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

Preliminary Geologic Map of the Little Piute Mountains, San Bernardino County, California

by

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GEOLOGIC SUMMARY

Introduction

The Little Piute Mountains in the eastern Mojave Desert expose a series of folds and thrust faults involving metamorphosed Paleozoic strata (Miller and others, 1982; Stone and others, 1983). Detailed mapping of these structures was undertaken to help elucidate regional Mesozoic structural evolution. Earlier geologic maps were prepared by Cooksley (1960a,b,c,d, generalized by Bishop, 1964) and Stone and others (1983).

Deformed and metamorphosed Paleozoic and Triassic rocks form a stratal succession that was originally deposited in shallow seas on the North American craton. Based on lithologic sequence the units are correlated with unmetamorphosed equivalents 200 km to the northeast in the Grand Canyon, Arizona, and 35-50 km to the west in the Marble, Ship, and Providence Mountains, California (Stone and others, 1983). The Paleozoic sequence rests nonconformably on a heterogeneous basement of polydeformed Early Proterozoic gneiss (Miller and others, 1982; Wooden and Miller, 1990). Triassic and older rocks were deformed, metamorphosed to staurolite or andalusite grade, and intruded concordantly at their base by Late Cretaceous granodiorite (Miller and others, 1982).

Large Mesozoic Structures

The Paleozoic formations are in allochthons (fault nappes) and are structurally thinned severalfold from an original total stratigraphic thickness of about 1-2 km (Stone and others, 1983). The strata, allochthons, isoclinal folds, and axial-planar foliation all dip northwestward on average 55-60°, or 40° if Miocene tilting is restored. Vestiges of pre-Paleozoic foliation in Proterozoic gneiss mostly now parallel this same orientation.

Tectonic slides in the metamorphic rocks define and separate the the Meteor and Scanlon nappes and sliver and imbricate them internally. The nappe names derive from exposures in Scanlon Gulch and the informally named Meteor wash, both in the Old Woman Mountains (Fig. 1) (Howard and others, 1987; Rothstein and others, 1994). Tectonic slides are ductile faults concordant to the metamorphic foliation and identified mainly by stratigraphic juxtapositions (Hutton, 1979). Thrust-fault slides duplicate section, and lag-fault slides excise crustal section.

The post-slide Old Woman pluton, consisting of the Old Woman Mountains Granodiorite of Late Cretaceous age, concordantly intrudes a roof of Proterozoic gneiss that forms a thin rind between the pluton and the lower allochthon--the Meteor nappe. The Meteor nappe (following the useage of Rothstein and others [1994] in the Old Woman Mountains) is soled by a lag fault here referred to as the Meteor slide. The Meteor slide was called the Little Piute fault by Dennis and Karlstrom (1992), but this name had previously been applied to a normal fault that projects under the map area from the west (Hileman and others, 1990). We tentatively equate the Meteor slide to a fault called the "Kilbeck thrust" by Jones (1973) and Evenson (1973) in the Kilbeck Hills 40 km to the southwest. There as in the map area the Kilbeck (Meteor) fault excises lower Paleozoic strata, and directly juxtaposes intricately folded and slivered strata of upper Paleozoic to Triassic age onto the footwall Proterozoic rocks. In the map area the Meteor slide soles the west-plunging Titina isoclinal syncline in the hanging wall. Higher parts of the Meteor nappe include intricate isoclines and slides.

