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Geology of the Benson Lake Pendant, Western Yosemite National Park, Central Sierra Nevada

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ABSTRACT

Detailed mapping of the geology of the Benson Lake pendant and surrounding intrusions is presented in a geologic map at 1:10,000 scale. Protoliths of the multiply deformed metasedimentary rocks of the pendant are Precambrian to Paleozoic shallow water passive margin deposits. The pendant is located between the 102 Ma intrusion of the Yosemite Valley intrusive suite to the west, and the 95–85 Ma Tuolumne Intrusive Complex to the east. The Yosemite Valley intrusive suite is characterized by dominantly granitic rocks, which locally mingled with granitic to gabbroic compositions near the metasedimentary pendant. Basic descriptions of the lithologies and their structural relationships are given.

INTRODUCTION

The ~7 km^2 Benson Lake pendant is located in the northern part of Yosemite National Park, central Sierra Nevada, California, ~180 km southeast of Sacramento and ~140 km north of Fresno. The ~60 km^2 geologic map includes detailed lithologic subdivisions of the metasedimentary pendant and the 102 Ma granites of the Yosemite Valley intrusive suite and associated mafic rocks to the northwest and southwest, and granodioritic units of the 95–85 Ma Tuolumne Intrusive Complex to the northeast and southeast. The topographic base for this map includes segments of the following USGS 7.5′ quadrangles: the southeast corner of Piute Mountain, the southwest corner of Matterhorn Peak, the northwest corner of Tuolumne Meadows, and the northeast corner of Ten Lakes. Elevations range from 10,554 ft (3217 m) at Regulation Peak in the southeast corner and 10,541 ft (3213 m) at Piute Mountain in the northwest corner to ~7400 ft (2256 m) in an unnamed canyon southwest of Benson Lake, demonstrating the large topographic relief within this area.

The Benson Lake pendant appears in the geologic map of Yosemite National Park (Huber et al., 1989) and the geologic map of the Tower Peak quadrangle (Wahrhaftig, 2000), where it

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is simply mapped as pre-Cretaceous, deformed metasedimentary rocks containing orthoquartzite, marble, biotite-andalusite schist, meta-conglomerate, and calc-silicate hornfels. Studies by Lahren (1989, 1991) and Lahren and Schweickert (1989) first suggested a correlation of rocks from the Snow Lake pendant to the north and the ones from Benson Lake and other pendants to the south to miogeoclinal rocks from the Mojave Desert near Victorville. These displaced rocks, collectively called the Snow Lake block, were interpreted to have been transported 400 km to the central Sierras by the enigmatic Mojave–Snow Lake fault during the Cretaceous (Lahren and Schweickert, 1989; Grasse et al., 2001). Based on a detrital zircon provenance study, Memeti et al. (2010) confirmed the miogeoclinal and displaced nature of these rocks, but suggested that they could have originated from a much larger region spanning the Death Valley and Inyo facies of the North American miogeocline.

MAPPED UNITS

The Benson Lake pendant as mapped by Huber et al. (1989) and Wahrhaftig (2000) is composed of an ~2-km-wide and ~4-km-long metasedimentary section in its main, northwestern part, and a 0- to 200-m-wide, highly mingled zone of mafic to felsic magmas and metasedimentary xenoliths in the pendant "tail" to the southeast.

Metasedimentary Units

p€-€q—White Quartzites

The Benson Lake pendant is dominated by thickly bedded, fine- to coarse-grained, white quartzites with more than 95% quartz content (Fig. 1). Other minerals are dark red-brown biotite, skeletal muscovite, which mainly occurs between quartz grains, sericitized K-feldspar and plagioclase, opaque phases, and rare amphibole pointing to a clean and well-sorted beach sand protolith. This shallow water depositional environment is also made evident by locally occurring crossbedding (Fig. 1). The quartzite beds are intercalated by laminae of fibrolite and andalusite-bearing biotite schist, more metapsammopelitic layers, and rare thin layers of calc-silicate, marble, and hornblende gneiss.

p€-€mp—Metapelite and Metapsammopelite

Metapelitic layers (Fig. 2) range from mm thin laminae of biotite schist within the white quartzites to several 10s of m thick beds that are shown on the geologic map. The maximum thickness of metapelitic rocks (200–300 m) is exposed at the southwest flank of the pendant. The thicker, dm-m scale layers tend to be predominantly quartzitic biotite schists that contain biotite schist laminae. Locally, these metapelitic and metapsammopelitic packages contain <1-m-thick layers of calc-silicate and marble. Relatively fine-grained hornblende gneiss occurs as <dm-thick layers at a few locations within the metapsammopelitic layers.

The biotite schists commonly contain abundant contact metamorphic index minerals such as sillimanite, fibrolite, rhombohedral andalusite, and cordierite as well as retrograde muscovite and pinite replacing cordierite crystals. Sillimanite tends to appear in crystals up to 15 cm long and rarely forms pseudomorphs after andalusite (Fig. 2), suggesting a change in metamorphic conditions to higher temperatures. Fibrolite appears to be intergrown with biotite. Cordierite is extremely rare and appears to be mostly pinitized. No visible changes in mineral assemblages were noted across the pendant to distinguish different metamorphic facies.

