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

Preliminary Geologic Map of Fort Irwin Basin, north-central Mojave Desert, California

by

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DESCRIPTION OF MAP UNITS

Mapping Conventions

Surficial geologic units commonly exist as thin (<1 m) veneers over older units. In areas where this relationship is common the unit designators are shown on the map as being separated by a slash (/). The younger, or overlying, unit is indicated first. Thus, Qya/Qoa indicates an area where a veneer of young alluvial fan deposits overlies old alluvial deposits and Qya/Kpg indicates an area where a veneer of young alluvial fan deposits overlies Cretaceous porphyritic granite. For those areas of veneer deposits, the map color is that of the underlying unit and a pattern designates the age and type of veneer deposit. The lateral extent of individual deposits is commonly so small that each deposit cannot be shown individually at the published map scale. Where areas are made up of deposits too small to show individually, the designators of deposits present are separated by a plus sign (+), with the most common deposit listed first. Thus, Qya_1 + Qya_2 indicates an area with both Qya_1 and Qya_2 deposits and associated surfaces, and that Qya_1 is more common than Qya_2. For the combined units, the color of the youngest unit is displayed on the map.

ml **Modified Land** (Holocene)--Areas disturbed by activities of man such that the original surficial geologic unit is unrecognizable. Includes areas with significant artificial fill, such as the sewage disposal plant and the Bicycle Lake Air facility, and areas that have been excavated, such as the waste disposal site

Qp **Playa Deposits** (Holocene)--Fine-grained, clay- and silt-rich, with minor interbedded fine sand. Pale gray to tan. Moderately stiff when dry; highly plastic to sticky when wet. Abundant polygonal and linear fractures varying in width from centimeters (cm) to tens of cm and in length from centimeters to hundreds of meters. Playa surface is subject to flooding during and after heavy rain. Generally unvegetated

Wash surfaces and underlying deposits

Qyw **Young Wash Deposits, Undifferentiated** (Holocene)--Moderately sorted, medium- to coarse-grained sand and sandy gravel. Sandier where crossing granitic bedrock units; more gravel-rich where crossing Tertiary volcanic units. White to light gray. Loose. Occupies active stream channels and thus is prone to flooding during heavy rain. Laterally grades to young alluvial fan surfaces (Qya)

Qyw_1 **Youngest Wash Deposits** (Holocene)--Moderately sorted, medium- to coarse-grained sand and sandy gravel occupying major ephemeral stream valleys. White. Loose. Unit deposited by active flow within the last few decades based on comparison of successive aerial photograph surveys. Prone to flooding during moderate to heavy rain. Grades laterally to youngest alluvial fan deposits (Qya_1). Unvegetated. Mapped contact between Qyw_1 and Qya_1 channels often is arbitrary

Qyw_2 **Young Wash Deposits** (Holocene)--Lithologically similar to Qyw_1, but surface lies 10 to 50 cm above active wash floor. Pale gray. Loose to slightly compact. Prone to flooding during heavy rain. Rarely seen to grade to young alluvial fan surfaces (unit Qya_2). Weakly vegetated. Lacks soil development

Qow **Older Wash Deposits, Undifferentiated** (Pleistocene)--Lithologically similar to deposits of unit Qyw_1, but surface lies 2 to 3 m above those of unit Qyw_1. Light brown. Compact. Lies above flood level. Moderately vegetated. Zone of subsurface clay accumulation (argillic horizon) 20 cm thick. Weak to moderate accumulation of carbonate (calcic horizon) below argillic horizon, also about 20 cm thick. Moderately developed desert pavement. Weak to moderate varnish coats on volcanic clasts. Mapped in north part of map area, in Coyote Canyon

Alluvial fan surfaces and underlying deposits--Classified as young, intermediate, and old based on surface micromorphology, pattern and degree of channel dissection of alluvial fan surfaces, and degree of soil, desert pavement, and rock varnish development

Qya **Young Alluvial Fan Deposits, Undifferentiated** (Holocene)--Moderately sorted, medium- to coarse-grained sand to sandy gravel. Sandier where sources made up of granitic bedrock; more gravely where sources include Tertiary volcanic and sedimentary rocks. All units become coarser grained near mountain fronts, where boulders are common. White to light brown. Loose to slightly compact. Deposits lie within active channels that are commonly incised into older alluvial fan surfaces near mountain fronts; away from mountain fronts, the channels spread out across fan surfaces as shallow braided rills. Prone to severe channelized flooding near mountain fronts and to shallow sheet flooding away from fronts during and following heavy rain. Unvegetated to moderately vegetated. Little or no soil development. Well-developed bar and swale topography. Lacks desert pavement. Little or no clast varnish cover

Qya_1 **Youngest Alluvial Fan Deposits** (Holocene)--Moderately-sorted, medium- to coarse-grained sand and sandy gravel. Coarser grained near mountain fronts where cobbles and boulders are common; finer grained in lower parts of fans where sand is most common. Confined to active parts of alluvial fans; mostly channels in upper parts and broad fan surfaces near basin axis. Significant water flow and subsequent deposition within the last few decades is indicated by comparison of successive aerial photograph surveys. Prone to severe flooding where channelized, generally near mountain fronts, and to shallow sheetfloods in lower parts of fans during and following heavy rain. White to pale gray. Loose. Unvegetated. Bar and swale microtopography well-developed, with numerous vertical cutbanks standing at channel margins. Surfaces are actively receiving sediment composed of moderately well-sorted sand and gravel. No soil or varnish development

Qya_2 **Younger Alluvial Fan Deposits** (Holocene)--Lithologically similar to unit Qya_1 with a similar tendency to be more bouldery near mountain fronts and sandier in the lower parts of fans. Unit surface lies 10 to 50 cm above active channels occupied by Qya_1 deposits. Twigs and grass caught on upstream side of shrubs indicate that surface is prone to sheet flooding. Pale gray to light brown. Loose to slightly compact. No soil development or desert pavement. Clasts unvarnished. Weakly vegetated. Bar and swale microtopography evident, but few vertical cutbanks remain

Qya_3 **Young Alluvial Fan Deposits** (Holocene)-- Moderately-sorted, medium- to coarse-grained sand with rare gravel. Unit lies as much as 2 m above Qya_1 surfaces and 1.5 m above Qya_2 surfaces. Possibly subject to shallow sheet-flow during heavy rain. Light brown. Loose to slightly compact. Weakly developed soil, expressed as incipient reddening of subsurface horizons (weak cambric horizons). Smooth microtopography, with only a faint suggestion of bar and swale topography. Weakly to moderately vegetated, especially with creosote bush. No desert pavement. Incipient varnish on volcanic clasts, particularly basalt

Qia **Intermediate Age Alluvial Fan Deposits, Undifferentiated** (Pleistocene)--Poorly to moderately sorted, fine- to coarse-grained sand, gravely sand, and sandy gravel. Rare silt interbeds. Clasts represent bedrock types in adjacent source areas. Granitic detritus commonly sandy, with rare boulders; volcanic detritus and reworked Tertiary sediment yield subangular to subrounded gravel and gravelly sand. Unit becomes coarser toward mountain fronts. Surfaces lie 1 to 5 meters above young alluvial fan (Qya) surfaces. Unit best preserved near mountain fronts, where channels occupied by Qya incise older surfaces such as Qia. Flooding rare to nonexistent in upper parts of fans, but extremely high-flow events may overtop some to the lowest Qia surfaces in the lower parts of fans. Light to dark brown. Slightly compact to compact. Moderately developed soil profile, with distinct zones of clay accumulation (argillic horizons) up to 50 cm thick and weak to moderate accumulation of carbonate (calcic horizons; Stage I to Stage III+ carbonate morphology of Gile and others, 1966). Degree of carbonate development varies with clast lithology: Granitic alluvium has weaker carbonate development (Stage I to Stage II) than alluvium rich in volcanic debris (Stage I to Stage III+). Surface remnants flat to slightly rounded between incised younger channels. Weakly to moderately vegetated. Well-developed interlocking desert pavement overlying silt that is as much as 20 cm thick. Moderate to strong varnish on volcanic clasts, weak on granitic clasts

Qia_1 **Intermediate Age Alluvial Fan Deposits** (Pleistocene)--Poorly to moderately sorted, fine- to coarse-grained sand, gravely sand, and sandy gravel. Rare silt interbeds. Clasts reflect bedrock types in adjacent source areas. Granitic detritus usually sandy with rare boulders; volcanic detritus and reworked Tertiary sediment yield subangular to subrounded gravel and gravelly sand. Unit becomes coarser toward mountain fronts. Surfaces lie 1 to 5 meters above adjacent younger alluvial fan surfaces (Qya). Rarely flooded. Light to dark brown. Compact. Soils moderately- to well-developed with common subsurface zones of reddish clay accumulation (argillic horizons) up to 50 cm thick. Weak to moderate accumulation of carbonate (calcic horizons), in places forming impermeable zones beneath the argillic horizons. Surface remnants flat and smooth. Weakly to moderately vegetated. Well-developed interlocking desert pavement with an underlying silt 10 to 20 cm thick. Moderate to strong varnish coating

Qia_2 **Intermediate Age Alluvial Fan Deposits** (Pleistocene)--Similar in lithology and form to Qia_1. Lies 1 to 2 m above Qia_1 and 1 to 2 m below Qia_3 surfaces. Mapped only where this inset relationship is observable. Lies above level of flooding. Morphology, color, and induration; soil, pavement, and varnish development all similar to Qia_1

Qia_3 **Intermediate Age Alluvial Fan Deposits** (Pleistocene)--Similar in lithology to Qia_1. Lies 1 to 2 m above Qia_2, where present, and 2 to 4 m above Qia_1 surfaces. Surface has distinct rounded appearance in areas between young incised channels, indicating that the original fan surface is beginning to degrade. Light brown. Slightly compact to compact. Argillic horizons tend to be thinner than on younger Qia surfaces, reflecting erosion of the landform. Calcic horizons weakly developed on granitic alluvium, moderately developed on volcanic alluvium. Older fan units (Qoa and QToa) show rounding of interfluves and landform degradation, but also contain much better developed calcic horizons. Pavement less extensive than on younger Qia surfaces. Varnish coatings moderate to strong.