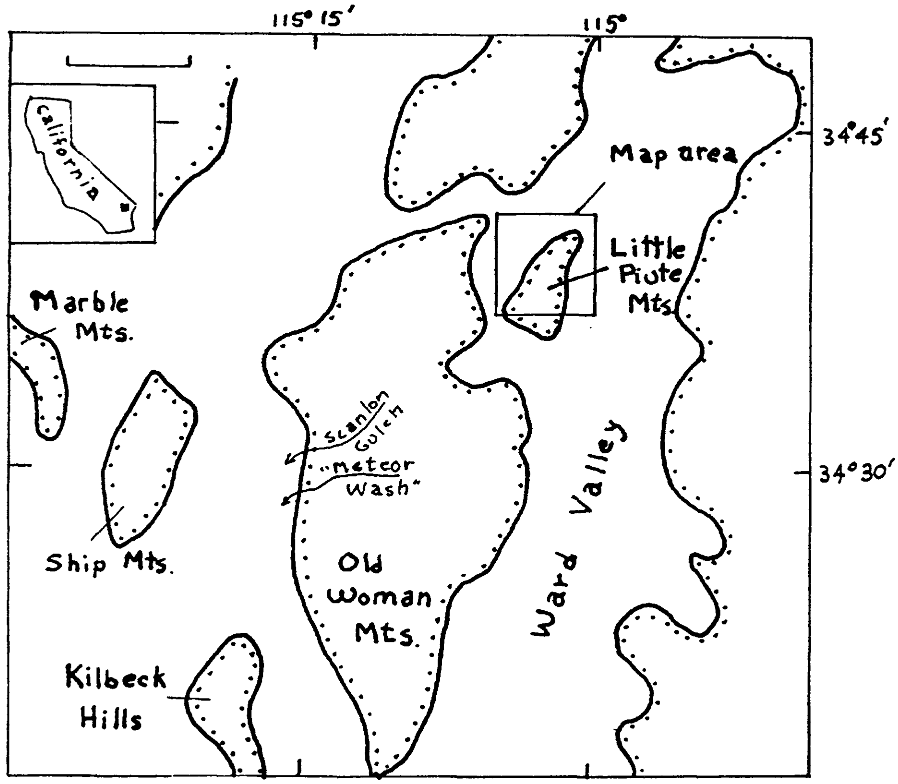

Figure 1. Index map showing the map area in relation to nearby ranges.

The higher Scanlon nappe rides over the folded strata of the Meteor nappe along a slide equated to the Scanlon thrust of Howard and others (1989a,b) . The Scanlon nappe in the map area consists of an allochthonous plate ≥350 m thick of Proterozoic gneiss and a succeeding higher series of slides that imbricate sections of inverted Cambrian and Proterozoic rocks. These latter slides are here called Tashas thrusts for their canine codiscoverer. Outside the map area the Scanlon thrust places inverted Cambrian rocks directly on the Meteor nappe (Howard and others, 1989a; Nicholson, 1990). The fact that Proterozoic gneiss is inverted along with the Paleozoic formations in this nappe indicate that the nappe may be a basement-cored fold nappe with its base sheared off.

The Scanlon and Meteor nappes, the underlying rind of footwall gneiss beneath, and the younger and deeper Old Woman pluton together define a northwest-dipping tectonic layering. This layering can be traced for 45 km along strike southwest from the Little Piute Mountains across the Old Woman Mountains and Kilbeck Hills (Miller and others, 1982; Howard and others, 1987, 1989a,b; Horringa, 1989; Rothstein, 1990; Rothstein and others 1994; Nickolson, 1990).

The Titina syncline in the Meteor nappe is the largest fold in the map area. Triassic schist cores the syncline, and in turn encloses a coaxial synformal anticline of successively older rocks in the core, as deep as the metamorphosed Coconino Sandstone. Mapped strata close northeastward around this interior anticline as they do for the enclosing syncline. Cenozoic deposits conceal whether the anticline has a refolded shape like a fishhook, as we suggest in cross section DD', or instead may be an eye fold. In either case its exposed axial surface, and that of its enclosing syncline, parallel the regional foliation.

A second mapped syncline, in the central upper part of the Meteor nappe just below the Scanlon thrust, appears eye-shaped but highly attenuated and partly disrupted by slides. The metamorphosed Bird Spring Formation in this fold encloses a core of the metamorphosed Hermit and Coconino formations, with the Hermit commonly cut out on the upper limb (section BB'). Truncation of the southwest end of the syncline's core by its upper limb along a small slide obscures the syncline's geometry relative to an underlying anticline.

Small mapped slides such as this one show complex patterns. An apparent lag slide clips the top of the anticline which intervenes between the two synclines, and traces northeastward where it is mapped to join and sole a west-opening thrust imbricate. Thin slices of Proterozoic and upper Paleozoic rocks interfinger along the Scanlon thrust zone. Above the Scanlon thrust, Tashas thrusts splay to the southwest in a pattern of mostly west-facing imbricate slices of inverted rocks that would be consistent with westward overthrusting. Dennis and Karlstrom (1992) offered an alternate interpretation from the map pattern of folds that thrusting was top-to the northeast.

Mesozoic Fabrics

Within 100 m of the Scanlon and Kilbeck slides, the Proterozoic rocks become highly fissle, dark, lineated tectonic schist showing evidence of intense strain in the plane of the regional foliation. Annealed petrographic textures in the schist record static recrystallization after deformation. Shiny, fine-grained micaceous foliation surfaces in this schist represent recrystallized phyllonite cleavage. Despite its recrystallization the tectonic schist in places preserves shear-sense indicators such as feldspar augen with tails (Simpson and Schmid, 1983). Observed shear senses measured parallel to the west-trending lineation at each slide (six localities adjacent to the Meteor slide and six adjacent to the Scanlon thrust) are equally disposed top-to-the-east and top-to-the west.

