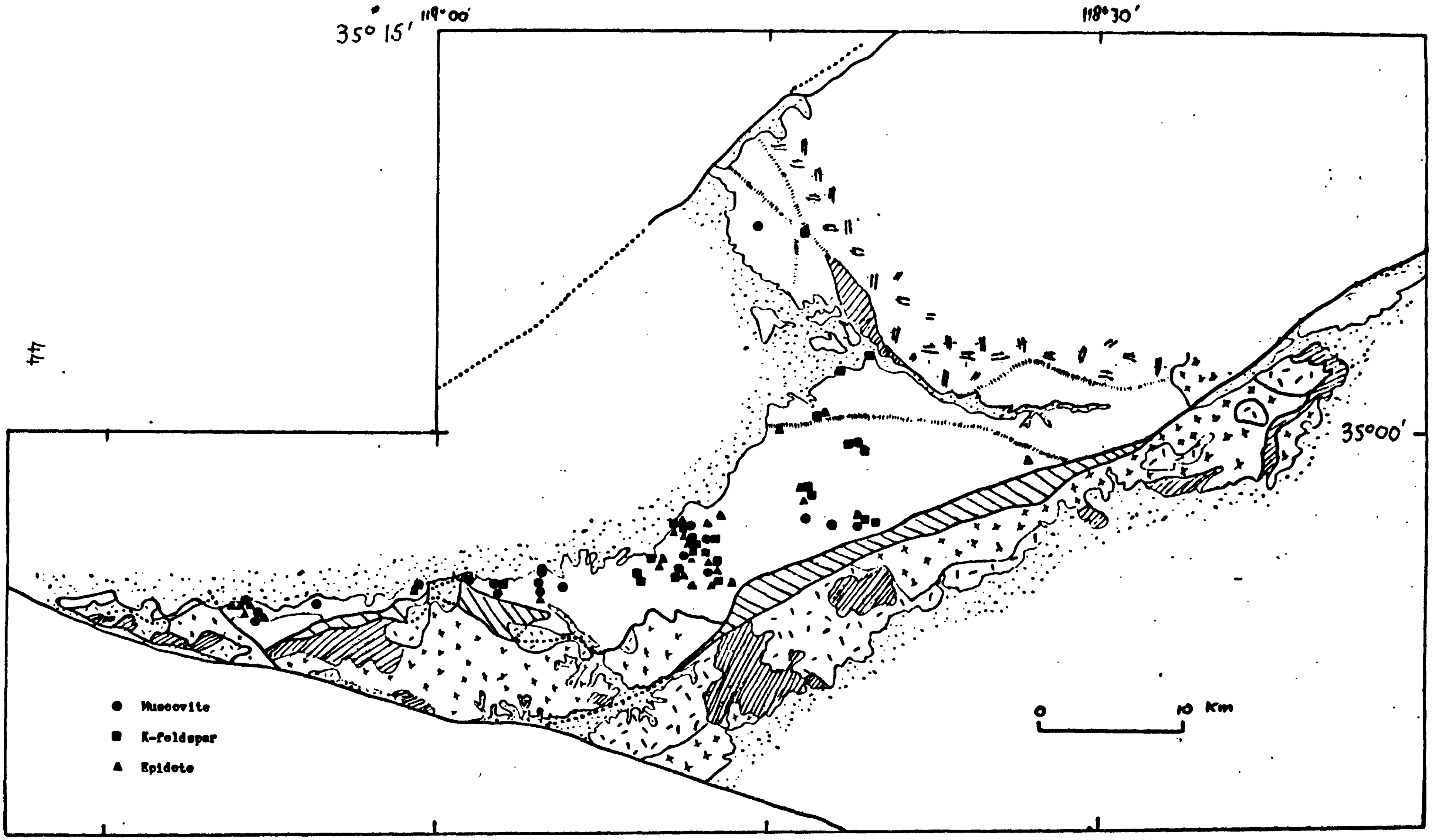

Figure 4 E. Generalized geologic setting of the San Emigdio-Tehachapi hornblende-rich terrane showing the location of samples containing K-feldspar, "primary" muscovite, and/or "primary" epidote (commonly with allanite).