Qoa **Old Alluvial Fan Deposits** (Pleistocene)--Poorly to moderately sorted, coarse-grained sand and gravel, with boulders common. Lithology reflects bedrock source that unit was derived from. Forms whaleback-like ribs (ballenas) up to 10 m above active (Qya_1) alluvial fans near mountain fronts. In lower parts of fans, remnant surfaces may stand as little as a meter above active wash floors. Flooding probable in lower fan settings, but unlikely near mountain fronts. Pale gray to white. Hard. Most upper soil horizons stripped off by erosion; only rare remnants of red-brown clay-rich argillic horizons. Strongly developed (Stage IV) calcic horizons up to 3 m thick common. Moderately to strongly rounded interfluves between channels. Desert pavement only rarely preserved. Occasional boulders, left as lags on the remnant calcic horizons, show strong varnish coatings

QToa **Old Alluvial Fan Deposits** (Pleistocene and Pliocene?)--Poorly sorted, coarse-grained sandy cobble- and boulder-gravel with minor interbedded medium- to coarse-grained sand. Mostly rhyolite and basalt clasts, with minor granitic clasts. Top of unit lies as much as 30 m above active wash floors. Original alluvial fan form difficult to reconstruct due to extensive dissection and erosion of landform. Light to dark brown. Compact. Original surface soil commonly completely stripped by erosion, but remnants of strongly developed (Stage IV) calcic horizons preserved in places. Present along western part of Coyote Canyon. Clasts mainly derived from local sources. Less indurated than Pliocene? younger gravel (unit Tyg)

Eolian (windblown) surfaces and underlying deposits

Qye **Eolian Deposits** (Holocene and Pleistocene)--Fine- to medium-grained sand and minor silt. Most commonly forms sheets overlying older units on the downwind side of major basins or playas, such as on the northwest flank of Northwest Ridge. Forms dunes in a few places, such as northwest of Langford Well Lake. Light brown. Very loose. No soil development. Forms smooth surfaces, but may be rilled where sand sheets ramp against steep hill fronts. Unvegetated to moderately vegetated. Widespread on west side of Northwest Ridge

Qoe **Older Eolian Deposits** (Pleistocene)--Fine- to medium-grained sand. Forms ramps against bedrock hills. Medium brown. Slightly compact. Weak soil development consisting of approximately 10-cm-thick weakly developed (Stage I) calcic horizon underlying 1 to 2 cm of interstitial silt accumulation in the top of the unit. Forms smooth to rilled surfaces. Moderately vegetated. Present on west side of Northwest Ridge

Qyc **Colluvial Deposits** (Holocene)--Poorly sorted, angular to subangular, sandy cobble to boulder gravel. Forms as talus or rockfall accumulations below steep bedrock escarpments. Also forms by minor downslope movement of weathered bedrock, producing a thin cover of debris that obscures the underlying bedrock. Loose to compact. Lacks soil development. No varnish

Qoc **Older Colluvial Deposits** (Pleistocene)--Poorly sorted, angular to subangular, cobble to boulder gravel. Forms ribs transverse to steep slopes on the flanks of bedrock ridges. White to light brown. Very compact. Argillic horizons up to 10 cm thick with strongly developed (Stage III to IV) underlying calcic horizons. Strong varnish coat on some clast types, particularly basalt

Qs **Spring Deposits** (Holocene and Pleistocene)--Moderately sorted, laminated, chalky, silt to fine-grained sand and carbonate-cemented sand and gravel. Abundant light brown secondary silica. Occasional preserved root tubes and root or reed casts or impressions. Unit white to pale gray. Slightly compact to hard. Mound-shaped bodies in vicinity of spring discharge points. Occurs in areas of active spring discharge (Garlic Spring) and in areas where discharge has ceased. Commonly aligned along known young faults (northeast splay of Garlic Spring fault)

Tyg **Younger Gravel** (Pliocene?)--Poorly-sorted gravel- to boulder-size clasts of mostly volcanic and granitoid rocks set in poorly sorted sand and gravel matrix. Poorly to well lithified. Underlies highly dissected hills of northern part of Northwest Ridge, in Coyote Canyon area. Grades to finer deposits that interfinger with paludal deposits (unit Tp) north of map

Tp **Paludal Deposits** (Pliocene?)--Fine-grained evaporites, mud, silt, and fine sand deposited in marsh and playa setting. Typically white to off-white in color. Numerous vuggy calcareous intervals and root casts indicate alternate wetting/drying of a marshy or playa lake setting. Coarsens upward and laterally to sand and pebble conglomerate of Tyg. Local outcrops of two biotite-bearing silicic tephras. Vertebrate fauna present north of map (sec. 8, T14N, R3E). Deposits lie near north edge of map

Tyb **Younger Basalt** (Pliocene?)--Dense to very vesicular and microvesicular, medium- to dark-gray andesitic basalt. Very fine-grained groundmass. Rare olivine phenocrysts. Generally glassy to dark bluish-gray on fresh surfaces. Forms gently sloping mesa tops south of Bicycle Lake. Located near young fault zones. Considered Quaternary by Byers (1960) but significantly predates Pleistocene older alluvium (Qoa) and lies under Pliocene? paludal deposits (Tp) north of map. Preliminary $^{40}Ar/^{39}Ar$ age (whole rock) is 5.6±0.2 Ma, approximately on the Pliocene/Miocene boundary

Tob **Older Basalt** (Miocene)--Dense to very vesicular, medium- to dark-gray basalt or andesite. Glomerophenocrysts of olivine and fine plagioclase generally are set in very fine to fine-grained groundmass; phenocryst abundance varies. Where present, olivine phenocrysts typically altered to iddingsite. Flows form gently sloping mesa tops on Southwest Ridge and extensive surfaces on Northwest Ridge. Locally, sets of flows are separated by tuff; these basalt units are lithologically similar, but are divided by stratigraphic position: lowest to highest Tob_1, Tob_2, Tob_3, Tob_4, Tob_5. Units Tob_1, Tob_3, and Tob_5 are known or suspected basaltic andesites; Tob_2, and Tob_4 are known or suspected basalts (Keith and others, 1994). Unit lies on rhyolite in most places, but locally a few flows lie beneath rhyolite

Tt **Tuff** (Miocene)--White to pale green or beige, silicic tuff and tuffaceous sediment. Typically laminated or thin- to thick-bedded, but locally massive. Ranges from laminated vitric tuff to lithic and pumice lapilli tuff, all typically crystal-poor. Tuff carries fragments of aphyric rhyolite lava (unit Tr), pumice, and varying amounts of lithic fragments derived from pre-Tertiary rocks. Tuffaceous sandstone is thin- to medium-bedded, locally fanglomerate. Tuff varies from primary unwelded ignimbrite and fallout deposits to reworked and/or water lain tuffs and debris flows. Includes massively bedded, poorly sorted tuffaceous sandstone that probably represents debris flows. Crops out extensively in Northwest Ridge. Locally, sections of tuff and tuffaceous sediment are separated by basalt; these tuff sections are lithologically similar, but are divided by stratigraphic position: lowest to highest Tt_1, Tt_2, Tt_3, Tt_4. Unit lies on rhyolite in most places, but locally a few flows lie under rhyolite

Tr **Rhyolite** (Miocene)--Light- to medium-gray aphyric to sparsely quartz-phyric rhyolite, devitrified, laminated and strongly flow-banded. Base of lava marked by vitrophyre and flow breccia composed of obsidian, devitrified rhyolite, and underlying comagmatic tuffs. Crops out extensively in Northwest Ridge

Kmg **Muscovite Granite** (Cretaceous)--Leucocratic, coarse-grained biotite-muscovite monzogranite. Typically forms tan-colored groups of tors characterized by close-spaced jointing, compared to other Cretaceous granitoids. Muscovite typically twice as abundant as biotite, but micas are subequal in area along north margin of pluton. Feldspars are white, quartz light gray or bluish gray. Cut by sparse aplite dikes. Possibly grades to biotite-dominant phase (units Kpg and Kbg) along south and east margins, but contacts not exposed; linear contacts suggest fault control. May be coextensive with muscovite granite near Goldstone dated by Miller and Sutter (1982) as 76.8 ± 0.6 Ma on the basis of $^{40}Ar/^{39}Ar$ analysis of muscovite. May be related to muscovite-garnet pegmatite dike swarms in Northwest Ridge, Beacon Hill, and northeast Noble Dome. Similar pegmatite dikes 6 km east of map area are dated at 83 Ma (Schermer and others, 1994) and at Iron Mountain (60 km to southwest) are 83 ± 1 Ma by U-Pb on monazite (Boettcher and Walker, 1993)

Kpg **Porphyritic Granite** (Cretaceous)--Medium- to coarse-grained biotite monzogranite forming tan and white tors with wide joint spacing. Alkali-feldspar phenocrysts compose 10 to 15% of the rocks, and are as large as 2 by 5 cm, but generally are 1.5 by 2.5 cm. Matrix consists of medium-grained biotite, coarse-grained light-gray quartz, and coarse-grained white feldspars. Biotite 7-10 percent. Underlies much of Noble Dome and region to west, perhaps as a group of similar-composition plutons. Pink alkali-feldspar–rich pegmatite and white aplite dikes are common in much of pluton. On some margins, grades to sparsely porphyritic version (unit Kbg). Along south margin, appears to be mutually intrusive with biotite-rich granitoid (unit Kb). Smaller bodies present in Garlic Spring area. Probably coextensive with porphyritic granodiorite in Paradise Range quadrangle dated by Miller and Sutter (1982) as 81.76 ± 0.96 Ma on the basis of $^{40}Ar/^{39}Ar$ analysis of biotite

Kb **Biotite-rich Granitoid** (Cretaceous)--Equigranular, medium- to fine-grained, biotite-rich rock that borders south part of unit Kpg. Extensively diked by aplite and pegmatite, as well as dikes that may represent fine grained versions of unit Kpg. Locally foliated. Typically encloses blocks of unit Jmd 2-3 m in diameter. Similar to unit Kgm

Kbg **Biotite Granite** (Cretaceous)--Medium-grained biotite monzogranite. Sparsely porphyritic (<3%) with alkali feldspar phenocrysts as large as 1.5 cm. Biotite about 10-15 percent. Pegmatite and aplite dikes common. Grades into porphyritic granite (unit Kpg) with increase in grain size, increase in number of phenocrysts and loss of biotite

Kg **Granite** (Cretaceous)--Medium- to coarse-grained biotite monzogranite. Sparsely porphyritic (<5%) with alkali feldspar phenocrysts as large as 1.5 cm. Biotite about 7-15 percent. Pegmatite and aplite dikes common. Grades with increased diking toward a central dike complex (Kgd). Lies northeast of Noble Dome

Kgd **Dike Complex** (Cretaceous)--Pegmatite and aplite dike complex. Dikes constitute 50 to 95 percent of rock, with primarily Jurassic gneissic igneous rocks between dikes. Dike complex grades east and west (outward) to less-diked regions with host rocks of both granite (unit Kg) and Jurassic gneiss; contact drawn arbitrarily where dikes comprise 50 percent of rock. Where dike complex crosses belt of metasedimentary rocks, rocks are mapped as the latter, although much of rock is igneous. Interpreted as dike complex in roof zone of pluton

Kgm **Medium-Grained Phase** (Cretaceous)--Medium-grained biotite monzogranite, subequigranular. Includes 5-15 percent of mafic wallrock locally. Cut by common aplite and pegmatite dikes. Biotite 15-18 percent. Generally foliated. Similar to unit Kb

Jg **Gabbro** (Jurassic)--Very dark-gray, medium- to coarse-grained hornblende gabbro with poikilitic phenocrysts of hornblende as large as 2 x 8 cm. Local variation is not poikilitic. Matrix consists of anhedral light-gray plagioclase and subhedral hornblende. Hornblende constitutes about 40 percent of rock. Unfoliated, even where intruding foliated granitoids. Forms small bodies in northern part of Langford Well quadrangle and elongate bodies and wide dikes in southern exposures east of Noble Dome. Similar rocks dated near Goldstone by Miller and Sutter (1982) by $^{40}Ar/^{39}Ar$ methods at 148.3 ± 2.0 Ma, and in the Shadow Mountains 100 km to the southwest by Martin and Walker (1990) by U-Pb on zircon at 148 Ma. Intruded by unit Kpg and by pegmatite and aplite dikes

Jfg **Fine-grained Granitoid** (Jurassic)--Weakly to moderately foliated, fine- to medium-grained, light-gray subequigranular biotite granodiorite to granite. Biotite about 5 to15 percent. Dikes the quartz monzodiorite unit (Jmd)

Jpg **Porphyritic Granodiorite** (Jurassic)--Moderately foliated, medium- to coarse-grained, porphyritic biotite granodiorite. Phenocrysts of alkali feldspar as large as 1.5 x 2.0 cm; pink to purple in color. Biotite about 15 percent. Mafic xenoliths common