Red almandine-spessartine garnet is restricted almost entirely to the metapelitic layer furthest southeast in the pendant, most likely reflecting the bulk composition of the metapelites. Partial melting and injection leucosomes are rare and were mostly found on the west side of Benson Lake right at the contact with the granites of the Yosemite Valley intrusive suite and in stoped metapelitic blocks (Fig. 2).

p€-€m—Calc-silicate and Marble

Calc-silicate and marble layers are rarely thick enough to map at 1:10,000 scale. They mainly occur as cm to dm scale intercalations in the metapelitic and metapsammopelitic packages. Larger occurrences of calc-silicate and marble were found in a small outcrop in the southeast of the pendant and on the southwest side in a 6-m-thick layer. Locally, a few cm to dm wide veins of epidote, grossular and calcite cut across the metasedimentary package and all dominant structures. This geometry suggests a hydrothermal origin for these deposits by dissolution of original marble and calc-silicate deposits and re-precipitation in veins.

Plutonic Units

Kyvg, Kyvd, Kyvmd, Kyvmg, Kyvlg, Kyvx—Granites and Associated Rocks of the Yosemite Valley Intrusive Suite

The granites to the north, west, and south of the pendant and thin zones of mafic rocks next to the pendant represent units of the Early Cretaceous Yosemite Valley intrusive suite (Huber et al., 1989). The main unit, Kyvg, is characterized by biotite granite that is fairly homogeneous in composition, but shows considerable variability in grain size and may contain porphyritic K-feldspar and quartz phenocrysts. Huber et al. (1989) and Wahrhaftig (2000) mapped the coarse-grained biotite granite and biotite granodiorite with blocky K-feldspar phenocrysts and conspicuous quartz grains directly to the west of the central part of the pendant as the "El Capitan granite and similar rocks." Huber et al. (1989) mapped the fine- to coarse-grained biotite granite and biotite granodiorite with local porphyritic K-feldspar phenocrysts to the northwest and the south of the pendant as the "Taft granite and granodiorite." In contrast, Wahrhaftig (2000) distinguished the two exposures to the north and south, naming the northwest exposure the "Granite of Piute Mountain" and the exposure to the southeast as the "Leucogranite of Ten Lakes." Our mapping mostly focused on the compositional variations and structure of the metasedimentary pendant and thus didn't

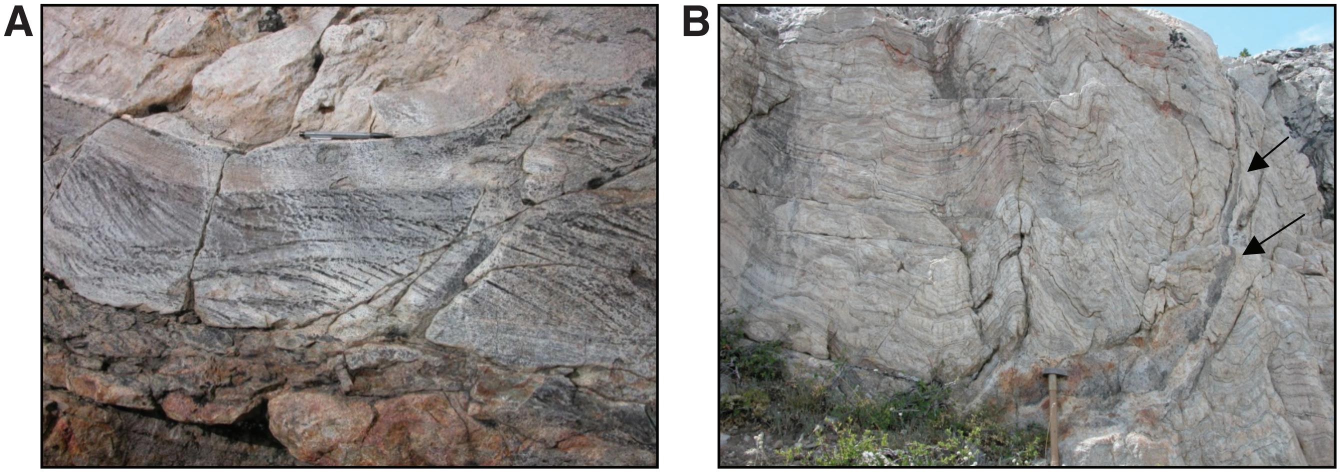

Figure 1. (A) Crossbedding in white quartzite; 15 cm pencil for scale. (B) Folded (F_2) white quartzite with gray El Capitan granite dike (arrows) that intruded parallel to axial planar foliation; 60 cm hammer for scale.

distinguish between the different units of the Yosemite Valley intrusive suite using grain size or texture.

The granites of the Yosemite Valley intrusive suite (or leucogranite of Ten Lakes after Wahrhaftig, 2000; or Taft granite after Huber et al., 1989) show evidence for intermingling with mafic magmas at both the magmatic "tail" that extends from the southeast end of the Benson Lake pendant as well as the smaller mingling zone on the north end of the pendant. While the east half of the "tail" is dominated by co-magmatic mingling of gabbroic to granodioritic magmas (Kyvmd), the western contact with the granite of the Yosemite Valley intrusive suite is characteristic of mingling of both felsic and more mafic magmas (Kyvmg). Larger leucogranite pods and two bodies of medium-grained diorite to gabbro intruding metasedimentary pendant rocks north of Benson Lake were mapped as units Kyvlg and Kyvd, respectively.

Adjacent to the southwestern and southern contacts of the pendant, a separate, ~50–300-m-wide granite unit of the Yosemite Valley intrusion (Kyvx) contains 30–40 vol% metasedimentary xenoliths (metapelite, calc-silicate and white quartzite, