

Text and references to accompany Nevada Bureau of Mines and Geology Map 137

GEOLOGY OF THE HILLER MOUNTAINS QUADRANGLE

CLARK COUNTY, NEVADA

by

**Keith A. Howard (USGS), Simon J. Hook (NASA),
Geoffrey A. Phelps (USGS), and Debra L. Block (USGS)**

INTRODUCTION

The Hiller Mountains Quadrangle lies within the Lake Mead National Recreation Area. The quadrangle was mapped as part of a team effort studying the Lake Mead 30' x 60' Quadrangle. Geologic mapping was supported by the National Cooperative Geologic Mapping Program of the U.S. Geological Survey, in cooperation with the National Aeronautics and Space Administration (NASA) and the National Park Service. The Nevada part of the quadrangle was previously mapped in reconnaissance by Volborth (1962) and Longwell and others (1965).

The quadrangle includes part of Lake Mead, which is impounded by Hoover Dam 50 km to the west. The quadrangle lies 20 km downstream from the mouth of the Grand Canyon, where the west-flowing Colorado River course, now drowned beneath Lake Mead, begins its path through the Basin and Range province. In the southern part of the quadrangle, the lake narrows through Virgin Canyon, which connects two broad basins that are partly within the quadrangle, the Temple Basin on the west and Gregg Basin on the east. Steep-walled Virgin Canyon is 300 m deep to the lake surface and another 100 m to the drowned Colorado River bed, and it marks the incised path of the Colorado River across the first major range of mountains downstream from the Grand Canyon. This north-trending range comprises the White Hills south of Virgin Canyon, the Hiller Mountains north of Virgin Canyon, and in the northern part of the quadrangle north of Jumbo Pass it forms part of the Gold Butte area of the South Virgin Mountains.

Field work and map interpretation benefited from NASA airborne surveys in 1997 and 1998 using the Thermal Infrared Multispectral Scanner (TIMS) and MODIS/ASTER Airborne Simulator (MASTER) (Hook and others, 2001a). These systems measure the energy emitted from the surface, which is a function of the temperature and emissivity of the surface. Differences in emissivity can be related to the

composition of surface materials. In the case of silicate rocks, the emissivity differences relate to the type of silicate bonds in the rock and can be used to infer the bulk composition of the rock. In sparsely vegetated arid areas like the Hiller Mountains Quadrangle, the TIMS and MASTER data have been used to measure compositional variation (Hook and others, 1994). It proved possible in the Hiller Mountains Quadrangle to use the MASTER data to map quantitatively a close approximation of silica content of the surface materials (Hook and others, 2001b). Processed MASTER images of the Hiller Mountains area show distinct patterns due to differing-composition silicate rock bodies that are not detectable in color air photographs or Landsat multispectral scanner images. Because of ubiquitous rock varnish, some of the rock distinctions that are imaged so well by MASTER are obscure even in the field until the rocks are carefully examined in hand specimen. The MASTER images demonstrate an extraordinary potential for using thermal-infrared multispectral imaging for identifying and mapping complex patterns of silicate rocks in remote arid areas. For this map, we combined geologic fieldwork with interpretation of the NASA imagery, calibrated in spots by geochemical and mineralogic studies of rock units (Hook and others, 2001b). One map unit (quartz-poor gneiss) was mapped mostly from the imagery.

STRUCTURAL FRAMEWORK

The Lake Mead area lies at the boundary between the northern and southern parts of the Basin and Range province, near the western margin of the Colorado Plateau province. The Hiller Mountains Quadrangle is 15 km west of the Grand Wash Cliffs and the Colorado Plateau beyond them. The quadrangle is in the north part of a large corridor of east-west-directed Miocene tectonic extension, framed by west-dipping extensional faults and northeast-striking strike-slip faults.

Proterozoic metamorphic and plutonic rocks underlie much of the White Hills, Hiller Mountains, and South Virgin Mountains in the quadrangle. These crystalline rocks form part of the Gold Butte-White Hills structural block. The block's Proterozoic rocks are nonconformably overlain 5 km northeast of the quadrangle by Paleozoic strata dipping about 60° east. Longwell (1936), Volborth (1962), and Beard (1996) viewed the block as a structural arch or monocline. Other authors have argued that much of the block is tilted eastward 50–60° and therefore exposes a crustal section on the order of 15 km or more thick (Wernicke and Axen, 1988; Fitzgerald and others, 1991; Fryxell and others, 1992; Duebendorfer and Sharp, 1998). Thermochronometry and metamorphic barometry of rocks north of the quadrangle in the Gold Butte-White Hills block suggest westward-increasing paleodepths in the Proterozoic rocks, in accord with the tilted crustal section interpretation (Fitzgerald and others, 1991; Fryxell and others, 1992; Reiners and others, 2000; Reiners, 2002). Apatite fission-track and (U-Th)/He cooling ages of ~15 Ma were interpreted by Fitzgerald and others (1991) and Reiners and others (2000) to record the age of tectonic unroofing beneath a west-dipping normal fault. Part of that fault system is the gently west-dipping Salt Springs fault 1–5 km southwest of the quadrangle; the Salt Springs fault carries a section of synextensional conglomerates, landslide breccias, and 15.2-Ma tuff in its hanging wall, over a footwall of metamorphic rocks in the White Hills (Duebendorfer and Sharp, 1998). This Miocene section dips 48° east into the fault on average and is capped unconformably by 14.6-Ma basalt. These ages bracket the time of tilting of the synextensional section, and are interpreted also to record tilting of the structurally underlying Gold Butte-White Hills block of basement rocks (Duebendorfer and Sharp, 1998). The bedrock mountain block in the quadrangle therefore was uplifted, tilted or folded down to the east, and unroofed tectonically during regional extension in middle Miocene time. Upper Miocene detritus in sedimentary basins on either side of the mountain range record erosion of the uplifted footwall block, and the basin fills have been exhumed during subsequent Pliocene and Quaternary incision of the Colorado River.