Ji **Intermediate-Composition Igneous Rocks** (Jurassic)--Medium- and coarse-grained, locally porphyritic, biotite-rich, dark-weathering rocks. Quartz 10 to 25 percent. Generally contains conspicuous sphene. More mafic rocks contain hornblende as well as biotite. Compositions mostly granodiorite to quartz monzodiorite. Biotite forms clots, discrete grains, and poikilitic plates as large as 1.5 cm^2. Rock types variable on scales of a few meters, with both composition and texture changing. Generally foliated and diked by mafic and felsic dikes, themselves locally foliated. Xenoliths locally abundant

Jmd **Quartz Monzodiorite** (Jurassic)--Coarse-grained biotite-hornblende quartz monzodiorite, grading to monzodiorite with more hornblende and, less commonly, biotite-hornblende diorite. Total mafic minerals typically 25 to 35 percent. Subequigranular, but common textural variations are characterized by black clots of mafic minerals, creating spotted appearance, and poikilitic biotite. Commonly foliated; in many places cut by mafic and felsic dikes, themselves locally foliated. Forms large relatively undeformed pluton north of Noble Dome. Farther south, unit is highly to moderately deformed and commonly heavily intruded by dikes from nearby Cretaceous plutons. At Northwest Ridge, unit is moderately deformed. Common associated rock types (not mapped separately) are fine-grained biotite-rich mafic rock, typically schistose or gneissic, and porphyritic medium-grained hornblende monzodiorite carrying phenocrysts of hornblende

Jqd **Quartz Diorite** (Jurassic)--Medium- to coarse-grained biotite quartz diorite, grading to monzodiorite, quartz monzodiorite, and granodiorite. Plagioclase is medium to coarse; other minerals are medium-grained. Quartz is bluish-gray. Locally contains hornblende. Total mafic minerals typically 35 to 45 percent. Subequigranular, commonly foliated; in many places contains lenses of mafic biotite and (or) hornblende rock. Similar rock, coextensive with mapped unit to east, is dated at about 170 Ma by U-Pb methods (Stephens and others, 1993)

Jm **Mafic Rocks** (Jurassic)--Complexly intergrading dark-colored mafic igneous rocks ranging from diorite to monzodiorite and biotite-rich granodiorite. Variably foliated; diked by felsic and mafic dikes. Lithology changes on scale of 2 to 25 meters

Jd **Hornblende Diorite** (Jurassic)--Medium- to coarse-grained hornblende diorite, grading to monzodiorite and quartz diorite. Plagioclase and hornblende are medium to coarse; other minerals are medium-grained. Locally contains biotite. Total mafic minerals typically 35 to 45 percent. Subequigranular, commonly foliated; highly folded in many exposures east of Garlic Spring

CZm **Marble** (Cambrian and Late Proterozoic)--Several metasedimentary rock types, most notably white marble. Apparent stratigraphic section is (top to bottom): White coarse calcite marble and lesser white marble with minor calc-silicate minerals; light gray impure marble containing garnet, micas, tremolite, sphene, phlogopite, olivine, or pyroxene; clean white and brown flaggy quartzite; schistose gray and brown quartzite; brown quartzose schist. Less common dolomitic marble, pelitic schist, and pelitic gneiss. Section differs among exposures: Mainly quartzitic near Garlic Spring, but mainly carbonate in Northwest Ridge and Noble Dome. Possibly represents metamorphosed Late Proterozoic siliciclastic strata and Cambrian calcareous shale, limestone, and dolomite. Marble and calc-silicate–rich compositional banding typically isoclinally folded. Locally intercalated with thin amphibolite schists.

s **Schist, gneiss, and amphibolite** (Proterozoic? and Paleozoic?)--Thick sequence of black and dark brown schist and schistose gneiss; black, coarse amphibolite gneiss; quartzite and quartzose schist; and thin layers of calcite and dolomite marble and calc-silicate rocks. Typically heavily diked by offshoots from nearby plutons; muscovite-bearing pegmatites are a common dike type in Northwest Ridge, Beacon Hill, and west of Garlic Spring. Locally includes mafic rocks such as diorite gneiss, biotite-plagioclase gneiss, and quartz diorite gneiss. Highly foliated, generally doubly folded, and locally migmatitic. Contains minerals such as sillimanite, wollastonite, and garnet, representing upper amphibolite facies metamorphic conditions. Located adjacent to marble section (unit CZm) in most cases. May in part represent Late to Middle Proterozoic strata such as the Pahrump Group and overlying units of the Death Valley region, and may represent metamorphosed eugeoclinal strata of Paleozoic age such as those at Goldstone (Miller, 1981) and Pilot Knob Valley (Carr and others, 1992).

gn **Gneiss** (Early Proterozoic?)--Augen gneiss and coarse biotite granitoid gneiss that are probably of igneous origin. Migmatitic and highly metamorphosed. Unit possibly underlies metasedimentary units (s, CZm) at Beacon Hill, suggesting an Early Proterozoic age for the gneiss

br **Breccia** (uncertain age)--Breccia composed mostly of highly fractured rocks belonging to the schist unit. May represent a landslide breccia. Lies east of Garlic Spring

INTRODUCTION

This report summarizes the results of detailed field investigations that were conducted to map and describe the bedrock and surficial deposits of Fort Irwin National Training Center, north-central Mojave Desert (Fig .1) and provide guidance on the implications of these findings for such purposes as mitigating geologic hazards and evaluating natural resources. Such studies are time-intensive. This initial report therefore covers only the part of the Center on which the main post is built and immediately adjacent lands. This map report is one of several that are intended to progressively cover the entire Center. These reports will describe earth materials, detail observations of various sorts on these materials, and provide interpretations of these data. Direct observations were made through the map area and were supplemented by photogeologic interpretation.

This report covers an area centered on the main post for Fort Irwin, which is con-structed on a broad valley within the Fort Irwin and Langford Well USGS 7.5-minute quad-rangles; herein informally termed "Fort Irwin basin". Past geological studies of this area have been few and generalized. Byers (1960) mapped the Langford Well quadrangle as part of a larger area mapped at intermediate (1:62,500) scale. The remainder of Fort Irwin was mapped at a scale of 1:250,000 by F.M. Byers, G.I. Smith, and R.C. Ellis as part of the Trona map sheet (Jennings and others, 1962). More recently, studies by Miller and Sutter (1982), Schermer and others (1991, 1994), Ford and others (1992), Schermer (1993a, b), Stephens and others (1993), Sabin and others (1993), and Keith and others (1994) in the Fort Irwin basin and adjacent ranges have provided much new information.

The USGS topographic base maps used for the geologic map have few place names. For this

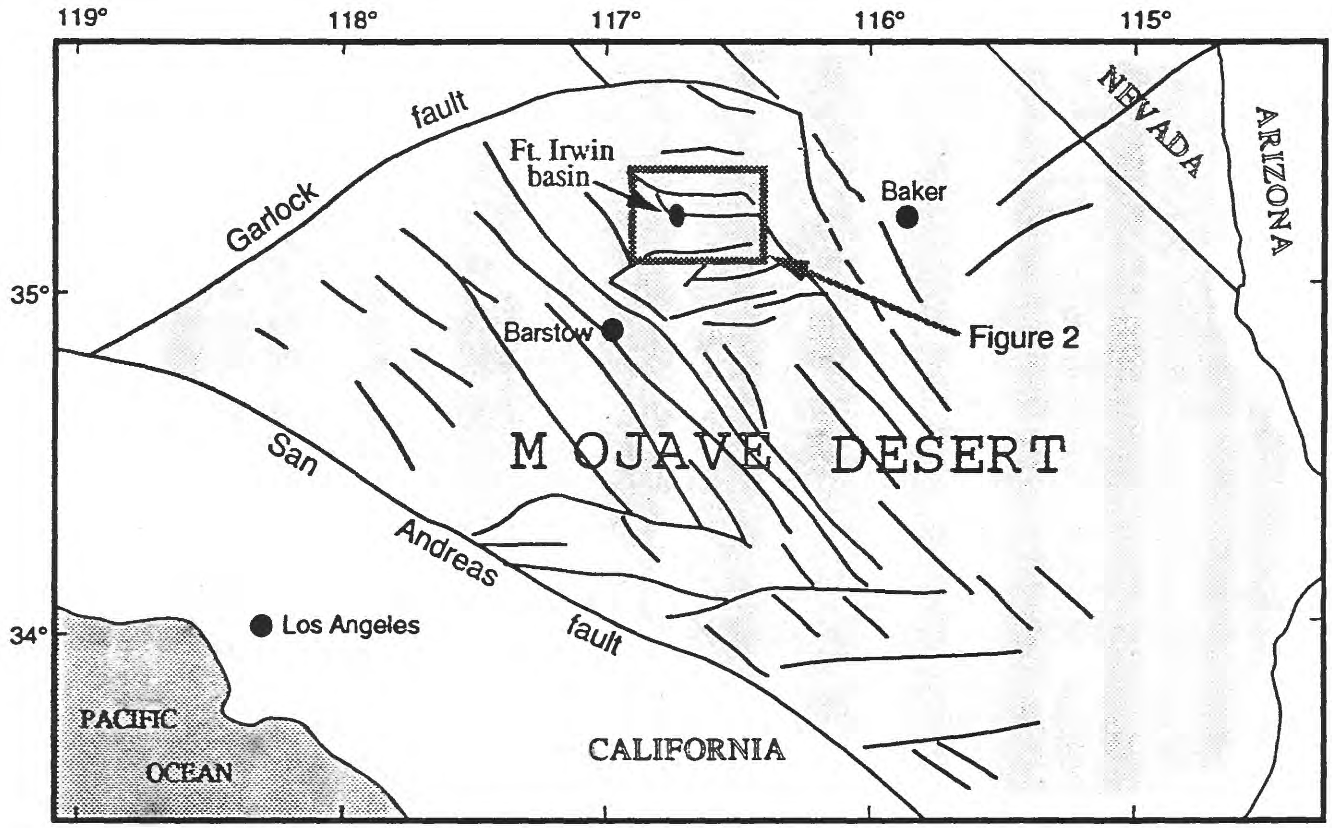

Figure 1. Location of Fort Irwin Basin in north-central Mojave Desert.

reason, we have informally named several locations, all of which are shown on the geologic map and some of which are shown in Figure 2. These names are provided only to facilitate description.

Data and interpretations in this report are preliminary, primarily because some analytical data (such as radiometric dates) are not yet available. The report is to be finalized and published with adjacent mapping in the USGS GQ (Geologic Quadrangle) Map series.

OVERVIEW OF GEOLOGIC HISTORY

As established for the central Mojave Desert region (Fig. 1) by many previous studies, the general framework of the Fort Irwin area is probably one of Early and Middle Proterozoic (1800 to 1400 million years old [Ma]) metamorphic and igneous rocks overlain by a sequence of sedimentary rocks (limestone, dolomite, sandstone, and shale) ranging from Middle or Late Proterozoic to early Mesozoic (1200 to 200 Ma) in age (Martin and Walker, 1992). The area lies near the boundary between offshore and nearshore Paleozoic sedimentary rocks (Miller, 1981; Martin and Walker, 1991, 1992; Carr and others, 1992; Boettcher and Walker, 1993; Stephens and others, 1993), so both assemblages may be present. The Mesozoic history of magmatism and deformation is still rather sketchy, but periods of magmatism from Middle Jurassic (175 to 160 Ma) to Late Cretaceous (70 Ma) time, in places accompanied by deformation, are established in some locations (Miller and Sutter, 1982; Walker and others, 1990a; Boettcher and Walker, 1993; Stephens and others, 1993).