Lineation in the metamorphosed strata and the tectonic schist mostly plunges moderately westward and is concordant across the various tectonic sheets. This lineation encompasses mineral lineations, stretching lineations parallel to shear (in the tectonic schist), stretched pebbles (in metaconglomerate of the metamorphosed Wood Canyon Formation), and rod-like fold hinges (prominent at the hinges of map-scale folds in quartzitic marble). Stretched pebbles where measured quantitatively show ratios of maximum-to-minimum pebble diameter of 2.6:1 to 5:1:1; strain-ellipsoid k values of about one suggest pure shear in the direction of pebble elongation (Kelly, 1991). Locally pebbles are highly prolate and we estimate the ratio of maximum-to-minimum diameter as great as 12:1.

Quartz and green amphibole fill tension gashes perpendicular to lineation in the Triassic schist. The gashes indicate stretching parallel to fold axes and lineation. Boudin alinement perpendicular to the west-trending lineation in Proterozoic gneiss of the Scanlon allochthon also suggests stretching along the lineation.

Mapped folds plunge parallel to the lineation and to mesoscopic folds. Lineations and fold axes steepen progressively toward the southwest and are nearly straight down the dip of the axial-planar foliation in and near the mapped exposures of Triassic schist in the Titina syncline. Lineations and folds thus steepen toward this area while remaining coplanar within the regional foliation. Planar foliation surfaces in the metamorphosed Coconino Sandstone in this area exhibit lineation that is wavy and locally varies abruptly as much as 50° in orientation in distances of a few centimeters. As a further complication, nearly coaxial mesoscopic second folds, with steeply north-dipping axial planes, fold the axial-plane foliation in the Triassic schist in this same area; no map-scale equivalents were recognized.

Other structures misalined with the main foliation and lineation in the range are rare. A north-trending intersection lineation, defined by pencil schist in a single outcrop of tectonic schist below the Meteor slide in the northeast part of the area, lies perpendicular to west-trending lineation nearby and is consistent with folding perpendicular to the local east-west shear direction defined by the lineation and shear indicators. Coplanar folds of variable plunge are found in the northwesternmost mapped exposure of the dolomite gray marker bed (DCdg).

The main foliation and lineation shared by the metamorphic rocks at all levels intensifies near the Scanlon and Meteor slides. The deformation that produced the fabric therefore apparently involved intense deformation along both slides.

Cross Sections

Cross sections (AA', BB', CC', and DD') are designed to highlight the shape of folds in the Meteor nappe. Construction of the cross sections was based on two premises. The first is that mapped Mesozoic folds project into the cross sections parallel to the (westward) plunge of mesoscopic folds and lineations, at varying plunge angles. (Dennis and Karlstrom in 1992 had instead suggested that the geometry of folds in relation to the imbricate thrusts can be viewed in a single north-looking projection.) The second premise for cross-section construction for this map is that the shape of the imbricate horses can be viewed by looking northward down the foliation, on the presumption that the lines of intersection between imbricate thrusts project into the cross sections as lines that lie within the foliation plane and perpendicular to the plunge of folds and lineation. This second premise has no supporting field evidence, but is inferred on the assumption that shear directions of thrusting and imbrication paralleled the lineations as is suggested by shear indicators.

Pluton Emplacement and Cooling

The concordant Old Woman pluton locally dikes across the metamorphic foliation in its roof. Final crystallization of the pluton at about 74 Ma and static recrystallization of metamorphic rocks therefore outlasted the ductile deformation of the metamorphic rocks. An apatite fission-track age of about 53 Ma for the pluton dates cooling to near 100° C (Foster and others, 1991). This date and other thermal history data from the adjacent Piute and Old Woman Mountains provide evidence that the metamorphic and plutonic rocks cooled and uplifted rapidly from mid-crustal depths after pluton intrusion (Foster and others, 1990, 1991, 1992).