METAMORPHIC AND INTRUSIVE ROCKS

Metamorphic rocks in the quadrangle are assigned to the Early Proterozoic (Paleoproterozoic) and resemble dated Early Proterozoic rocks elsewhere in the region (Wasserburg and Lanphere, 1965; Wooden and Miller, 1990; Chamberlain and Bowering, 1990; Duebendorfer and others, 2001). The oldest of these rocks in the quadrangle (garnet gneiss unit) consists of dark paragneisses derived probably from protoliths resembling shaley graywacke. Metamorphic garnets, or else pseudomorph relics after garnet, are common in the paragneisses in the northern part of the quadrangle but become scarce to the south. This accords with abundant garnet north of the quadrangle (Volborth, 1962; Fryxell and others, 1992) and rare garnet south of the quadrangle

(Theodore and others, 1987). Sillimanite is a common metamorphic mineral in the garnet gneiss unit; kyanite, partly replaced by sillimanite, is present locally (UTM coordinates 3994700 N, 751200 E). Kyanite has also been described from the White Hills south of the quadrangle (Theodore and others, 1987).

The paragneisses are intruded by metamorphosed orthogneisses ranging in composition from quartz diorite and diorite (Xqd), to quartz syenite (Xqs), and to granite and granodiorite (Xgg). TIMS and MASTER images proved excellent for delineating the quartz diorite gneiss, granitic gneiss, and quartz syenite gneiss units. Those images indicate compositionally distinct areas within the granitic gneiss unit, likely to be separate deformed plutons. The quartz syenite gneiss, described as syenite by Volborth (1962), is compositionally unusual among Early Proterozoic rocks in the region. Its coarse, porphyritic texture indicates a primary igneous composition, in contrast to altered rocks described as episyenite by Theodore and others (1987) 10–20 km south of the quadrangle.

Metamorphosed intrusions of mafic and ultramafic gneiss (Xm) and leucogranite gneiss (Xlg, part) intrude the older gneisses. A prominent very light gray zone of leucogranite gneiss (Xlg) dips gently west across the central part of the quadrangle. This zone parallels the regional foliation and consists of a network of sills, parallel to the zone, and crosscutting dikes, as illustrated schematically in cross section A–A'. Some of the dikes terminate abruptly upward at the structural top of this mapped leucogranite zone, and some dikes (2 km southeast of the quadrangle center) abruptly bend into sills parallel to foliation at this boundary. Some of the dikes (unmapped) cross into other rock units mapped above the main zone as mapped (Xlg). Possible origins for the top of the mapped zone include a shear zone or an intrusion level controlled by neutral buoyancy. If Miocene tilting rotated this boundary 50° east, its pre-tilt orientation was moderately steep.

Metamorphism reached granulite grade where studied in the Gold Butte area north of the quadrangle (Volborth, 1962; Thomas and others, 1988; Fryxell and others, 1992). Prograde metamorphism and polyphase deformation that affected many or most of these rocks may date from the 1700-Ma Ivanpah orogeny of Wooden and Miller (1990). Garnets are now pseudomorphs, replaced partly or wholly by sericitic and chloritic pseudomorphs indicative of younger retrogressive metamorphism. The presence of either complete or partial garnet pseudomorphs forms the basis for subdividing the garnet gneiss unit into a retrograded garnet gneiss subunit (Xgr, garnet totally replaced), and a partially retrograded garnet gneiss subunit (Xgrp, contains relict garnet in the cores of the garnet pseudomorphs). The approximate boundary between the two subunits is arbitrarily indicated as vertical on the map and section, but its dip is not known. As with farther north in the Gold Butte block (Fryxell and others, 1992), the retrogressive metamorphic effects increase westward toward originally deeper levels of the exposed crustal section. Fryxell and

others (1992) found that garnets are fresh and not retrograded in eastern areas of the garnet gneiss in the Gold Butte block near the unconformity with overlying Cambrian rocks.

Blacet (1975) correlated a leucogranite pluton near the southwest corner of the quadrangle (Xhl, leucogranite of Greggs Hideout) with the porphyritic monzogranite of Garnet Mountain 20 km southeast of the quadrangle. This correlation is attractive because both rocks contain coarse discrete quartz grains, even though the leucogranite contains a lesser mafic mineral content and lacks K-feldspar phenocrysts. The porphyritic monzogranite of Garnet Mountain was first dated as 1660 Ma (Rb-Sr, Wasserburg and Lanphere, 1965) and later as 1680 Ma (U-Pb, Chamberlain and Bowring, 1990).