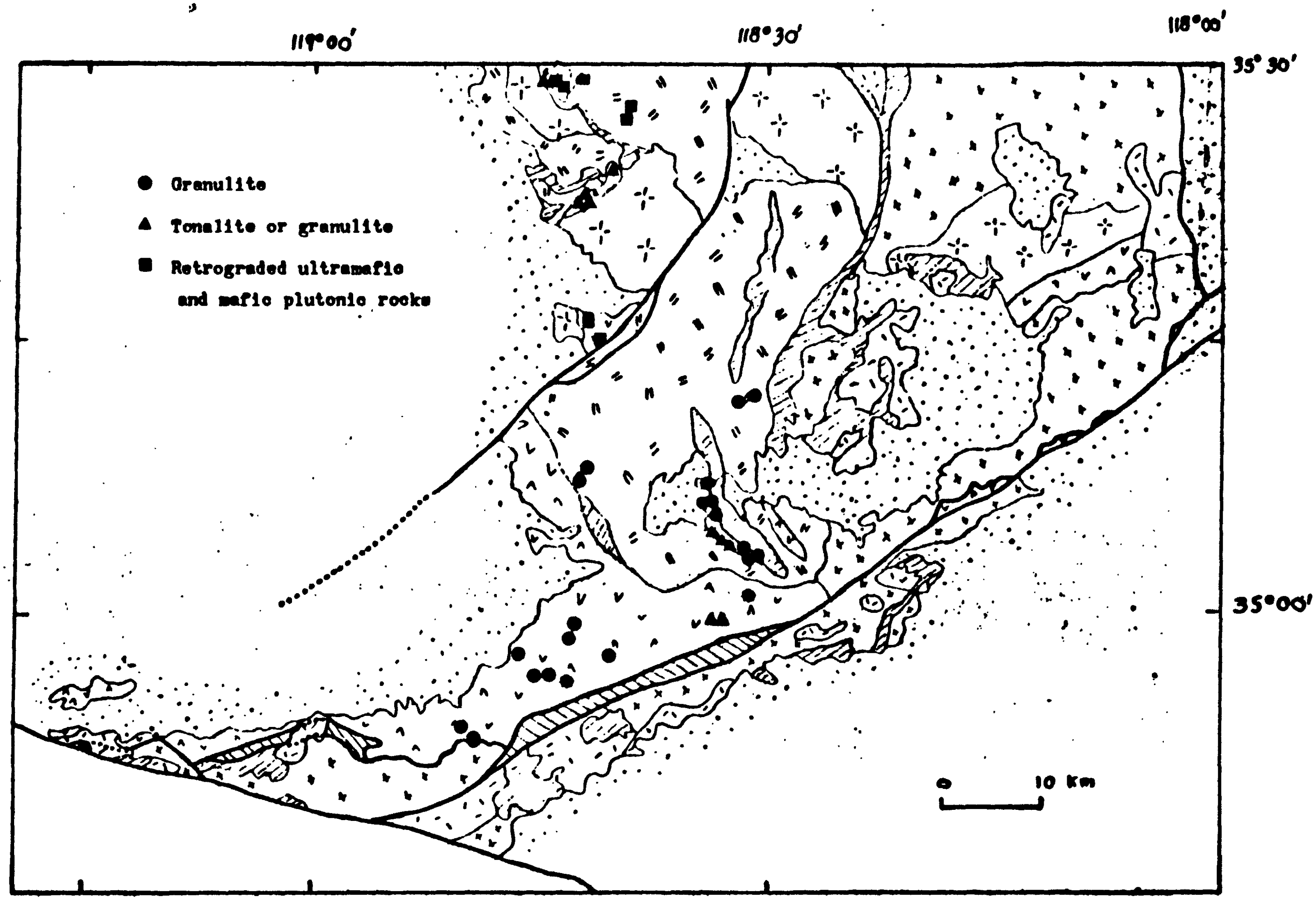

Figure 5 A. Generalized geologic map of the southernmost Sierra Nevada, California showing the location of samples containing hypersthene.