Tertiary Rocks and Structures

Early Miocene rocks rest nonconformably on the pre-Tertiary rocks. Knoll (1985) detailed the early Miocene section and described a paleovalley fill at the south margin of the map area and a shallower paleovalley fill near the outcrops of Triassic schist to the north. Our mapping suggests the southern paleovalley fill is on the order of 250 m thick below the Peach Springs Tuff. This is less than Knoll's proposed 830-m thickness. These paleovalley fills are defined by conglomerate, sandstone, tuff, and flows of basalt and andesite. The 18.5-Ma Peach Springs Tuff, a regional ignimbrite, overlies these paleovalley fills and locally rests directly on the pre-Tertiary rocks at the edges of the paleovalleys. A sequence of sandstone, tuff, and conglomerate succeeds the Peach Springs Tuff.

Tertiary normal faults in the map area strike northwest and northeast. Breccia zones along the Tertiary faults demonstrate their brittle character, and breccia zones also indicate that small brittle movements locally modified parts of the Meteor slide and smaller slides. Travertine and silica fill a northeast-striking fault in the southwest part of the map area

The Miocene stratigraphic units dip northwestward 5-20°. This dip is considered to reflect middle Miocene rotation on the underlying Little Piute normal fault, which dips southeast under the Little Piute Mountains from exposures west of the map area (Howard and John, 1987; Hileman and others, 1990). Those authors considered the Little Piute fault and its hanging-wall block to be near the western breakaway for Miocene detachment faults in the Colorado River extensional corridor.

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DESCRIPTION OF MAP UNITS

Alluvial-fan materials (Quaternary)--Poorly sorted sandy gravel and gravely sand. Clasts subangular to angular. Deposited by sheet floods, channelized floods, and debris flows. Subdivided into:

Qya **Younger alluvium (Holocene)**--Unconsolidated sand and gravel in active washes

Qa **Intermediate-age alluvium (Holocene)**--Forms undissected alluvial fans. Light-colored on aerial photographs

Qoa **Older alluvium (Pleistocene)**--Forms moderately dissected alluvial fans. Surface is dark desert pavement of varnished clasts where source materials are mafic or volcanic rocks, and surface is light colored where source materials are granodiorite or marble. Reddish soil

Qoc **Calcareous older alluvium (Pleistocene)**--Calcrete and calcrete-cemented arkose thicker than 1 m. Represents a partly eroded paleosol developed on alluvium

Ttr **Travertine and chalcedony (middle Miocene?)**--Fills a fault in Miocene rocks in southwest part of map area. Contains opaline veins. Interpreted as hot-spring deposits

Conglomerate, sandstone, and tuff (middle to early Miocene)--Divided into:

Tcg **Granite-clast conglomerate**--Arkosic conglomerate dominated by cobbles and pebbles of granite and granodiorite and rarer basalt

Tcv **Volcanic-clast conglomerate**--Dominated by cobbles and, locally, boulders derived from the Peach Springs Tuff and mafic volcanic rocks. Clasts include lesser amounts of quartzite, marble, gneiss, and muscovite granite

Tct **Tuff, tuffaceous sandstone, and sandstone**--Uppermost 10-15 m consist of white tuff and interbedded brown arkosic sandstone. Lower beds are pale yellow tuffaceous sandstone and light gray fine-grained sandstone. Vertebrate faunal assemblage described by Reynolds (1992)

Tcs **Sandstone**--Coarse to medium-grained gray to light red arkosic sandstone and conglomerate. Beds generally 0.5-1 m thick. Rare cross beds and symmetrical ripple marks suggest northward-directed currents. Locally contains boulders as wide as 0.5 m derived from Old Woman Mountains Granodiorite and more rarely from muscovite granite

Tp **Peach Springs Tuff of Young and Brennan (1974) (early Miocene)**--Welded rhyolite ash-flow tuff. Weathers pink, brown, or (where poorly welded) white. Contains abundant phenocrysts of sanidine, commonly showing blue adularescence, and small amounts of plagioclase, quartz, biotite, hornblende, sphene, and pyroxene. Forms resistant ridge-capping outcrops. Dated by K-Ar method on sanidine at 18.3 $\pm$ 0.6 Ma (Howard and others, 1982, Table 3, map no. 14); accepted age of unit as dated by $^{40}Ar/^{39}Ar$ methods from near Kingman, Arizona, is 18.5 $\pm$ 0.2 Ma (Nielson and others, 1990)

Ta **Hornblende andesite (early Miocene)**--Forms an isolated inselberg near the north edge of the map area; another present just north of the map area. Stratigraphic position relative to other Miocene units is inferred

Tba **Basalt and andesite flows (early Miocene)**--Dark gray. Two analysed samples of olivine-bearing basalt contained 52% and 50% SiO_2 (Knoll, 1985: appendix 3, units LP6 and LPN)