Blacet (1975) also correlated the undeformed Burro Spring pluton (YXb, granite of Burro Spring, near the southeast part of the quadrangle) with the porphyritic monzogranite of Garnet Mountain. Both are porphyritic biotite granites, but the granite of Burro Spring lacks the discrete quartz present in the Garnet Mountain body. The granite of Burro Spring more closely resembles the Gold Butte Granite, with which it apparently was included by Longwell (1936) and Volborth (1962).

The Gold Butte Granite (Longwell, 1936) as mapped in the quadrangle forms a composite pluton in and near the northeastern Hiller Mountains. Other bodies lie as far as 20 km north of the quadrangle (Volborth, 1962; Fryxell and others, 1992). The Gold Butte Granite was stated to be ~1.450 Ma (Silver, in Stewart, 1980). U-Pb dates on titanite are consistent with this age (Reiners and others, 2000). The pluton of Gold Butte Granite in this quadrangle intrudes older rocks concordantly along its southwestern side, which restores as originally a pluton floor if the Gold Butte block is assumed to be an east-tilted block. North of the quadrangle, bodies of the Gold Butte Granite show a steady eastward increase in content of K-feldspar megacrysts, which Fryxell and others (1992) ascribed to flotation of the megacrysts toward the original top of the pluton. In the Hiller Mountains Quadrangle the opposite pattern is mapped: megacrysts characterize a porphyritic facies (Ygp) forming the southwestern part of the pluton but not a separate (originally structurally higher) equigranular facies (Yge) to the east. A sharp boundary separates the two facies.

Diabase dikes (Yd) lithologically correlated with Middle Proterozoic (Mesoproterozoic) 1100-Ma diabase in Arizona and California intrude the Gold Butte Granite in the northern part of the quadrangle and a few kilometers north. They dip variably, most commonly moderately to the west. This orientation restores to subvertical, on a north strike, if 40-50° of Miocene eastward tilt is removed. Correlative diabase dikes at Garnet Mountain, 20 km to the southeast, are either steep with northwest strike, or subhorizontal, subparallel to overlying Cambrian sandstone (Blacet, 1975). Correlative sheets in Arizona and California most commonly intruded as horizontal sheets (Howard, 1991).

Pegmatite and aplite dikes (TYg) intrude the Gold Butte Granite. Small unmapped aplite dikelets also intrude the

Middle Proterozoic diabase. A Mesozoic age for the post-diabase aplite is likely, as no post-diabase Proterozoic or Paleozoic granites are known in the region. Late Cretaceous two-mica granites are known in both the White Hills and the South Virgin Mountains (Theodore and others, 1987; Brady, 1998). Rare Tertiary(?) mafic to intermediate dikes (Tmd) that intrude the Gold Butte-White Hills block have chilled margins, which is taken to suggest that intrusion postdated Miocene uplift and cooling of the block.

MIOCENE ROCKS

Breccia derived from gneiss (Tbx) near the southwest corner of the quadrangle is in fault contact with other rocks, and is partly fault gouge. The unit may correlate in part with middle Miocene (~15 Ma) landslide megabreccia that Duebendorfer and Sharp (1998) mapped in Salt Springs Wash 5 km to the southwest.

Temple Basin, which lies west of the exposures of Proterozoic rocks in the Gold Butte-White Hills highlands block, and Gregg Basin, east of the block, each contain upper Miocene basin fills. These fills include the Hualapai Limestone and underlying arkosic conglomerate, which some have grouped as parts or members of the Muddy Creek Formation (Longwell and others, 1965; Lucchitta, 1966; Blair, 1978; Theodore and others, 1987). In accord with Bohannon (1984) we do not assign these rocks to the Muddy Creek Formation, which occupies an apparently separate basin. We informally locally subdivide the Hualapai Limestone, and map it as interfingering with subjacent conglomerate.

The upper Miocene deposits buttress against Proterozoic rocks on a basal nonconformity that exhibits paleovalleys and tens to hundreds of meters of local relief. Four partly exhumed late Miocene-age paleovalleys that drained westward off the highlands into Temple Basin can be identified: (1) Spring Canyon, (2) 2 km northeast of Burro Bay, (3) west from Gold Cross Peak, and (4) at Jumbo Pass. Three paleovalleys that probably drained east into Gregg Basin are identified: (1) at Virgin Reef, (2) 2 km southeast of Gold Cross Peak, and (3) at the Joker Mine-Scanlon Hill area east of Jumbo Pass. The upper Miocene deposits thicken east and west away from the highlands.

The arkosic conglomerate (Tc) is poorly sorted debris-flow and other alluvial fan deposits derived from Proterozoic gneiss and granite. The conglomerate unit includes Lee's (1908) "Greggs breccia" (and part of his Temple Bar conglomerate, a now-abandoned unit that included Colorado River deposits). The conglomerate unit (Tc) interfingers with 8.4-Ma basalt, and 8 km southwest of the quadrangle the conglomerate contains a tuff bed tentatively dated using tephrochronology as 12.0 Ma (A. Sarna-Wojcicki, written commun., 1998).

Parts of the Hualapai Limestone appear to bridge the White Hills from the Hualapai Wash area of the southeast corner of the quadrangle (part of Gregg Basin) across westward into Temple Basin. We follow previous authors

in assigning rocks from both areas to the Hualapai Limestone. Most workers have interpreted the limestone as lacustrine (Longwell, 1936; Lucchitta, 1979; Faulds and others, 1997; Wallace, 1999; Wallace and others, in press), although a marine origin was proposed by Blair (1978). In Temple Basin this map distinguishes a lower member, the limestone of Temple Mesa, which intertongues eastward with the mostly subjacent conglomerate (Tc).

The basins on either side of the Gold Butte-Hiller Mountains-White Hills block served as upper Miocene sediment sinks for arkosic conglomerate shed off the block and as lacustrine depocenters. The upper Miocene sections exposed in the two basins resemble each other. Gregg Basin exposes, in the southeast part of the quadrangle, locally present conglomerate (Tc), resting on Proterozoic rocks, and up to 150 m of overlying undivided Hualapai Limestone. Longwell (1936) suggested the limestone may be as much as 300 m thick. Temple basin exposes a more varied sequence in the southwest part of quadrangle. The sequence there rests on Proterozoic rocks, or locally on the older Tertiary breccia derived from gneiss (Tbx) unit. Low in the upper Miocene sequence is conglomerate up to hundreds of meters thick (Tc). The lowest exposed part of this conglomerate in the quadrangle is near the southwest corner of the quadrangle. Conglomerate (Tc) at Greggs Hideout campground there likely correlates approximately with conglomerate 8 km south-southwest of the quadrangle, which contains a white tuff bed tentatively correlated, using chemical tephrochronologic methods, with tuff dated as 12.1 Ma (Andrei Sarna-Wojcicki, written commun., 1998). The conglomerate at both localities is in the hanging wall of the west-dipping Salt Springs fault. Gneiss clasts dominate most of the conglomerate, but near the southwest corner of the quadrangle, and also in the Wild Burro Bay area, the conglomerate includes clasts of porphyritic granite derived from the granite of Burro Spring or from the Gold Butte Granite. Clasts of porphyritic granite as large as ~5 m occur 150 m higher in the conglomerate near Greggs Hideout. Clasts of fresh garnet gneiss that are not retrograded, present in the conglomerate in Wild Burro Bay and near Salt Spring Bay, possibly derive from eastern or northeastern sources beyond the quadrangle.

The upper part of the Miocene sequence is most varied in the southwest part of the quadrangle at Temple Mesa and in adjacent parts of the Hiller Mountains. There, a basalt flow (Tb) dated as about 8.4 Ma and the lower part of the Hualapai Limestone above it (Temple Mesa member) both interfinger with the upper part of the conglomerate (Tc). The basalt and 10 m of succeeding conglomerate and sandstone (Tc) are overlain by this lower part of the Hualapai Limestone, which here is described informally as the limestone of Temple Mesa (Tht) member. That member was included in the Hualapai Limestone by Longwell (1936) and Lucchitta (1979). It consists of 3–25 m of limestone, sandstone, and (at the member's eastern feather edge) limestone-matrix gneiss-clast conglomerate. It caps mesas at about 500 m in elevation.

Map relations 1–3 km northeast of Burro Bay document that higher limestone beds lie above the limestone of Temple Mesa. Ten meters of the conglomerate (Tc) overlie the limestone of Temple Mesa before being succeeded by 20 m of arkosic sandstone (Ts), in turn overlain by the rest of the mapped Hualapai Limestone sequence in the southwestern Hiller Mountains. That sequence, in ascending order, consists of resistant limestone (Th, 10 m), a subunit of mudstone, limestone, and sandstone (Thm, 15 m), more resistant limestone (Th, 35 m), more of the mudstone, limestone, and sandstone subunit (Thm, 50 m), and finally, resistant limestone (Th, 50 m) capping the sequence. Each of the mapped limestone layers tends to stand as mesas. The stratigraphically and topographically highest limestone mesa, at 700-m elevation, likely approximates the final bed of the Hualapai Limestone lake.

South of Virgin Canyon, flat-lying limestone layers assigned to the Hualapai Limestone (Th) appear at two stratigraphic levels above the conglomerate (Tc). The higher one caps a hill at 650–670 m elevation 1 km east of Greggs Hideout. The lower one, at 600 m elevation, is 1 km to the east of the higher one, across a scissor or strike-slip fault having less than 5 m of throw down to the east as measured on the base of the conglomerate (Tc). The fault juxtaposes the eastern limestone westward against the conglomerate (Tc). The absence of the lower (eastern) limestone west of the fault but lack of much apparent throw nearby on the fault suggests the fault acted as a depositional facies boundary for the eastern (lower) limestone against conglomerate to the west. The two limestone outcrops project southeast toward nearby outcrops of Hualapai Limestone that trace into Gregg Basin, and they thereby help bridge the Hualapai Limestone from Temple Basin to Gregg Basin.

PLIOCENE AND QUATERNARY DEPOSITS

Geologic units and landforms younger than the Hualapai Limestone relate to the incision of the Colorado River, the inception of which followed the deposition of Hualapai Limestone (Longwell, 1936; Lucchitta, 1972). Deposits of the Colorado River first appear in the regional stratigraphic record above the Hualapai Limestone. Subsequent downcutting by the river and local tributaries partly exhumed the Temple and Gregg basins, and the downcutting stranded channel gravels of the ancestral Colorado River.

The distinctive ancestral Colorado River gravels contain well rounded limestone, quartzite, and chert clasts. An older group of these deposits (Trg) marks abandoned channels in multiple passes through the Gold Butte-White Hills range. The channels are stranded as high as 350 m above where the historical river grade crosses the range in Virgin Canyon. The abandoned channels occupy yet-older passes where strands of Hualapai Limestone or locally derived conglomerate (Tc) had crossed the range. Two of the

abandoned parallel ancestral Colorado River channels, 11 km apart and on opposite sides of Virgin Canyon, crest ~350 m above the floor of Virgin Canyon (elev. 250 m) and > 75 m below the top of the Hualapai Limestone.

Ancestral Colorado River gravel in the southern of these paleochannels, at Spring Canyon in the south part of the quadrangle, reaches a maximum elevation in the quadrangle of 570 m, and lag rounded pebbles as high as 605 m record its maximum elevation. This gravel at Spring Canyon rests most places on very coarse rubble derived entirely from the Hualapai Limestone. The origin of the rubble is enigmatic. It could represent debris flows, or blocks that slumped when channels eroded into the Hualapai Limestone. Very coarse rubble of porphyritic granite boulders, with clasts as large as 5 m across, lies at an equivalent position beneath ancestral Colorado River gravel 2 km north of Spring Canyon. It may represent boulders on the ancient channel floor, carried by debris flows from a tributary into the ancestral Colorado River.

The northern high-level channel across the highlands occupied the wind gap of Jumbo Pass, north of the Hiller Mountains in the north part of the quadrangle. Distinctive Colorado River-deposit roundstones occur there in float as high as 605 m elevation, and the distinctive roundstone clasts are reworked into a younger unit mapped as the deposits of Jumbo Pass (QTj).

The Jumbo Pass unit contains algal limestone with tubular plant casts, travertine, reddish orange fluvial sand, and eolian sand. The eolian-sand facies (QTje) descends a paleoslope close to the modern slope as it traces westward to the west edge of the quadrangle and beyond. This suggests that the eolian facies was deposited on a westward-descending paleoslope into an already partly exhumed Temple Basin. Conglomerate exposures of the deposits of Jumbo Pass exhibit clast imbrication indicating currents directed westward where measured north of a bedrock promontory at Black Box, and directed south-southwest parallel to the modern drainage where measured south of Black Box at elevations as low as 500 m. These paleocurrent directions support the inference that the deposits of Jumbo Pass were deposited on paleoslopes into an already exhumed Temple Basin.

The presence of travertine and algal limestone in the deposits of Jumbo Pass suggests spring deposition, fed from a source terrain of calcium-carbonate-rich waters. The presence of reddish orange clastic sediments suggests a source terrain that included an erodible source of reddish muds or sands. The Jumbo Pass rocks are stranded far from either reddish source rocks, or from carbonate-rock sources that could have fed calcareous springs. The nearest source terrain of either limestone or red sediment lies 100–150 m lower in the South Cove area in Gregg Basin, 3 km east of the quadrangle; more distant possible sources underlie higher Grapevine Mesa and part of the Grand Wash Trough northeast of the quadrangle. Structural evidence presented below suggests that the rocks in South Cove were lowered in a monocline relative to an original level a little higher

than Jumbo Pass. This leads us to speculate that the deposits of Jumbo Pass were deposited when this source area was as high as Jumbo Pass, before being structurally lowered by downfolding. We hypothesize the following sequence of events to account for the deposits of Jumbo Pass. (1) A Miocene basin fill including Hualapai Limestone and reddish mudstone filled the ancestral Gregg Basin as high as Jumbo Pass. (2) A Pliocene course of the Colorado River crossed this fill and crossed a gap through the highlands at Jumbo Pass, and then was abandoned. (3) Abandonment of the channel left distinctive roundstones and quartz sand in the channel, available for reworking. (4) newer Colorado River channels crossed the highlands near present Virgin Canyon and Spring Canyon, incised into the sedimentary Temple basin, and exhumed that basin, leaving long low slopes resembling those of today. (5) An eastern tableland of Hualapai Limestone with interbedded reddish mudstone remained in the Gregg Basin area, west of an incising Colorado River canyon, and extended west toward Jumbo Pass at or above the Jumbo Pass elevation. (6) The mudstone and limestone tableland fed streams and springs westward into the Jumbo Pass wind gap. (7) Wind and streams redistributed some of the red sediment westward down slope into an exhumed Temple Basin. (8) The eastern source terrain was structurally lowered in an east-facing monocline and removed by further incision. This sequence of events implies that the Colorado River had already incised Temple basin over 200 m deep before the hypothesized Hualapai Limestone source in the Gregg Basin-Jumbo Pass area was structurally lowered or eroded away.

The distribution of an undeformed unit of older alluvium (QTa) suggests that Gregg Basin was either steeper or continued to deepen after Temple Basin did, perhaps into Quaternary time. This unit, in the north part of the quadrangle, forms a fanlomerate that slopes southwestward down toward Temple Basin. Streams draining southeast toward Gregg Basin since captured the older west-flowing drainage system through piracy, in late Pliocene or Quaternary time; so the unit is now being dissected by drainages such as Gregg Wash and Scanlon Wash that drain southeastward, across a ridge of Gold Butte Granite.

GEOLOGIC STRUCTURE

The mapped Proterozoic rocks exhibit steep, northwest-striking metamorphic and plutonic foliations in and near plutons of the Gold Butte Granite and the granite of Burro Spring. The tilt-block model for the Gold Butte block predicts that the foliations and pluton boundaries may be tilted as much as 50–60° east from original orientations. But because the quadrangle lies far from attached Paleozoic strata, the degree to which foliations may be tilted east or warped remains uncertain.

Away from the plutons, in the south and western parts of the quadrangle, foliations dip gently west and locally are mylonitic. Migmatitic leucogranite veinlets cut gently dipping mylonitic foliation and west-striking lineation at

Black Box in the northwestern Hiller Mountains, indicating that the fabric predates the (probably Paleoproterozoic) migmatization. South of Virgin Canyon the gently dipping mylonitic foliation defines west-trending antiforms and synforms, and dips west less steeply than do lithologic boundaries between gneiss units. The sense of ductile shear was determined at six mylonitic gneiss localities, in the White Hills in the southern part of the quadrangle and within 1 km south of the quadrangle. Using s-c or asymmetric porphyroclast shear-sense indicators, five of the six localities indicated top-to-east shear, and one indicated top-to-west. The prevailing top-to-east sense of shear is opposite to top-to-west shear found in mylonitic rocks along the west side of the Gold Butte block northwest of this quadrangle, where the mylonitization was interpreted as formed during the westward-directed Miocene-age tectonic unroofing of the block (Fryxell and others, 1992). Perhaps the gently west-dipping foliation influenced the shape of the unroofing fault (R. Brady, written commun., 2001).

Mylonite and ultracataclasite fault zones of variable orientation and as thick as a few meters deform the Gold Butte Granite and the Granite of Burro Spring in several places. Similar mylonite zones near the Lakeshore Mine, 2 km north of the quadrangle, locally contain gold (Longwell and others, 1965, p. 133); they are intruded by the Middle Proterozoic diabase, so they can be dated as rare examples of Middle Proterozoic fault zones. They dip gently north, and exhibit E-W slickenlines. If 40°–50° eastward Miocene tilt of the Gold Butte block were restored, the faults would restore to moderate to gentle dips to the WNW, and the slickenlines would be nearly down the dip. This orientation suggests small-displacement Middle Proterozoic reverse or normal faults.

A prominent physiographic grain of linear west-trending valleys in the Hiller Mountains includes several valleys aligned along faults and others that are not along faults. A steep, left-separation, east-striking fault was mapped by Blacet (1975) 1 km south of the southwest part of the quadrangle. A fault with this trend but dipping 30°–50° north is exposed in this quadrangle just north of Jumbo Pass, where it exhibits northwest-trending slickenlines, and displaces steeply dipping plutonic contacts in a left-oblique normal sense. Mapped irregular contacts of plutonic and metamorphic rocks appear to be separated left-laterally across Jumbo Pass, suggestive of several concealed east-striking faults of similar left-separation sense. Virgin Canyon may follow yet another concealed east- to east-northeast-striking left-separation fault, judging from apparent left separation of metamorphic rock units. The newly recognized family of east-striking left-separation faults is cut by northwest-striking strike-slip(?) faults and is undated. The orientation and sense of separation are midway between and compatible with either or both of two sets of regional Miocene-age faults: (1) WNW-dipping down-to-west normal faults that cut the upper (Azure Ridge) part of the Gold Butte block and its footwall north and northeast of the quadrangle (Brady and others, 2000), and (2) northeast-

striking left-lateral faults that are present in the South Virgin Mountains 20–40 km north of the quadrangle and as the Lake Mead fault system 25 km northwest of the quadrangle (Anderson, 1973; Duebendorfer and others, 1998). Movement on those faults was part of a complex three-dimensional Miocene tectonic strain field (Wernicke and Axen, 1988; Anderson and others, 1994). The deformation included tilting and tectonic unroofing of the Gold Butte-Hiller Mountains-White Hills crustal block above a system of west-dipping normal faults (Fryxell and others, 1992; Duebendorfer and Sharp, 1998; Brady and others, 2000).

Fanning eastward dips in Miocene beds that now are submerged by Lake Mead in Temple Basin just west of the quadrangle demonstrate that strata in the hanging wall progressively tilted eastward into the underlying fault that unroofed the Gold Butte footwall block (Longwell, 1936). Duebendorfer and Sharp (1998) viewed the middle Miocene synextensional deposits that they mapped southwest of the quadrangle as deposited during major tectonic extension that tilted them above the Gold Butte-White Hills block. Duebendorfer and Sharp (1998) proposed that the west-dipping Salt Springs fault that they mapped connects north with the Lakeside Mine fault (Fryxell and others, 1992) and south with the Cyclopic fault (Theodore and others, 1987). Duebendorfer and Sharp (1998) proposed to combine the three faults as the South Virgin-White Hills detachment fault. This fault system is viewed as responsible for unroofing the Gold Butte-White Hills block (Fitzgerald and others, 1991; Fryxell and others, 1992; Duebendorfer and Sharp, 1998; Brady and others, 2000). A high-level manifestation of the Salt Springs fault, recording its youngest movement, crops out in the Hiller Mountains Quadrangle at Greggs Hideout campground and in nearby Virgin Canyon (fault mapped with square teeth). The fault dips 16° to 45° northwest and carries in its hanging wall the lower part of the exposed section of the conglomerate (Tc). Superb exposures of the fault at Greggs Hideout campground display varicolored banded and lenticular gouge. In the fault's immediate vicinity the sub-horizontal conglomerate unit (Tc) in the hanging wall rolls into dips as high as 38°, nose down into the subjacent fault. Fault exposures 100 m higher nearby exhibit very small displacement and grooves striking east-west. A few meters higher the conglomerate overlaps the fault. These relations demonstrate that the mostly middle Miocene tectonic unroofing of the Gold Butte-Hiller Mountains-White Hills block continued, by westward down-to-basin fault slip, until the late Miocene, about 12–8 Ma, a time when sediments accumulating in the flanking basin overlapped the fault.

A nearby northwest-striking vertical fault through Slide Cove and Burro Bay is younger. The fault offsets the basalt unit (Tb) and some Hualapai Limestone but is overlapped by the highest part of the limestone of Temple Mesa. At the south boundary of the quadrangle, the Hualapai Limestone drags sharply up on the fault's east side indicating throw down to the east, but the base of the underlying conglomerate shows negligible throw. The fault exhibits variable sense

and amount of throw, suggesting it is a scissor or strike-slip fault. A steep northwest-striking fault north of Jumbo Pass exhibits horizontal slickenlines. Similarly oriented faults elsewhere in the region are right-lateral and Miocene.

The Hualapai Limestone in the southeast part of the quadrangle, the conglomerate unit (Tc) east of Jumbo Pass and along the west flank of Gregg Basin, and the Spring Canyon paleochannel of ancestral Colorado River gravel (Pliocene) together define a large, gently east-facing monocline through much of the quadrangle. Dips and structure contouring of these deposits indicate that the monocline crest trends north through the center of the quadrangle, and the flank averages about 5° east dip. We view the monocline as a rollover or “reverse-drag” fold in the hanging wall of the west-dipping Wheeler fault system that lies east of the quadrangle. The monocline lowered the Hualapai Limestone in Gregg Basin, and accentuated the eastward tilt of the east side of the Gold Butte block.

REFERENCES

- Anderson, R.E., 1973, Large-magnitude late Tertiary strike-slip faulting north of Lake Mead, Nevada: U.S. Geological Survey Professional Paper 794, 18 p.
- Anderson, R.E., Barnhard, T.P., and Snee, L.W., 1994, Roles of plutonism, midcrustal flow, tectonic rafting, and horizontal collapse in shaping the Miocene strain field of the Lake Mead area, Nevada and Arizona: *Tectonics*, v. 13, p. 1381–1410.
- Beard, L.S., 1996, Paleogeography of the Horse Spring Formation in relation to the Lake Mead fault system, Virgin Mountains, Nevada and Arizona: Geological Society of America Special Paper 303, p. 27–60.
- Blacet, P.M., 1975, Preliminary geologic map of the Garnet Mountain quadrangle, Mohave County, Arizona: U.S. Geological Survey Open-File Report (1:48,000).
- Blair, W.N., 1978, Gulf of California in Lake Mead area of Arizona and Nevada during late Miocene time: *American Association of Petroleum Geologists Bulletin*, v. 62, p. 1159–1170.
- Bohannon, R.G., 1984, Nonmarine sedimentary rocks of Tertiary age in the Lake Mead region, southeastern Nevada and northwestern Arizona: U.S. Geological Survey Professional Paper 1259, 72 p.
- Brady, R.J., 1998, The geology of the Gold Butte breakaway zone and the mechanical evolution of normal fault systems [Ph.D. thesis]: California Institute of Technology, Pasadena.
- Brady, R., Wernicke, B., and Fryxell, J., 2000, Kinematic evolution of a large-offset continental normal fault system, South Virgin Mountains, Nevada: *Geological Society of America Bulletin*, v. 112, p. 1375–1397.
- Chamberlain, K.R. and Bowring, S.A., 1990, Proterozoic geochronology and isotopic boundary in NW Arizona: *Journal of Geology*, v. 98, p. 399–416.
- Duebendorfer, E.M., and Sharp, W.D., 1998, Variation in displacement along strike of the South Virgin-White Hills detachment fault: Perspective from the northern White Hills, northwestern Arizona: *Geological Society of America Bulletin*, v. 110, p. 1574–1589.
- Duebendorfer, E.M., Beard, L.S., and Smith, E.I., 1998, Restoration of Tertiary deformation in the Lake Mead region, southern Nevada: The role of strike-slip transfer faults: *Geological Society of America Special Paper* 323, p. 127–148.
- Duebendorfer, E.M., Chamberlain, K.R., and Jones, C.S., 2001, Paleoproterozoic tectonic history of the Cerbat Mountains, northwestern Arizona: Implications for crustal assembly in the southwestern United States: *Geological Society of America Bulletin*, v. 113, p. 575–590.
- Faulds, J.E., Schreiber, B.C., Reynolds, S.J., Gonzalez, L.A., and Okaya, D., 1997, Origin and paleogeography of an immense, nonmarine Miocene salt deposit in the Basin and Range (Western USA): *Journal of Geology*, v. 105, p. 19–36.
- Fitzgerald, P.G., Fryxell, J.E., and Wernicke, B.P., 1991, Apatite fission track constraints on the extensional evolution of the Gold Butte crustal section, South Virgin Mountains, Nevada: *Geology*, v. 19, p. 1013–1016.
- Fryxell, J.E., Salton, G.G., Silverstone, J., and Wernicke, B., 1992, Gold Butte crustal section, South Virgin Mountains, Nevada: *Tectonics*, v. 11, p. 1099–1120.
- Hook, S.J., Karlstrom, K.E., Miller, C.F., and McCaffrey, K.J.W., 1994, Mapping the Piute Mountains, California, with thermal infrared multispectral scanner (TIMS) images: *Journal of Geophysical Research*, v. 99, p. 15,605–15,622.
- Hook, S.J., Myers, J.J., Thome, K.J., Fitzgerald, M., and Kahle, A.B., 2001a, The MODIS/ASTER Airborne Simulator (MASTER) - A new instrument for earth science studies: *Remote Sensing of Environment*, v. 76, p. 93–102.
- Hook, S.J., Howard, K., and Rowan, L., 2001b, Mapping lithological variations with visible to thermal infrared spectroscopy: A case study from Gold Butte, NV: *Geological Society of America Abstracts with Programs*, v. 33, no. 6.
- Howard, K.A., 1991, Intrusion of horizontal dikes: Tectonic significance of Middle Proterozoic diabase sheets widespread in the upper crust of the southwestern United States: *Journal of Geophysical Research*, v. 96, p. 12, 461–12, 478.
- Lee, W.T., 1908, Geologic reconnaissance of a part of western Arizona: U.S. Geological Survey Bulletin 352, 96 p.
- Longwell, C.R., 1936, Geology of the Boulder Reservoir floor, Arizona-Nevada: *Geological Society of America Bulletin*, v. 47, p. 1393–1476.
- Longwell, C.R., Pampayan, E.H., Bowyer, B., and Roberts, R.J., 1965, Geology and mineral deposits of Clark County, Nevada: Nevada Bureau of Mines Bulletin 62, 218 p.

- Lucchitta, Ivo, 1966, Cenozoic geology of the upper Lake Mead area adjacent to the Grand Wash Cliffs, Arizona [Ph.D. thesis]: The Pennsylvania State University, University Park, 218 p.
- Lucchitta, Ivo, 1972, Early history of the Colorado River in the Basin and Range province: Geological Society of America Bulletin, v. 83, p. 1933–1948.
- Lucchitta, Ivo, 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent lower Colorado River region: Tectonophysics, v. 61, p. 63–95.
- Reiners, P.W., 2002, (U-Th)/He chronometry experiences a renaissance: Eos, American Geophysical Union Transactions, v. 83, no. 3, p. 21–27.
- Reiners, P.W., Brady, R., Farley, K.A., Fryxell, J.E., Wernicke, Brian, and Lux, Daniel, 2000, Helium and argon thermochronometry of the Gold Butte block, South Virgin Mountains, Nevada: Earth and Planetary Science Letters, v. 178, p. 315–326.
- Spencer, J.E., Peters, L., McIntosh, W.C., and Patchett, P., 1998, 6 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ date from the Hualapai Limestone and implications for the age of the Bouse Formation and Colorado River: Geological Society of America, Abstracts with Programs, v. 30, no. 6, p. 37.
- Stewart, J.H., 1980, Geology of Nevada: Nevada Bureau of Mines Special Publication 4, 136 p.
- Theodore, T.G., Blair, W.N., and Nash, J.T., 1987, Geology and gold mineralization of the Gold Basin-Lost Basin Mining Districts, Mohave County, Arizona: U.S. Geological Survey Professional Paper 1361, 167 p.
- Thomas, W.M., Clark, H.S., Young, E.D., Orell, S.E., and Anderson, J.L., 1988, Proterozoic high-grade metamorphism in the Colorado River region, Nevada, Arizona, and California, in Ernst, W.G., ed., Metamorphism and crustal evolution of the western United States (Rubey Volume 7): Prentice Hall, Englewood Cliffs, N.J., p. 526–537.
- Volborth, A., 1962, Rapakivi-type granites in the Precambrian complex of Gold Butte, Clark County, Nevada: Geological Society of America Bulletin, v. 73, p. 813–832.
- Wallace, M.A., 1999, Cenozoic stratigraphic and structural framework of the southern Grand Wash trough, northwestern Arizona; Paleogeographic implications [M.S. thesis]: University of Iowa, Ames, 119 p.
- Wallace, M.A., Faulds, J.E., and Brady, R., in press, Geologic map of the Meadview North Quadrangle, Arizona and Nevada: Nevada Bureau of Mines and Geology Map, 1:24,000.
- Wasserburg, G.J., and Lanphere, M.A., 1965, Age determinations in the Precambrian of Arizona and Nevada: Geological Society of America Bulletin, v. 73, p. 813–832.
- Wernicke, B., and Axen, G.J., 1988, On the role of isostasy in the evolution of normal fault systems: Geology, v. 16, p. 848–851.
- Wooden, J.L., and Miller, D.M., 1990, Chronologic and isotopic framework for Early Proterozoic crustal evolution in the eastern Mojave Desert region, SE California: Journal of Geophysical Research, v. 95, p. 20,133–20,146.
- Wooden, J.L., Nutman, A.P., Miller, D.M., Howard, K.A., Bryant, B., Dewitt, E., and Mueller, P.A., 1994, Shrimp U-Pb zircon evidence for Late Archean and Early Proterozoic crustal evolution in the Mojave and Arizona crustal provinces: Geological Society of America Abstracts with Programs, v. 26, p. 79.