Cenozoic magmatism and strike-slip faulting are evident at Fort Irwin. Thick piles of Miocene (>19 to 6 Ma) volcanic rocks are present in Northwest Ridge and ranges farther north and west, and a few locations of younger basalt flows have been mapped (Luyendyk and others, 1993; Keith and others,1994). Volcanic rock compositions are bimodal; mafic rocks are mostly basalt and andesite lava flows and felsic rocks mostly are rhyolite tuff and lava. These volcanic rocks filled in earlier topographic lows with paleotopography as great as 100 m, and created new

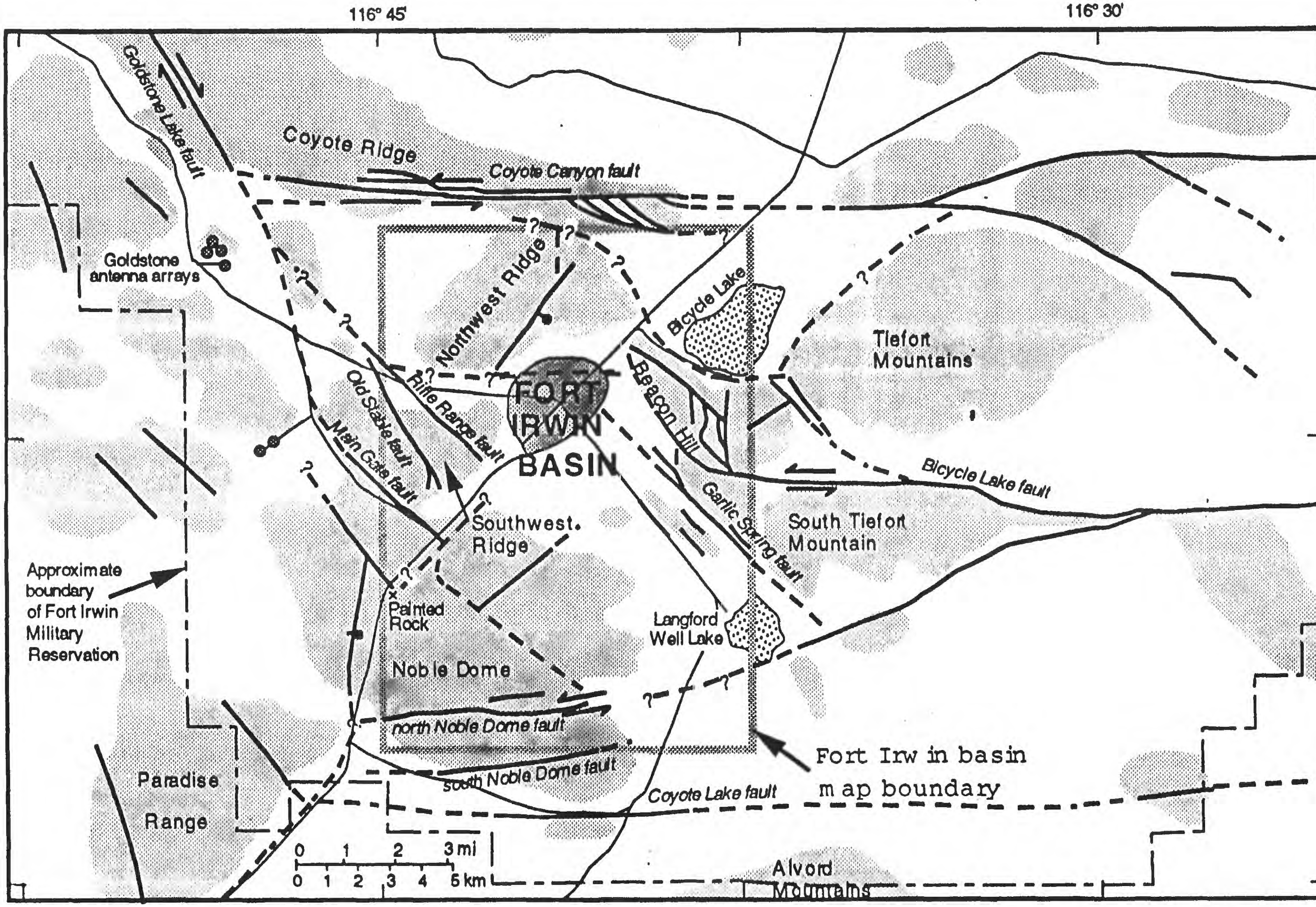

Figure 2. Map of faults and physiographic and cultural features, southwestern Fort Irwin. Operations base is patterned area in Fort Irwin basin. Filled circles represent approximate locations of deep-space antennas operated by NASA. Approximate locations of faults from Byers (1960), Jennings and others (1962), Dokka (1992), Schermer (1993), this report, and our unpublished geologic mapping.

topography of the same magnitude on felsic and andesitic eruptive edifices.

Prominent faults belonging to the eastern California shear zone of Dokka and Travis (1990a,b) extend through the Fort Irwin area. Local studies confirming that these faults are late Cenozoic include Schermer and others (1991), Ford and others (1992), Luyendyk (1992), Luyendyk and others (1993), Ron and others (1993), Sabin and others (1993), Schermer (1993a), and Valentine and others (1993). Late Miocene, Pliocene, and early Quaternary timing (~10 to 1 Ma) of the strike-slip faulting is inferred by most of these studies, although a paucity of dated late Cenozoic materials that are offset by the faults limits the interpretations in most cases.

During the last few million years, the present geomorphology of the Fort Irwin basin was established. Broad alluvial fans lead from mountain fronts to wide basins that in some cases contain playas. In some places the geomorphology is controlled by youthful faulting and uplift; in other places features such as pediments and domes indicate a more stable and mature geomorphology.

MESOZOIC AND OLDER STRUCTURE

The once-stable continent was modified in the late Permian or early Triassic by a major plate-tectonic change that truncated a large part of the continent (Burchfiel and Davis, 1981). Subsequently, subduction west of the Fort Irwin area created most of the typical features of Andean margins: magmatic arcs with their copious volcanic and intrusive rocks, thrust belts and zones of tectonic extension, and widespread deep metamorphism. Scattered Permian and Triassic plutons suggest incipient magmatic arc development. Thrust faults, ductile shear zones, and extensional structures have been documented in much of the Mojave Desert for mid-Jurassic time (Miller and Sutter, 1982; Busby-Spera, 1988; Walker and others, 1990a; Boettcher and Walker, 1993; Schermer, 1993b, Stephens and others, 1993). In particular, the Jurassic deformation belt of Walker and others (1990a,b) and Dunne and others (1978, 1983) passes near or within southern Fort Irwin National Training Center. The many uncertainties of interpreting the early Mesozoic history is partly due to the voluminous Cretaceous plutons that obliterate much of story.

Ductile deformation features are mainly observed in Jurassic and older, metamorphosed, rocks. Foliation and lineation are variably developed in the Jurassic plutonic rocks, which range from intensely strained mylonite to weakly foliated gneissic granitoid. Fabrics vary from intensely developed foliation and streaky lineations defined by elongated minerals to only vaguely defined grain-shape foliations. Variation in ductile structures is represented both as differences within 5-km-scale blocks and within these blocks on 50-m spacing. Much of the granitoid in the central part of the map, particularly north of Noble Dome, is weakly foliated at most, although even here local zones approach mylonitic fabrics. Jurassic granitoids in the remainder of the quadrangle, as well as the rocks they intrude, are typically moderately to strongly deformed. Mylonitic gneissic fabrics vary from L-tectonites (lineation intensely developed with vague foliation) to S-tectonites (foliation intensely developed and no lineation). The variations in strain intensity and kinematics are of uncertain significance, for no planar markers are present to outline the geometry of ductile flow. However, the fabric style and intensity varies with changes in foliation orientation, suggesting that heterogeneous strain may have produced folds; L-tectonites may occupy the fold cores and S-tectonites the limbs.

Because of the variability of foliation and lineation, it is difficult to decipher their meaning. In the southern half of the map area, foliation dips northwest, north, and northeast, giving the sense that foliation is basically north-dipping by a moderate amount. Lineation is variable, but the lineations for mylonitic rocks cluster in the southwest—northeast azimuth. Limited observations of asymmetric indicators of sense of shear in mylonitic granitoids consistently yield top to the southwest, giving thrust-sense shear in present orientation. Although the foliation may be folded, the kinematic data are compatible with those described by Martin and Walker (1991), Walker and Martin (1991), and Stephens and others (1993), who noted similar deformational styles in nearby Alvord Mountain and south Tiefort Mountain and suggested that a broad zone of southeast-directed shear affected Middle Jurassic and older rocks of this area. Elongate screens or septa of metasedimentary rocks between deformed Jurassic plutons parallel locally measured foliation, and may provide clues to map-scale structure. Septa south, west, and north of Fort Irwin basin strike northeast and east-northeast, whereas those in Beacon Hill strike north and northwest. The discontinuity between these domains, at Garlic Spring, may represent a major fault zone, possibly late Mesozoic in age because Jurassic granitoids differ across it but Cretaceous porphyritic granite on both sides is similar.

Ages of deformation and metamorphism are not well constrained, but comparisons with rocks studied in adjacent mountain ranges (Walker and others, 1990a; Martin and Walker, 1991; Walker and Martin, 1991; Stephens and others, 1993; Boettcher and Walker, 1993) suggest strain, and probably metamorphism, was mid-Jurassic. Plutons dated at 165-155 Ma are deformed in several nearby ranges, whereas dikes dated at 148 Ma are not. Plutons assigned Cretaceous ages in the Fort Irwin basin map area are generally undeformed, although parts of the biotite-rich granitoid and the medium-grained granodiorite (units Kb and Kgm) are strongly foliated. These foliated rocks contain inclusions of even more strongly foliated Jurassic quartz monzodiorite, so the second foliation-forming event postdates the development of the main Jurassic foliation. Because these units are undated, deformation may have locally extended into the Cretaceous, or these units may be Jurassic in age. Mutual intrusive relationships and compositional affinities with dated Cretaceous granites suggest the former. Deformed Early Cretaceous granitoids about 10 km east of the map area (Schermer and others, 1994) also support an interpretation of a second deformational event.

LATE CENOZOIC STRUCTURE

There is little information about the early Cenozoic evolution of this part of the Mojave Desert, but Late Cretaceous granites were deeply eroded before widespread Middle Miocene volcanic rocks were deposited and younger faults developed. Strike-slip faults that cut the Miocene volcanic sequence are inferred by many workers to be late Miocene to Holocene in age. Dokka and Travis (1990a) termed this strike-slip realm the Eastern California shear zone, and followed previous syntheses and models such as Dibblee (1961), Garfunkel (1974), and Dokka (1983) in describing several kilometers of separation on most faults and proposing that blocks bounded by the faults rotated as fault separation accumulated.

Main fault sets in the Eastern California shear zone strike east and northwest; a boundary between these sets lies in western Fort Irwin (Dokka and Travis, 1990a; Schermer and others, 1991; Luyendyk and others, 1993; Schermer, 1993a), roughly along the west side of the Fort Irwin basin map area (Fig. 2). Much of the central part of the Eastern California shear zone is seismically active, and scattered seismicity extends to the eastern part of the zone, making careful assessment of recency of movement on faults necessary to assess seismic shaking and related hazards. The Landers earthquake on June 28, 1993 and related preshocks and aftershocks caused fault rupture in a huge area south of Fort Irwin (Hauksson and others, 1993), leading to models for the development of a new major fault system across the Eastern California shear zone (Nur and others, 1993). Specific studies at or close to Fort Irwin, mostly in preliminary stages, are by Schermer and others (1991), Ford and others (1992), Luyendyk (1992), Luyendyk and others (1993), Ron and others (1993), Sabin and others (1993), Schermer (1993a), and Valentine and others (1993).

Structures possibly of late Cenozoic age include faults, fractures, and breccia zones, all of which may contain striae and other kinematic indicators. Jointing in intrusive and extrusive igneous rocks is probably also late Cenozoic in age, but we did not systematically study these structures because they are less likely to record tectonic information.

Faults

Most faults in the ranges around Fort Irwin basin strike northeast, east, or northwest. Those that strike northwest and east in many cases can be shown to have had latest movement during the Quaternary, whereas faults that strike northeast last moved before the Quaternary. A group of faults that strikes east includes the Coyote Lake fault, which was mapped and described by Byers (1960), and several parallel faults that lie within 4 km north of the Coyote Lake structure (Fig. 2). We refer to these northern faults as the Noble Dome faults for the desert dome that they traverse (named on the geologic map of Byers). Another major east-striking fault is the Bicycle Lake fault, which in the Fort Irwin basin area is composed of west- to northwest-striking segments (Fig. 2). Northwest-striking faults probably extend northwest as the Goldstone Lake faults (Fig. 2); these lie on the west side of the map area. Several faults extend toward basins, where they cannot be mapped by surface exposures in young materials, but must exist in the shallow subsurface. Their locations and recency of movement are important to determine, but require methods such as geophysics, drilling, and trenching.

North Noble Dome Fault. The north Noble Dome fault lies 0.6 km north of the south margin of the map. It strikes N 85° E but bends right at a step near its midpoint. The western half is represented by an alignment of north-facing mountain fronts that may indicate down-to-the-north movement. The eastern segment is defined by breccia and gouge within granite and shows about 110 meters of left-lateral displacement of a gabbro (Jg) dike. A parallel breccia zone lies about 200 m north of the eastern segment of the North Noble Dome fault. It may be genetically related to the north Noble Dome fault, which has a much longer trace. Typical surface exposures of the eastern fault zone consist of linear subdued topography, with the trough generally trending N. 85° E. and being 2 to 10 m wide. The surface of the materials in the zone is marked by grus that is generally white or lighter in color than surrounding rocks. Materials of the fault zone consist of brecciated granite and dike rocks, with clay seams along many fractures. Fracture spacing is less than 3 cm through most of the zone and numerous orientations of fractures occur. One zone composed entirely of clay was observed. It is 4 cm wide, and its margins are lineated. Most fracture surfaces are not lineated, but striae measured on fractures that are close to parallel with the overall zone (N.85°E., 70°N.) at one locality are within 23° of horizontal and plunge both east and west.

During our mapping in late October, 1993, open cracks along 2.4 km of the fault were observed. Later mapping (Dec. 19, 1993) following some rainfall-caused degradation identified a 3-km-long cracked zone. The cracks were observed from just west of the contact between units Kpg and Jmd, and 3 km westward along most of the segment where the fault coincides with the straight topographic north fronts of hills. Crack intensity, as measured by percentage of the fault zone containing cracks and by width of cracks, was greatest in the center of the cracked zone.

Cracks were observed in a variety of surficial materials: clay, silt, sand, and gravel (to 8 mm). In most cases, surficial materials are less than 1 or 2 m thick. Cracks formed in both moderately lithified and unlithified materials, but fresh cracks were not discerned in rock. In detail, cracks at the surface underwent 2-8 cm zig-zags, with no preferred stepping, but the lines of cracking were remarkably linear and confined to the breccia zone in granite. Cracks stepped en echelon left and right, although the major steps consistently were to the right at the bend in the fault about midway along its length. Crack width varied, but was about 1 cm at greatest.

Sense of separation was not well constrained, but a few matched features across the crack indicated components of left-lateral and normal movement; any net movement was probably less than a few mm. At one location, where the cracked soils lay on a steeper slope than other places (~15% slope perpendicular to the crack), as much as 2 cm of normal displacement occurred. Two crack traces existed along part of this segment, each with normal displacement. Displacement was probably accommodated by lateral movement of colluvium.

Cracking took place after the last water movement in washes, which was probably March, 1993. Cracking possibly occurred during a time when soils were moist, because in some places grass appeared to have been growing in the crack. Two rainfalls in December 1993 rapidly degraded the cracks, supporting the inference that cracking took place in 1993 after the last rainfall.

Several attributes suggest a tectonic origin, most likely creep, for cracking. Non-tectonic origins can be ruled out because (1) no nearby sedimentary basins exist that might have deformed due to groundwater withdrawal, and (2) the presence of cracks in sand and gravel containing little clay strongly suggests that cracking was not caused by desiccation. Lack of cracks on nearby fault zones containing similar fault-zone materials argues against causes from dynamic shaking. The long crack, the jog in the crack that conforms to a bend in the older breccia zone, and the presence of lateral down-slope movement strongly suggest cracking by tectonic causes. Triggered slip during the Landers earthquake (1992) appears to be ruled out by the spring 1993 time for cracking. Seismicity in the vicinity since January 1, 1992 consists of a few small-magnitude (<3.0) events about 3 km distant, and 2 or 3 slightly larger events (magnitude 3 to 4) about 10 km distant. These seismic events probably are insufficient to produce surface movement, but if they are inaccurately located and actually represent shocks on the north Noble Dome fault, it is remotely possible that one of these earthquakes caused surface rupture. The much more likely alternative is aseismic creep. Cracks caused by creep in 1988 in the Pine Nut Mountains, Nevada, degraded rapidly (Bell and Hoffard, 1990) and appear to be a good analog for those at Fort Irwin.

Bicycle Lake Fault Zone. East of the Fort Irwin basin, Byers (1960) mapped the Bicycle Lake fault zone as a generally east-striking fault zone (Fig. 2). There, the fault is bounded on the north by a Quaternary basin and on the south by Jurassic granitoids. It offsets Pliocene(?) basalt by 3 to 8 km, and a band of marble by 2.9 km (~3.5 km if drag is taken into account), in a left-lateral sense (Byers, 1960). Within the Fort Irwin basin map area, the fault bifurcates to bracket Beacon Hill, with main faults probably lying along the north (south margin of Bicycle Lake) and along the southwest sides of Beacon Hill. These segments appear to accomplish a stepover of about 3.5 km to the right. Between the two main strands lie several faults, within the Beacon Hill block, that appear to be both strike-slip and thrust faults (Fig. 3).

The presence of Quaternary basins north of the Bicycle Lake fault and, in particular, Bicycle Lake itself, suggests that there is some down-to-the-north movement on this northern fault strand as well as the left-lateral movement seen farther east. The Bicycle Lake fault appears to cut middle- to late-Pleistocene surfaces immediately east of the map area. The northern strand by Bicycle Lake is not exposed and therefore no direct dating of the fault has been made.

Faults that cut southern Beacon Hill, and probably some that border the southwest front of Beacon Hill, are mappable eastward toward the Bicycle Lake fault system proper, where about 3.2 km of offset is known on this southern strand. Where the fault cuts across southern Beacon Hill as a discrete fault zone of gouge and breccia, it dips 70° to 80° south and striae plunge 30° west. The limited striae data suggest reverse movement (if the fault is sinistral here) but the higher topography to the north suggests a component of normal movement. The fault apparently bends to a northwest orientation and breaks into several smaller breccia and gouge zones that crop out over about 50 m in gully exposures perpendicular to the faults along the southwest front of Beacon Hill. These zones strike N30°W to N55°W and dips range from 40° NE through vertical to 52° SW. Striae at one locality rake from 20° to 42° to the southeast, suggesting oblique motion on that fault plane. Other markers of movement sense (offset unconformities) indicated both southwest and northeast sides down. Older alluvium is faulted and fractured, but not intermediate alluvium, so latest movement was before the late Pleistocene. This part of the fault zone evidently underwent complex motion through time; it may contain splays that exhibit both dextral and sinistral movement. Complicating the interpretation of the southwest Beacon Hill frontal faults is a likely right step of faults in the Garlic Spring system, described below in the section on Garlic Spring faults.

Faults within Beacon Hill consist of a central strike-slip fault that passes the length of the hill, several nearly north-striking faults, and a northeast-striking fault that cuts 5.6-Ma basalt (Fig. 3). The strike-slip fault is marked by a breccia and gouge zone about 10 m wide, within which are horizontal striae. At its west end, nearly horizontal flows of older basalt (unit Tob) are offset down about 10 m to the north. At its east end the fault is truncated by a north-striking reverse fault. Amount of separation is not well constrained, but lateral separation must be greater than 0.8 km in order to explain lack of matching plutons and dikes, and separation is most likely left-lateral. The fault does not cut intermediate-age alluvium.

Four north-striking faults within the Beacon Hill block appear to be reverse faults, numbered 1 to 4 from west to east (Fig. 3). Fault 1 forms a straight trace across steep topography, indicating a steep dip, but no direct measurements of structures in fault materials were possible. It probably extends north of the strike-slip fault in Beacon Hill, but is concealed by intermediate and younger alluvium. Fault 2 is a low-angle, probably reverse, fault marked by a 5- to 10-m thick zone of breccia and gouge. The most reliable measurements of the zone indicated dips of about 55° to the northeast, but dips measured ranged from 35° to 70°. Striae measured on fractures near the breccia zone and on fracture planes within the gouge were quite variable and are of uncertain significance. Fault 2 is truncated by the central strike-slip fault of Beacon Hill. Fault 3 is a short north- to northwest-striking fault between the central strike-slip fault and fault 4. In one exposure, it strikes N42°W and dips 47° NE. It is overlapped by older alluvium in its central sector. A lack of correspondence of bedrock units across it indicates at least tens of meters of separation. Fault 4 strikes north and terminates several faults to the west. It bounds the mountainous part of Beacon Hill on the west, and a linear valley and lower areas covered by younger basalt on the east. One fault plane measured has a strike of N15°E and dip of 58°W; striae in the plane plunged 10° to the N10°E. Judging from effects on topography,

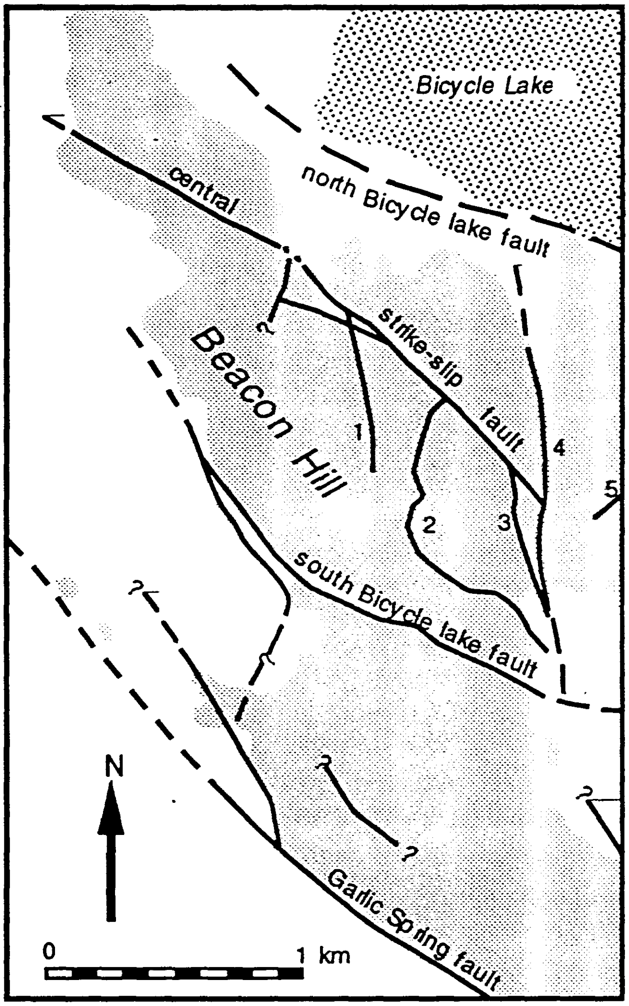

Figure 3. Map of Beacon Hill showing principal faults

the fault is probably reverse sinistral oblique. It is overlapped by intermediate-age alluvium. East of fault 4, a north-northeast-striking fault (fault 5, Fig. 3) cutting younger basalt displays about 6 m of down-to-the-southeast separation of the basalt.

The west or northwest extrapolation of the Bicycle Lake fault zone is uncertain. Also uncertain are the possible relations with the Garlic Spring fault. Because the system of faults has a cumulative separation of several kilometers, it probably should have a noticeable expression westward from Beacon Hill. A probable left step in the gently northwest-tilted Miocene volcanic rocks of Southwest and Northwest Ridges (compare locations of the base of unit Tob) may represent the Bicycle Lake fault zone. In this case, the fault zone extends west, under a few meters of Quaternary strata, across Fort Irwin basin. An alternative position north or east of Northwest Ridge (Fig. 2) is possible but has little supporting data. Yet another alternative is that a northeast-striking fault passing from the Main Gate to the west side of Bicycle Lake truncates the Bicycle Lake fault system. These possibilities require testing with data from subsurface studies such as drilling holes and conducting geophysical experiments.

Garlic Spring Fault. The Garlic Spring fault was mapped by Byers (1960). It consists of a northwest-striking linear breccia and gouge zone. Near Garlic Spring, an alignment of springs, seeps, and spring deposits mark the fault. Parallel fault traces are mapped near the main trace on the basis of subtle scarps in alluvium, a few excellent exposures of faults cutting intermediate-age alluvium (Qia), and aligned spring deposits interbedded with intermediate-age alluvium (Qia). Striae here are about horizontal and minor shear planes and fractures yield right-lateral sense of offset. This fault zone is mid-Pleistocene and older and presumably has right-lateral movement like other faults of this orientation in the region, but neither sense nor magnitude of separation are directly determined on the fault. If outcrops of Cretaceous porphyritic granite (unit Kpg), present on both sides of the fault near Garlic Spring, were once continuous, the fault has about 1 km of left-lateral offset. Apparent right-lateral displacement of marble by the parallel fault along the Langford Well Road supports the assumption that the Garlic Spring fault is a right-lateral system. Dokka (1992) predicted the Garlic Spring fault to have 0.5 km of right-slip separation, based on his model of the Eastern California shear zone. We extrapolate the fault zone northwest to the vicinity of the sewage treatment plant on the basis of the anomaly represented by two small hills exposing Mesozoic rocks in the center of Fort Irwin basin. Bedrock may shallowly underlie the entire eastern side of the basin, based on widespread bedrock exposures in gullies along the east margin and the several small hills of bedrock near the axis of the basin.

We have documented several subparallel splays of the Garlic Spring fault, including one that can be mapped almost continuously from its departure from the main fault to a position 200 m to the northeast. This splay has prominent spring deposits adjacent to it, which interfinger with intermediate-age alluvium (Qia) and the fault cuts and deforms alluvium of similar age in excellent exposures. A small right step in the topographic front northeast of the Garlic Spring fault coincides with the location of this right-stepping splay, indicating a probable component of down-to-the-southwest on the fault system. A much larger right step of the topographic front takes place a little farther north along the fault, raising the possibility that a 1-km step in the Garlic Spring fault system is responsible. No faults were identified in gully exposures close to the mountain front, but a fault location farther from the front is possible. We show on Figure 2 a possible configuration of faults here. If a strand of the Garlic Spring fault system does step right at this location, the interaction of the strand and the western part of the (south) Bicycle Lake fault is probably complex and may account for the variable fault orientations and senses of movement seen in faults along the southwest front of Beacon Hill.

Jurassic plutonic rocks are considerably different on either side of the Garlic Spring fault. On the northeast, most rocks are fine-grained granite and diorite. On the southwest, most are intermediate and mafic magmatic rocks. Further, Paleozoic metamorphic rocks mostly strike north to northwest on the northeast side of the fault, in contrast to the northeast strikes on the other side. Pseudotachylite veins, present just northwest of Garlic Spring in the fault zone, suggest relatively large magnitude seismic shocks along this fault at some time, and therefore movement at a deeper level, which probably indicates a pre-late Cenozoic history for the fault zone. Cretaceous porphyritic granite (unit Kpg) appears to cut across both structural and lithologic domains. The data point to a Jurassic or Early Cretaceous fault zone at Garlic Spring. Late Cenozoic faulting probably reactivated this zone.

Old Stable Fault. The Old Stable fault is informally named for a series of faults that lie northwest of the old stables (sec. 12, R2E, T13N). The fault system probably belongs to the Goldstone Lake east fault zone of Dokka (1992); with further study of connections to the Goldstone Lake faults farther northwest, the name is subject to revision. The fault drops basalt down to the west by 20 to 40 m. These faults strike north-northwest and pass southward to north strike. The curving splay of faults has relatively youthful appearing geomorphic expression, with intermediate-age alluvium (Qia) inset against, and (or) faulted against, older alluvium (Qoa). The faults appear to have undergone both right-lateral and down-to-the-west sense of movement at this point. The main fault scarp is as much as 4 m high where older alluvial fan surfaces are elevated east of the fault. The same fault trace is marked by a scarp less than 1 m high where it cuts intermediate age alluvial surfaces. Such patterns of larger scarp heights on older surfaces is taken to indicate recurrent movement on the Old Stable fault. Trenching investigations will be required to determine how many events have built the observed scarps and how much offset has taken place on each event. The curving splay is appropriate for a horse tail splay interpretation at the termination of a right-lateral fault zone. Alternatively, the fault may curve around the margin of the rhyolite mass to the west.

Rifle Range Fault. The Rifle Range fault system is named for exposures southwest of the Goldstone Road, near the several rifle ranges. The fault system probably belongs to the Goldstone Lake east fault zone of Dokka (1992); with further study of connections to the Goldstone Lake faults farther northwest, the name is subject to revision. One obvious strand in the northwest part cuts older basalt (Tob), older alluvium (Qoa), and intermediate-age alluvium (Qia). Although locally a fault scarp approximately 1 m high marks the uplift of intermediate-age alluvial fan deposits (Qia) on the east relative to older alluvial fan deposits on the west, along most of the fault alluvium is faulted down to the west against older basalt. A probable second fault strand (not shown on the map) lies to the southwest. To the southeast, two faults cut outcrops of Miocene volcanic rocks in Southwest Ridge. They appear to cause small displacement of the basal noncoformity, but each offsets basalt on the northeast side up by 40 to 80 m. The northeastern fault splays within the volcanic rocks.

Main Gate Fault. The Main Gate fault is a nearly vertical breccia zone that strikes northwest and extends to the southeast to a position near the main gate of Ft. Irwin, for which it is named. The fault probably belongs to the Goldstone Lake east fault zone of Dokka (1992); with further study of connections to the Goldstone Lake faults farther northwest, the name is subject to revision. This breccia zone contains mostly subhorizontal slickensides on two sets of fractures, one striking about east and the other northwest, suggesting that it underwent mainly strike-slip movement.

Fibrous quartz forming asymmetric steps on the northwest set indicate right slip.

The fault separates rocks with different histories and different ages. Simple calculation of strike-slip movement by offset of the margin of a muscovite granite pluton (unit Kmg) suggests about 3 km of left-lateral movement, but it is not known if this margin of the pluton is high-angle and a good measure of offset. Furthermore, the wallrocks at the respective margins of the Kmg pluton differ (Jurassic on the northeast side, Cretaceous (Kpg) on the southwest side). Minor structures support Dokka's (1992) findings of right slip (farther to the northwest), so we tentatively conclude the fault underwent mainly right slip. We extrapolate this fault to the southeast where Cretaceous and Jurassic rocks of somewhat different character are apparently juxtaposed by a fault zone of the same orientation, although direct exposures of the fault are not present. Fractured and altered granitoids at one point on the extrapolated fault support the inference that it continues to the southeast. The fault probably jogs right near the main gate. This may be accomplished by offset on a younger northeast-striking fault or it may be a right-step within a strike-slip fault system. Breccia in the fault is overlain by older alluvium (Qoa), and therefore last movement on the fault was early Pleistocene or older.

A parallel fault probably lies about 1.5 km southwest of the Main Gate fault. It is not directly exposed within the map area, but is inferred by the linear juxtaposition of two large plutons and by small fracture zones paralleling the inferred fault. This fault may correspond to the Goldstone Lake west fault zone of Dokka (1992). Studies of the fault farther northwest are needed.

Northeast-striking Faults. Two northeast-striking fault systems are present and a third fault may exist. The most impressive northeast-striking fault zone is a 10- to 15-meter wide zone of breccia and gouge that lies in the central part of the Langford Well quadrangle (north of Noble Dome) and separates Jurassic and Cretaceous plutonic rocks of very different characteristics. The fault zone predates all Quaternary deposits in that area and, indeed, may be largely Mesozoic in age. Another northeast-striking fault system that lies in Northwest Ridge down-faults the Miocene rhyolite and basalt sequence to the southeast and tilts the Tertiary sequence northwest of the faults to the northwest. It therefore appears to be simply a normal fault system. This inference is supported, and the youth of this normal fault is indicated, by thickness of sediment under Fort Irwin basin (Jill Densmore, U.S. Geological Survey, oral commun., 1993). The sedimentary basin deepens from about 30 m near the sewage ponds to about 110 m under the logistics base to 210 m on the northwest side of the base. This geometry of the basin fill is reminiscent of tilt-basin geometry developed during normal faulting.

A possible northeast-striking fault near the main gate, nowhere directly observed, explains the termination of the muscovite granite unit (Kmg) and the jog in the Main Gate fault. It could possibly extend northeast across Fort Irwin basin and along the west side of Bicycle Lake.

SUMMARY OF QUATERNARY DEPOSITS

Quaternary deposits and associated landforms contain a record of the recent history of the Fort Irwin area. For this reason, these deposits provide valuable information about destructive processes such as flooding and earthquakes. The geomorphology of the region around Fort Irwin basin contains many of the classic elements of desert landscapes. The prototypical desert basin, with closed internal drainages feeding from exposed bedrock mountain ranges, through alluvial fan systems to a flat-floored valley bottom occupied in part by a dry lake or playa is typified by the basins containing Bicycle Lake and, to some degree, Langford Well Lake. These closed basins, termed bolsons by Great Basin geomorphologists (Peterson, 1981), contain most of the Quaternary deposits covering the map area. A particular closed basin type that lacks a central playa, the semi-bolson, is the setting for Fort Irwin's logistics base, and accounts for most of the remaining Quaternary deposits. Additional geomorphic features and their associated Quaternary deposits are found mainly in the hills and mountains surrounding Fort Irwin. These features include hill-slope deposits such as talus, colluvium, and rockfall debris that reflect mass wasting (breaking down in place and moving downslope) of the bedrock; windblown sand and silt; and local dry washes that transport debris intermittently, usually by way of flash floods, through the mountains and onto alluvial fans on the flanks of the bolsons.

Erosion of much of the bedrock in the southern part of the map area leads to some special geomorphic features that are common to desert regions around the world. The relatively rapid grain-by-grain disintegration of the Cretaceous granitic rocks near Painted Rocks and over Noble Dome (Fig. 2) yields low relief, symmetrical, broad hills with craggy granitic boulder piles (tors) protruding along their flanks and near their summits. These features, termed granite domes or desert domes (Davis, 1933, 1938), contrast sharply to the more rugged topography developed on the more resistant Jurassic granitic and metamorphic rocks immediately to the north and to the deeply eroded topography developed on the Tertiary volcanic rocks of Southwest and Northwest Ridges. A consequence of the extensive erosion of mountain fronts back away from basin axes is that many of the Quaternary deposits along the flanks of the domes and hills are very thin. These beveled low-relief slopes with thin veneers of Quaternary debris are termed pediments. Pediments are extensive throughout the southern part of the map area as well as between the sewage ponds and Beacon Hill.

Criteria for subdividing and mapping the Quaternary deposits and their associated landforms depend as much on observations of features that make up the surface of the landform as they do on observation of the deposits themselves. After deposition ceases in building up a geomorphic feature, such as an alluvial fan, processes that alter the form of the feature begin to take place. Channels passing through the fan to lower points in the basin begin to dissect and erode into the fan alluvium. Wind- and rainstorm-derived sheetwash moves fine material around on the surface of the fan, filling in small channels and smoothing out the microtopography on the fan. Desert pavements begin to develop on the smoothed surfaces. Soils begin to form as a response to weathering of the stable surface. Desert varnish builds up on clasts that litter the fan surface. With time, the fan surface begins to become deeply dissected, side slopes along incised channels expand, and the original fan surface begins to erode away. Ultimately, the entire fan-shaped body of alluvium becomes so eroded that the original fan form is difficult to discern.

Using this evolutionary progression in the build up and decay of landforms with time, we can classify the relative ages of these features and their underlying deposits by comparing certain geomorphic and geologic criteria that are thought to vary with time. In the Mojave Desert and southern Great Basin such relative age criteria include: 1) in-filling of bar and swale microtopography on wash or alluvial fan surfaces (Ritter, 1987), 2) depth and pattern of incision of channels that erode into the landform, 3) degree of flatness or roundness of surfaces between dissecting channels (interfluves), 4) decrease in overall grain-size of surface clasts reflecting progressive breakage with time (McFadden and others, 1989), 5) degree of soil development on all geomorphic surfaces (McFadden and others, 1989; Reheis and others, 1989), 6) degree of development of interlocking desert pavement, 7) degree of desert varnish cover of clasts at the surface of the landform (McFadden and others, 1989). Table 1 presents generalized observations of some of these and other criteria for the alluvial fan and wash units defined for this map. Tentative age estimates for these units are taken from correlation with the indicated studies where independent dating of Quaternary units has been possible. These ages are useful for constraining the times of last movement on fault zones.

SUMMARY OF YOUTHFUL TECTONICS

The Fort Irwin basin map area lies within the zone of Miocene to Holocene strike-slip faulting that encompasses much of the west-central Mojave Desert. The potential hazard of earthquakes on these faults is important to evaluate. In the vicinity of Fort Irwin, these faults mostly strike east-west but along the west and northeast sides of the Fort Irwin they strike northwest. This framework of relatively young strike-slip faulting has been explained by Garfunkel (1974), Dokka (1983, 1989, 1992), Nur and others (1993), Luyendyk and others (1993), and Schermer (1993a) by various models of blocks that rotate as their bounding faults move. The boundaries of the province are represented by the Garlock and San Andreas faults (Fig. 1). The age constraints for movement on faults in the Fort Irwin area are sparse. The faults appear to have displaced Miocene rocks, about 17 Ma, and also to have cut younger basalts (Byers, 1960; Schermer, 1993a), about 5.6 Ma. With the exception of the north Noble Dome fault, all of the faults we have studied in the Fort Irwin basin map area had last movement during the early- to late-Pleistocene. This age of last movement is not firmly known in many cases but the general lack of extremely young-looking geomorphic features, combined with the character of soil development in surficial deposits that overlap the most recently faulted materials, suggest that many of the faults within the Fort Irwin basin area have not sustained significant movement in the last 10,000 years, but probably sustained significant movement in the past 100,000 years. In contrast, the Coyote Canyon fault (just north of the Fort Irwin basin map, Fig. 2) does show evidence of movement during the last 10,000 years.

Modern seismicity, which is extremely abundant west of the Goldstone Lake fault, and is scattered farther east along, in particular, the Coyote Lake fault and faults bracketing Tiefort Mountain (Fig. 2), suggests that this area is still seismically active and still capable of sustaining a ground-rupturing seismic event. In addition to the strike-slip faults that appear to be quite youthful in the Fort Irwin area, normal faults that strike northeast and dip southeast are probably quite young as well. The best example of one of these normal faults lies immediately northwest of the central base of Fort Irwin along Northwest Ridge. The fault has down-dropped Miocene rhyolite and basalt in a series of steps toward the Fort Irwin basin. The northwest-thickening sediment fill of Fort Irwin Basin, revealed by sparse wells in the basin at the townsite of Fort Irwin, show a geometry like a tilted basin, suggesting that the northwest side of the basin tilted down as faulting in Northwest Ridge progressed. It would be important to date these tilted sediments to estimate how recently the normal fault was active.

Movement on north Noble Dome fault during 1993

Creep movement in 1993 on the north Noble Dome fault may have significant impli-cations for planning for seismic and creep-type ground-breaking events. At this point, we cannot confidently state the cause of this creep event, which limits our ability to predict future fault movement at Fort Irwin. Two scenarios for creep on the north Noble Dome fault are (1) the creep event was one of many that repeatedly occur, and was unusual only in that it was recorded, and (2) the creep event was induced by stress changes following the Landers (1992) earthquake and associated shocks.

So much of the western Mojave Desert is sparsely populated it is entirely possible that creep-induced cracking on a continuing basis could go unnoticed. If the cumulative slip on the creeping faults is small enough (perhaps five centimeters in 10,000 yr) it would not leave visible permanent records in Holocene alluvium. If a single creep event results in a 1-3 mm of slip, then the maximum number of creep events for the record to be unnoticed in Holocene alluvium is about 50, which corresponds to a recurrence rate of about 200 yr. In this case, chances of creep-induced cracking on any given fault at Fort Irwin may be small enough to not warrant mitigation measures.

If the second scenario for the north Noble Dome fault holds, creep was caused by far-field strain caused by the Landers event, or even a new stress regime that is reorganizing faulting patterns in the Mojave Desert (Nur and others, 1993). In this case, the creep event could represent new fault activity and be repeated by many faults at Fort Irwin in the near future. A model of the stress field resolved on the north Noble Dome fault as a result of all fault movements triggered by the Landers and Big Bear earthquakes indicates that small components of left-lateral shear stress and fault-normal tensional stress were added (R.G. Simpson, 1994, written commun.). Movements appropriate for these stresses were observed on the north Noble Dome fracture. Evidence therefore supports the interpretation of new activity as a result of far-field stress from the Landers event. As we learn more about the locations of active faults, we may be able to better predict any resumption of movement on faults. By this scenario, all of the Quaternary faults, and even the older faults, are capable of creep and possibly seismic activity. Accordingly, it is important to acquire as much data as possible for surface and subsurface faults to be able to predict future behavior from the standpoint of mitigation measures.

PRACTICAL APPLICATIONS

The geologic map contains information that should be useful for such things as planning facilities, locating sources of building materials, and delineating regions prone to geologic hazards such as faulting or flooding. The scale of the mapping (1:24,000) is too small to allow the map to be used for predictions of site-specific geotech-nical properties, but the map does provide a guide for determining what types of detailed studies might need to be performed.

Properties of the geologic units and some of the considerations relevant to flood hazards are listed in Table 2. Delineating hazards related to earthquakes and faulting, such as predicting sur-face rupture zones, estimating maximum credible earthquakes and their locations, and estimating ground response characteristics for specific sites within the Fort Irwin basin, must await more detailed studies and derivative maps. However, the present mapping does highlight some of the faults that appear to have the most potential for earthquake hazards. The section on faulting describes these faults and gives estimates of the youngest geologic feature cut by the fault system.

The fissures mapped on Bicycle Lake represent a type of structural feature that may not be formed by earthquakes, but that may still have practical significance for siting buildings, runways, or roads. The features most likely form by drying out of the playa silts and clays as desiccation cracks. The cracks can be long-lived, in that a number of them that are prominent today show up on aerial photographs taken in 1947. Elsewhere in the Great Basin and Mojave Desert, these cracks have been observed to intercept surface water flow and transport large volumes of water downward along the crack. This process can enlarge the crack at depth resulting in subsurface erosion (piping) and eventual collapse of surface materials along the crack. Sinkholes along such eroded cracks have been reported as wide and deep as several meters and as long as one kilometer.

GROUND-WATER BASINS

Ground-water basins generally are largest and most productive under physiographic basins such as Bicycle Lake, Fort Irwin basin, and the Langford Well Lake area. Understanding water movement within and between the basins relies on a combination of extrapolating surface geology and of subsurface knowledge gained by such techniques as drilling and geophysical methods. With the knowledge from our geologic mapping of the Fort Irwin basin area, we cannot predict the details of ground water locations and movement, but the structural controls exerted by faults mapped in hills adjacent to basins provide some information with which subsurface data should be combined. Faults near and within the basins in most cases form nearly vertical zones of brecciated rock and gouge and thus may form impediments or barriers to water movement. Springs along faults such as Garlic Spring demonstrate the effect of dammed ground water. Many of these faults are as young as late Pleistocene, and therefore faulted materials that can affect water movement are at most only shallowly buried by Holocene alluvium (only a few meters in most cases). Some faults, such as the Garlic Spring fault and its splays and the southern strand of the Bicycle Lake fault, are well known and can be projected with confidence for 1 to 2 km into the Fort Irwin basin. Other faults, such as a western projection of the south Bicycle Lake fault and the north Bicycle Lake fault adjacent to Bicycle Lake, are less certainly present and are poorly located (and not shown on the map for this reason). All of these faults might affect ground-water movement and therefore require more investigation by subsurface methods to accurately locate them and better assess their affect on water.

MINERAL AND OTHER RESOURCES

Few economic mineral resources were discovered during geologic investigations. No manifestations of mineral occurrences were observed in bedrock units. In general, quantities of metamorphic rock such as marble are low and the composition and quality of the rock varies drastically over centimeters to a few meters, making it not amenable to bulk mining methods. Opaline material is locally abundant along the Rifle Range fault and at the contact between basalt and tuff on western Southwest Ridge; also common here is brightly-colored altered tuff. In northern Northwest Ridge, the contact between units Tob_2 and Tt_2 is marked by opaline material. Archeological relics were observed in several places.

SUMMARY

Geologic mapping of the Fort Irwin basin has delineated new bedrock map units and surficial deposits, greatly increased knowledge about the properties of these rocks and materials, and delineated locations potentially subject to hazardous geologic processes such as fault creep and rupture, floods, and sand storms. Aspects of this study that are most pertinent for the property owners are primarily the properties of geologically youthful deposits and the currently active processes that formed the deposits. No economic mineral resources were identified during geologic investigations.

Engineering properties of the various Quaternary deposits vary considerably, but some generalizations are possible. Coarser materials are present in deposits close to mountain fronts and finer materials close to basin floors. The best targets for clean, well-sorted coarse sand and gravel are probably alluvial veneers and fans on or near Cretaceous granites of the Noble Dome area. Finer sand can be found in eolian deposits, such as those west of Northwest Ridge and fringing Langford Well Lake. Most intermediate and older deposits have strongly developed soils that emphasize clay in some layers and hard calcium carbonate build-ups in others, making these deposits more difficult to excavate than younger deposits. Hard rock resistant to weathering, for uses such as rip-rap, are abundant in the Tertiary volcanic sections (mainly unit Tob). Finer grained granites (such as unit Jfg) are better suited for these purposes than coarser grained granites, marble, and schist.

The main potentially hazardous geologic processes are a variety of seismic hazards and flooding. Hazard from direct ground rupture during an earthquake is still difficult to assess, but cannot be ruled out, so structures should not be sited on or near faults shown on the geologic map. Seismic shaking will in general be greater at sites located above thicker unconsolidated deposits (central Fort Irwin basin, Bicycle Lake basin, and near Langford Well lake) than those located above thin unconsolidated deposits or bedrock. Liquefaction of sediment may occur during shaking; it develops where sand-size sediment is saturated with water, so the severity of liquefaction is controlled by depth of groundwater and the type of sedimentary deposit. Finer grained alluvial materials, present near the floors of the basins, are susceptible to liquefaction, particularly if the water table is shallow, as it may be at the two lakes. Channelized floods during and following rain storms are a hazard in all areas underlain by young alluvial and wash deposits (Qya_1, Qya_2, Qyw_1, Qyw_2), particularly those close to mountain fronts. Broad, shallow sheet floods may occur farther from the mountains on these deposits, in lower reaches of alluvial fans and washes. Intermediate and older alluvial fan surfaces are less prone to flooding, but may be flooded infrequently in the lower reaches of fans.

Additional hazards include desiccation cracking in Bicycle and Langford Well Lakes, swelling clays in many of the fine-grained deposits (primarily in the basin floors) and older deposits with clay-rich soils, and wind-blown materials from basin floors and playas. Most wind-blown deposits form along the flats and hills east of these sites. Destabilizing the vegetation in areas underlain by fine-grained sediment enhances wind erosion. Rock falls and landslides are a potential hazard in areas underlain by colluvium (units Qyc, Qoc) and other places near steep cliffs.

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Table 1. Geomorphic and soil properties of alluvial fan and wash units and estimates of their ages.

UNIT/SURFACE	SURFACE PROPERTIES	SOILS	AGE ESTIMATE
Qya_1, Qyw_1	Well-developed bar and swale topography; Sparsely vegetated; loose; confined to active wash channels	None	Less than 100 years before present (ybp)
Qya_2, Qyw_2	Well-developed bar and swale; no pavement; no varnish; moderately to sparsely vegetated; loose; 10-50 cm above Qya_1; can show evidence of recent flooding	Weak A-horizon to 5 cm thick; No discernible rubification below A-horizon.	Less than 1000 ybp. Correlates with surface Qf_5 of Wells and others (1984) and Reheis and others (1989)
Qya_3	Weak bar and swale to smooth microtopography; no pavement; very weak varnish; moderately vegetated; 1 to 2 m above Qya_1 and Qya_2	Weak vesicular A-horizon to 5 cm thick; weak to moderately developed cambic horizon to 15 cm thick; Stage I carbonate	1000 to 8000 ybp; correlates with surfaces Qf_3 and Qf_4 of Wells and others (1984) and Rohois and others (1989)
Qia; Subdivided into Qia_1, Qia_2, and Qia_3 based on inset relationships with older surface being higher by a few meters than the younger surfaces	Flat surfaces with moderate to strong interlocking pavements; moderate to strong varnish; weakly vegetated; 1 to 4 m above Qya_1 and Qya_2; 1 to 2 m above Qya_3	Moderate to strong vesicular A-horizons to 10 cm thick; moderately developed argillic horizons 10 to 40 cm thick; up to Stage II+ carbonate	May be as young as 20,000 ybp based on correlation with soil on Qf_1 surface of Wells and others (1984) and Rohois and othors (1989); may bo as old as 180,000 years based on correlation with soils in the southern Great Basin (Taylor, 1986)
Qoa, Qow	Rounded interfluves lacking pavement due to erosion of much of the original surface; some strongly varnished clasts as a lag left over from erosion; weakly vegetated; 1 to 5 m above Qya surfaces; often only 1 m or less above Qia surfaces	A-horizons lacking due to erosion; argillic horizon remnants rarely preserved; Stage III and weak Stage IV carbonate; surface remnant is commonly eroded completely to the calcic horizon	>250,000 ybp based on correlation with soils and surfaces in the southern Great Basin (Taylor, 1986; Peterson and others, in press)
QToa	Rounded surfaces similar to Qoa_1 but standing as much as 25 m above Qya surfaces in western Coyote Canyon	Calcic horizons with moderate to strong Stage IV development common; upper horizons missing due to erosion	>500,000 ybp based on correlation with unit QTa in southern Great Basin (Hoover and others, 1981; Taylor, 1986)

Table 2. Selected practical properties for materials in map units of the Fort Irwin basin region.

Map Unit	Material Type	Ease of Excavation	Foundation Stability	Flood Hazards	Possible Uses	Special Features
SURFICIAL UNITS						
Alluvial Fans:						
Qya, Qya_1, Qya_2, Qya_3	Moderately to poorly sorted medium- to coarse-grained sand and gravel. More bouldery near mountain fronts; sandier in low parts of fans	Generally easy; occasional boulders.	Moderate to high; slight compaction possible in loose sand; expansive clays may be present near centers of basins	High; Qya_1 and Qya_2 mark areas of historic flooding, especially during thunderstorms	Good sources of sand and gravel. Source of disintegrated granite (DG) where unit derived from Cretaceous granitoids	Qya_1 often very loose and soft in active channels; difficult driving without 4WD
Qia, Qia_1, Qia_2, Qia_3	Moderately to poorly sorted sandy cobble to boulder gravel with silt- and clay-rich near-surface soil horizons. Weakly carbonate cemented. More bouldery near mountain fronts	Variable; moderately difficult where carbonate-cemented or where upper clay-rich soil horizons are thick. Boulders common, especially near mountain fronts	Variable; high where upper soil horizons are non- expansive, but low if significant expansive clay exists in upper soil horizons	Moderate to low. Some Qia_1 surfaces could be inundated during heavy rain	Source of gravel where carbonate cementation is weak.	Upper clay-rich soil horizons can be highly sticky and slippery when wet
Qoa, QToa	Poorly sorted, heavily carbonate-cemented cobble to boulder gravel	Difficult; strongly carbonate-cemented gravel may be up to 3 m thick; boulders common	High	Low, except for local sheetwash	Possible source of coarse aggregate if excavation can be done in carbonate-cemented deposits	
Wash Deposits:						
Qyw, Qyw_1, Qyw_2	Moderately sorted, medium- to coarse-grained sand and gravel	Easy; occasional boulders near bedrock sources	Moderate to high; slight compaction possible in loose sands	High; intense flow probable where washes are channelized; sheet-flooding probable where washes empty onto fan surfaces	Good source of sand and gravel; disintegrated granite (DG) available where washes drain Cretaceous granitoids	Qyw and Qyw_1 often soft and loose; difficult driving without 4WD
Qow	Moderately sorted cobble gravel and medium- to coarse-grained sand; carbonate cemented; rare boulders	Difficult due to carbonate cement and presence of boulders	High	Low except for local sheetwash	Fair source for sand and gravel if excavated below the zone of carbonate cementation	Limited geographic extent
Eolian Deposits:						
Qye, Qoe	Well sorted fine- to medium-grained sand	Easy	Moderate to low	Variable; subject to sheet-flooding where unit mantles toes of alluvial fans in low-lying regions	Good source of sand	Unit is of limited lateral and vertical extent. Unit is soft; driving difficult without 4WD
Colluvial Deposits:						
Qyc	Poorly sorted, angular, cobble to boulder gravel with minor sand and silt	Moderate	Moderate; usually occurs on steep slopes	Variable; steep slopes intensify sheet-flooding, but unit often is open-work, allowing rapid infiltration	Moderate to poor source of coarse aggregate	Often accumulates in area below cliffs where hazard from rockfall is high

Qoc	Poorly sorted, angular cobble to boulder gravel; carbonate cemented	Moderate to difficult depending on amount of carbonate cement	Moderate to high; usually occurs on steep slopes	Variable; sheet-flooding during heavy rain intensified on steep slopes	Moderate to poor source of coarse aggregate	

Playa and Spring Deposits:

Qp	Moderately sorted silt and clay with minor sand	Easy	Low; compaction common; shrink-swell common where expansive clays present	High; often inundated following rainstorms	Moderate source of fine-grained fill where compactable or impermeable fill is desired	Extremely soft and sticky when wet. Driving difficult even with 4WD when wet. Prone to fissuring
Qs	Moderately sorted silt, sand and gravel; chalky to carbonate cemented	Variable; easy where chalky; difficult where carbonate cemented	High	Low; usually elevated above flood-prone areas	Poor source of secondary silica (opal)	Limited areal extent

TERTIARY UNITS

Sedimentary Rocks:

Tyg	Poorly sorted cobble to boulder gravel with minor sand	Moderate to difficult	High	Low	Poor source of coarse aggregate	
Tp	Moderately to well sorted sand, silt, and clay with chalky to well cemented carbonate-rich intervals	Variable; usually easy, but difficult where carbonate cement is extensive	Variable; possible shrink-swell in regions underlain by expansive clays	Low	Moderate to poor source of fine aggregate where compactable or impermeable fill is needed	Fossil plants, invertebrates, and vertebrates present

Volcanic Rocks:

Tyb, Tob	Dense, fine-grained basalt	Difficult	High	Low	Good source of rip-rap; possible source of building stone	Opaline material locally at base
Tr	Dense, fine-grained rhyolite	Difficult	High	Low	Poor source of rip-rap due to rapid breakdown during weathering	
Tt	Moderately sorted tuffaceous sandstone, conglomerate, and laminated tuff	Easy to moderate	Moderate; some shrink-swell possible	Low	Fair source of pumice, lightweight aggregate	Some deposits of opaline material and brightly-colored sandstone

CRETACEOUS AND OLDER UNITS

Kmg, Kpg, Kb, Kbg, Kg, Kgd, Kgm	Fine- to coarse-grained granites containing muscovite, biotite	Difficult where rock is unweathered; moderate to easy where weathered	High	Low	Good source of disintegrated granite (DG) where weathered. Fair to poor source of rip-rap and building stone where fractured into proper size	Useful medium for painting Training Unit Logos
Jfg, Jpg, Ji, Jmd, Jqd, Jm, Jd, s, gn, br	Medium- to coarse-grained granitic to gabbroic rocks, many containing abundant hornblende and biotite	Difficult	High	Low	Fair source of angular rip-rap, although high content of mafic minerals may allow unit to weather rapidly	
CZm	Coarse-grained, layered marble	Moderate	High	Low	Source of several minerals including garnet, mica, tremolite, phlogopite, pyroxene. Probably not economic due to limited extent of unit and highly variable composition	