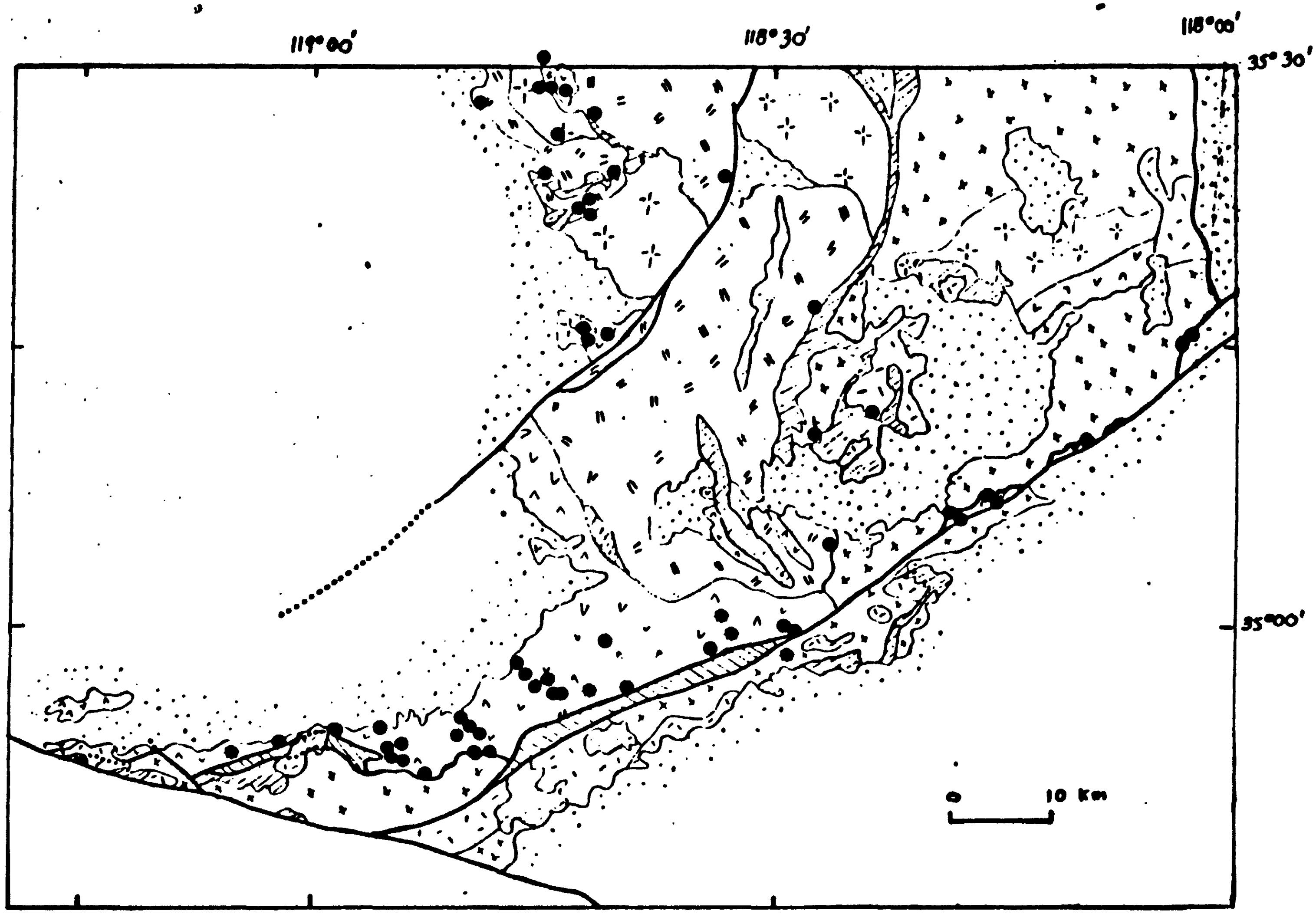

Figure 5 B. Generalized geologic map of the southernmost Sierra Nevada, California showing the location of samples containing brown hornblende.

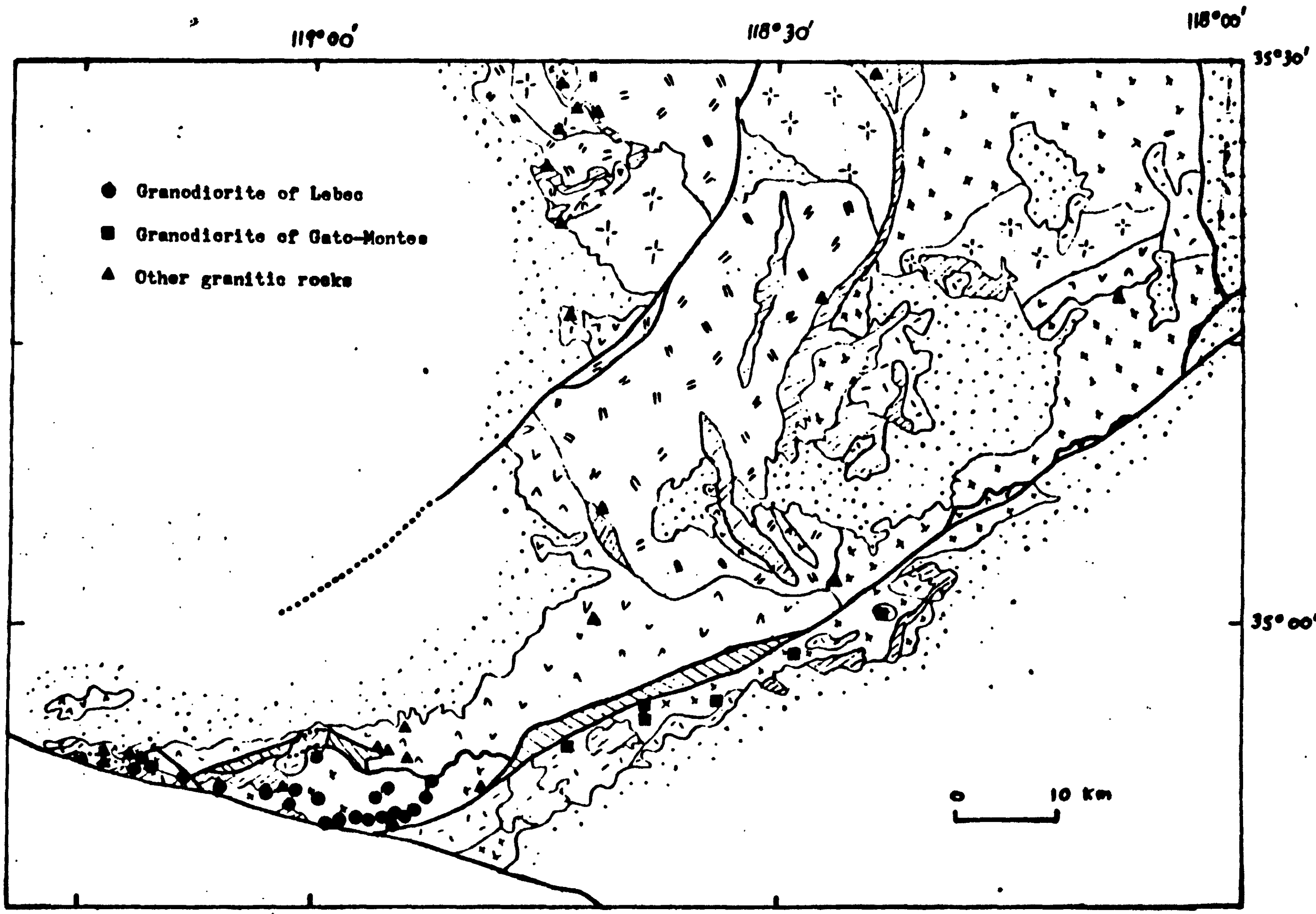

Figure 5 C. Generalized geologic map of the southernmost Sierra Nevada, California showing the location of samples of granitic rock that contain reddish brown biotite (reddish allanite is commonly associated in the granodiorite of Lebec).

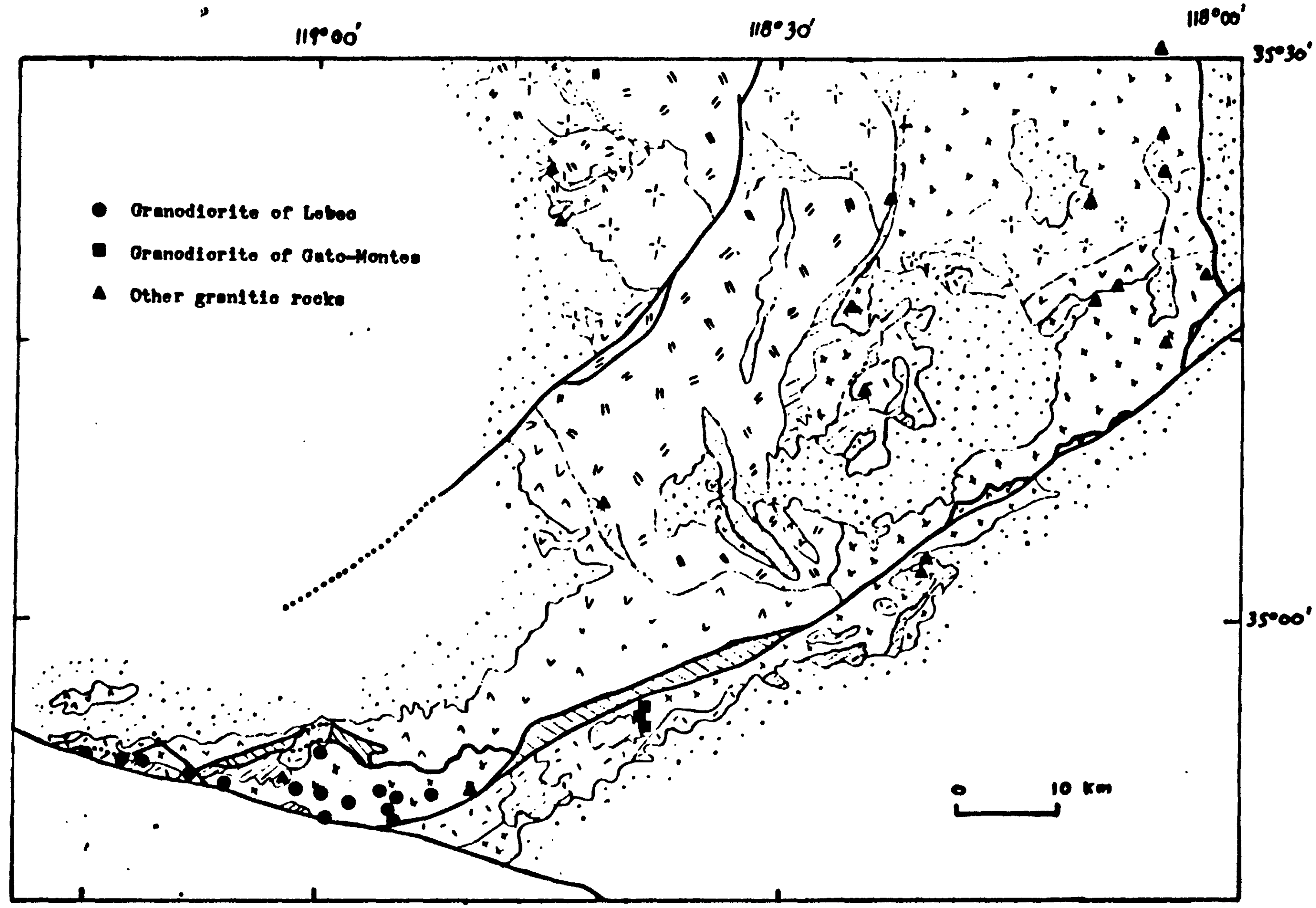

Figure 5 D. Generalized geologic map of the southernmost Sierra Nevada, California showing the location of samples of granitic rock that contain "primary" muscovite.

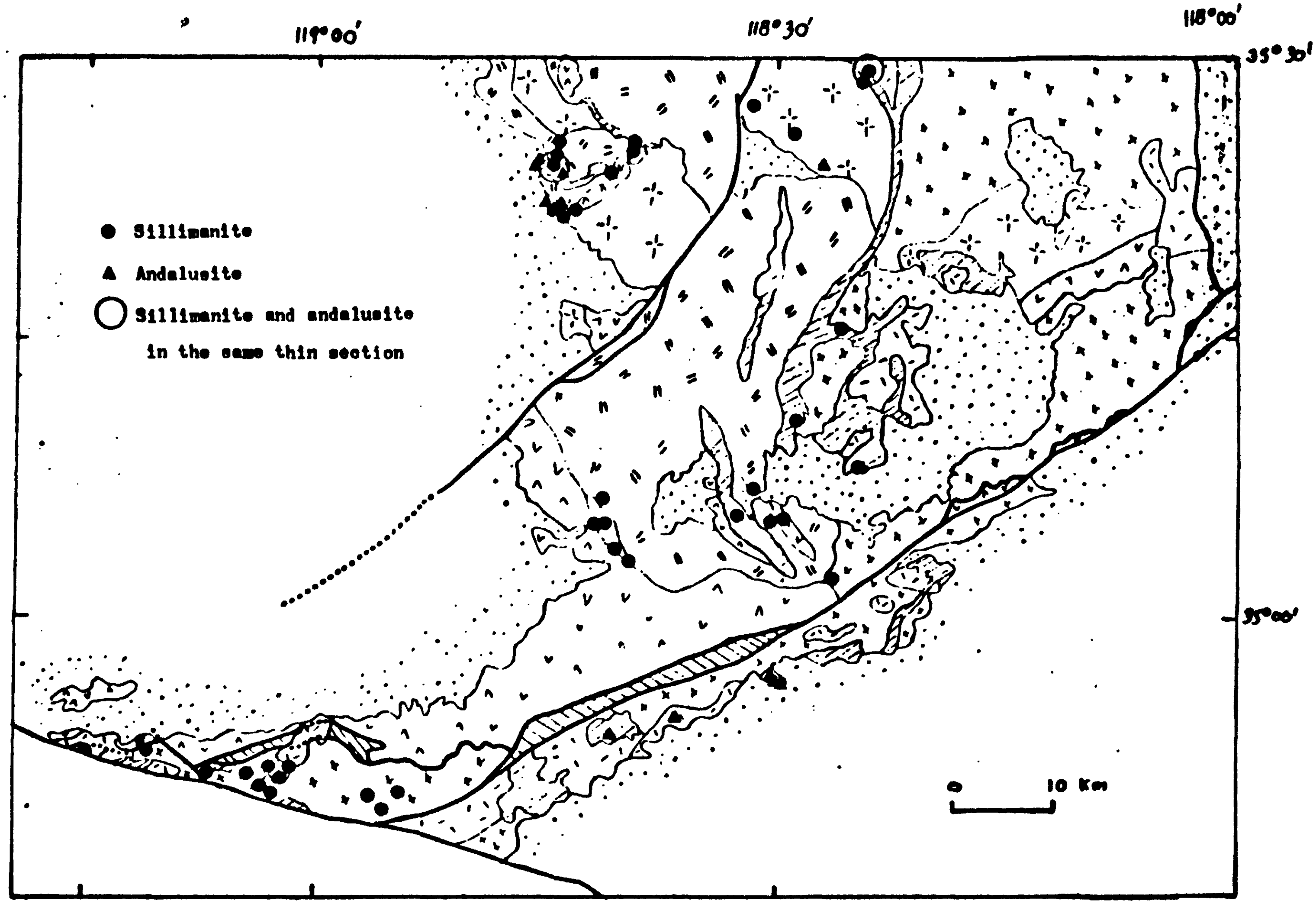

Figure 5 E. Generalized geologic map of the southernmost Sierra Nevada, California showing the location of samples of metamorphic rock containing sillimanite and andalusite.

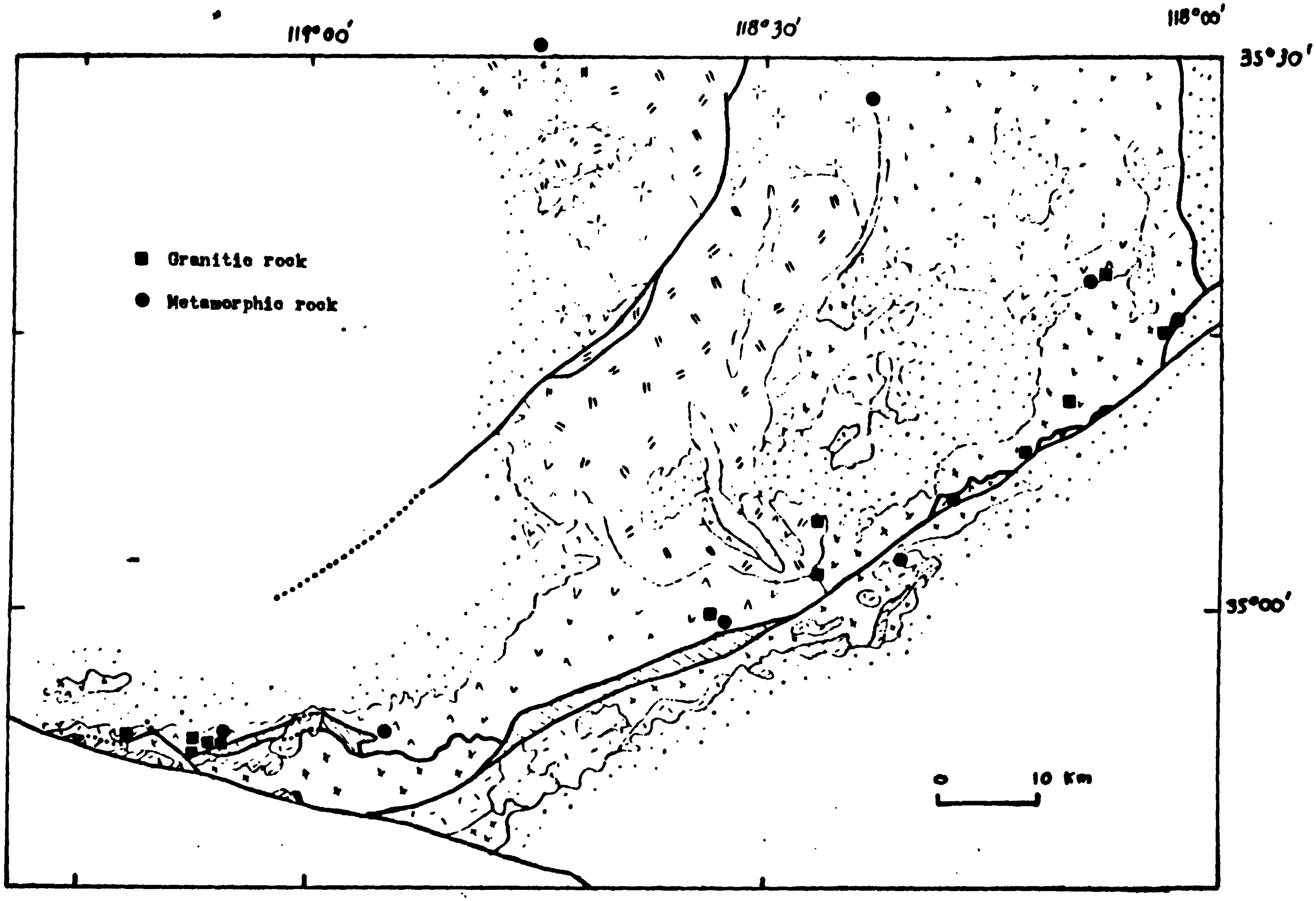

Figure 5 P. Generalized geologic map of the southernmost Sierra Nevada, California showing the location of samples containing prehnite.

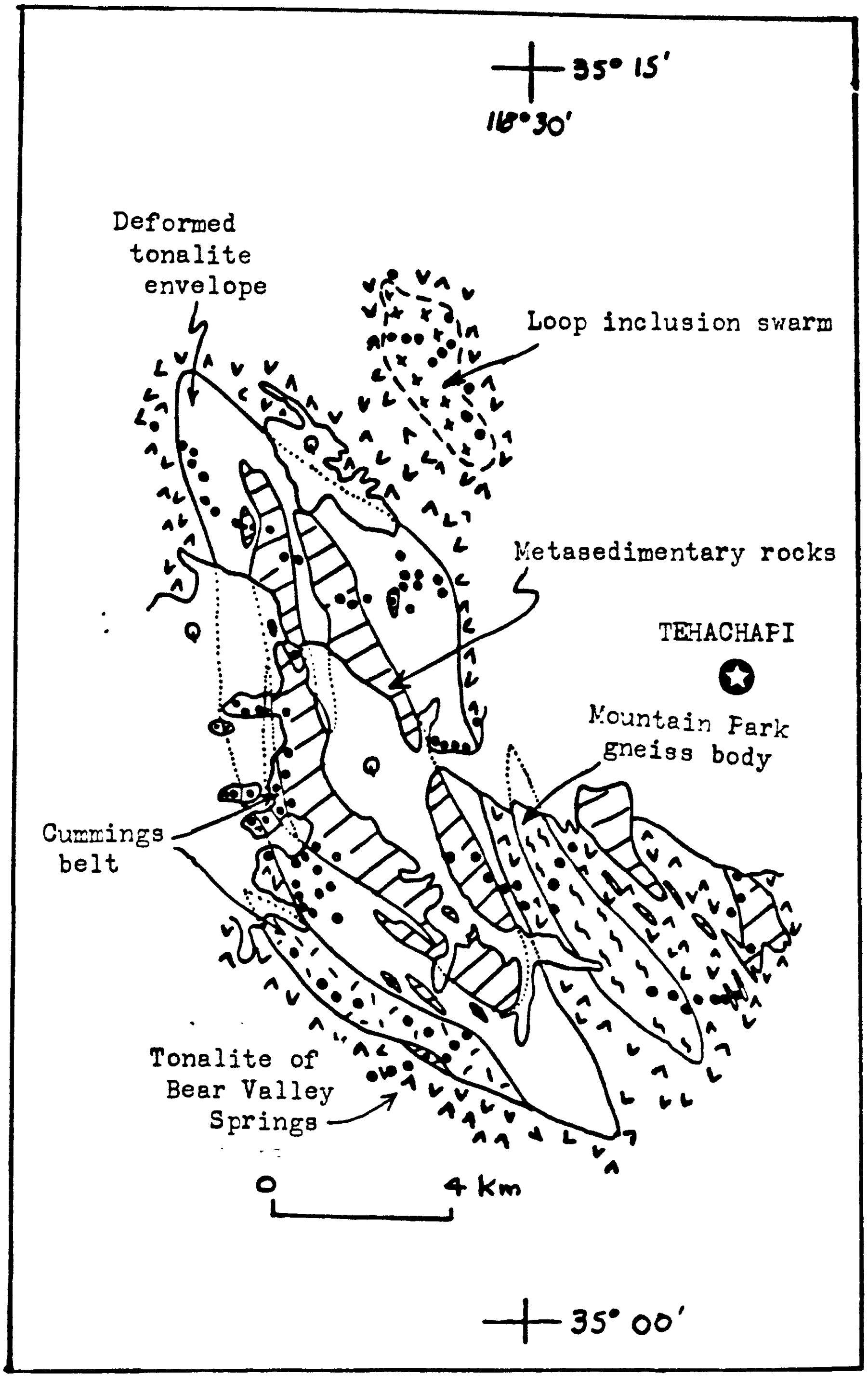

Figure 6. Generalized geologic map showing the setting of the envelope of deformed tonalite west of Tehachapi. (Heavy dots mark sample locations)