Tta **Tuff and arkosic conglomerate (early Miocene)**--Contains angular pebbles of granite. Locally present; 2-3 m thick. Interbedded in the basalt and andesite flows

Ts **Sandstone (early Miocene)**--Sandstone, tuffaceous sandstone, and minor claystone and siltstone. Color ranges from red to white or (where tuffaceous) green. Red sandstone in section 36 exhibits mud cracks and tracks of several kinds of vertebrates (Reynolds, 1992). In sec. 11, T.6 N., R. 18 E. according to Knoll's (1985) descriptions, the unit consists (in ascending order) of white to gray, medium-grained sandstone of largely felsic volcanic grains, a medial boulder conglomerate consisting of clasts similar to those of the boulder conglomerate unit (Tbc), and a gray coarse arkosic sandstone derived in part from Old Woman Mountains Granodiorite

Tbc **Boulder conglomerate (early Miocene)--**Unsorted diamictite and poorly sorted, matrix-supported boulder and cobble conglomerate, both with red sandy matrix. Clasts are angular to rounded and are largely quartzite, as wide as 1.5 m, derived from the metamorphosed Zabriskie Quartzite and Wood Canyoin Formation. Quartzite boulders exhibit dark-red rinds as thick as 6 mm. Gneiss clasts are next most common and increase in abundance southward. Includes exotic boulders of granite porphyry not recognized in outcrop in the region. Clasts derived from Old Woman Mountains Granodiorite are rare. Forms basal conglomerate that lies nonconformably on pre-Tertiary rock units

Ko **Old Woman Mountains Granodiorite (Late Cretaceous)**--Light-gray-weathering, medium-grained sphene-hornblende-biotite granodiorite. Aplite dikes and pegmatite dikes at the margins contain muscovite. A porphyritic facies, which contains phenocrysts of alkali feldspar 0.5-1 cm in maximum dimension, has gradational boundaries and is present in the west 1/2 sec. 6, T. 6 N., R. 19 E. and east 1/2 sec. 1, T. 6 N., R. 18 E. Unit forms part of the Old Woman pluton (Miller and others, 1982). Top or northwest margin of pluton is concordant against gneiss and marble and intrudes gneissic country rock *lit par lit.* Age about 74 Ma by U-Pb and $^{40}Ar/^{39}Ar$ dating (Foster and others, 1989; Miller and others, 1990)

TRs **Schist (Triassic)**--Green to gray, brownish-gray-weathering, finely laminated epidote-quartz-biotite calc- schist and lesser quartz-biotite schist. Commonly folded and well lineated; in places shows two generations of folds. Locally includes a thin, basal calcareous quartzite. Schist protolith is inferred to be calcareous siltstone. Correlated in a general way with the Moenkopi Formation to the northeast and probably with the Fairview Valley Formation to the west, both of Early Triassic age (Stone and others, 1983; Walker, 1987)

Pk **Metamorphosed Kaibab Limestone (Permian)**--White, light-gray, bluish gray and dark-gray calcitic marble that contains siliceous, folded, dark-brown-weathering metachert lenses. Locally associated with pods of very coarse-grained secondary calcite. May include metamorphosed equivalents of the Toroweap Formation

Pc **Metamorphosed Coconino Sandstone (Permian)**--Very light gray- to pink-, red-, or tan-weathering, laminated, fine-grained vitreous quartzite. Well lineated commonly. Forms fine rubble or bold outcrops; locally consists of siliceous breccia that forms bold outcrops. Yellow carbonate layer is present in one fold hinge. Fine, even fracturing may reflect aeolian lamination

Ph **Metamorphosed Hermit Shale (Permian)**--Green to reddish brown calcareous and chloritic phyllite, and massive, dark-brown-weathering sandy metalimestone. Typically weathers as rounded knobs. Thin-bedded (5-10-cm thick) maroon and gray calcareous metasiltstone is present locally. Quartz and green amphibole fill tension gashes oriented perpendicular to lineation

PPb **Metamorphosed Bird Spring Formation (Permian and Pennsylvanian)**--Thick-bedded, ledgy, light gray calcitic marble, sandy marble, brown-weathering quartzitic marble, brown-weathering green calc-silicate rock, buff dolomitic marble, quartzite, and rare fine-grained quartz-mica schist. Brown-weathering siliceous grains scattered through marble reflect quartz sand grains in the protolith; cross-bedding is locally preserved. A bed of vitreous quartzite as thick as 1 m is present near the top of the unit. Lower part of formation gradational with underlying Redwall Limestone. Locally, includes:

PPbs **Siliceous marker beds**--Resistent beds of dark brown-weathering calcareous quartzite and calc-silicate rock, and a medial marble bed. This subunit is correlated with similar beds within a section of the Bird Spring Formation 40 km to the west in the Ship Mountains, where they directly underlie beds containing Early Permian (Wolfcampian) fusulinids. Subunit is interpreted as a westward-thinning sandy tongue of the Supai Group (Stone and others, 1983)

Mr **Metamorphosed Redwall Limestone (Mississippian)**--White, massive, coarse-grained calcitic marble. Locally contains gray marble beds, alternating thin layers of gray and white marble and rare calc-schist, and irregular patches of buff dolomite. Locally, includes:

Mrm **Metachert**--Marble containing resistant, closely-spaced siliceous lenses and nodules of dark-brown-weathering white metachert. Commonly silicified by secondary quartz

DCd **Dolomite (Devonian and Cambrian?)**--Massive to thick-bedded tan dolomite marble. Local vesicle-like pits where ovoid calcitic pods a few millimeters across have weathered out resemble features in the Valentine Member of the Sultan Formation (Devonian) mapped 70 km to the north in the New York Mountains by Burchfiel and Davis (1977). Rare tremolitic clots 10-30 cm across may be remnants of silicic stromatoporoids as in the Sultan Limestone in the Victorville area, 200 km west of the map area (Miller, 1981). Stratigraphic position below the Redwall Limestone further indicates that this unit includes the metamorphosed Sultan Limestone of Devonian age; unit may also include rocks of Cambrian age (Stone and others, 1983). Locally includes:

DCdg **Gray marker bed**--Dark gray dolomite marble 2-20 m thick. Shows small internal isoclines

Cm **Marble (Cambrian)**--Tan to gray calcitic marble. Considered to include metamorphosed rocks of the Chambless Limestone, Cadiz Formation, and lower part of the Bonanza King Formation

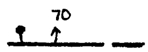
Cb **Metamorphosed Bright Angel Shale (Cambrian)--**Mica schist, phyllite, and minor gray and buff calcitic marble

Cz **Metamorphosed Zabriskie Quartzite (Cambrian)**--White to light gray or tan, fine- to medium-grained, massive, vitreous quartzite. Interpreted to represent a shallow-marine environment (Prave and others, 1991)

Cw **Metamorphosed Wood Canyon Formation (Cambrian)**--Gray to brown micaceous quartzite, cross-bedded quartzite, and metaconglomerate. As much as the lower 12 m of the section is quartz-pebble metaconglomerate (Prave and others, 1991). Considered to represent an alluvial braidplain by Prave and others (1991). Nonconformably overlies Proterozoic gneiss. Pebbles are stretched parallel to lineation; Kelly (1991) measured ratios of maximum-to-minimum diameter ranging from 2.6 to 5.1; ratio locally reaches 12

Xg **Gneiss (Early Proterozoic)**--Gneiss, granite gneiss, veined gneiss, pegmatitic gneiss, augen gneiss, muscovite granite gneiss, amphibolite, micaceous schist, garnet schist, staurolite schist, and feldspathic quartzite. Veined gneiss exhibits ptygmatic folds of dark-bordered leucocratic veins. Within10-100 m of the Scanlon thrust and Meteor slide, the rock is commonly a highly fissle but annealed tectonic schist, shiny where recrystallized mica defines relict phyllonitic cleavage surfaces

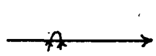
Contact--Dashed where approximately located



Fault--Showing dip. Dashed where inferred. Bar and ball on downthrown side

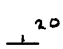
Tectonic slide--Teeth on upper plate. Ductile thrust or lag fault. Dashed where inferred. Open teeth indicate major lag fault (Meteor slide)

Overturned anticline--Showing direction of plunge

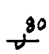


Overturned syncline--Showing direction of plunge

Lineaments--Fractures in Old Woman Mountains Granodiorite. Mapped from air photos

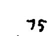


Strike and dip of bedding



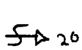
Strike and dip of overturned bedding--Top direction known from sedimentary structures or stratigraphic sequence

Strike and dip of magmatic foliation



Strike and dip of metamorphic foliation

Trend and plunge of lineation--Double-headed arrow indicates mylonitic lineation. May be combined with foliation symbol



Trend and plunge of mesoscopic fold axis--Showing sense of asymmetry. May be combined with lineation symbol

CORRELATION OF MAP UNITS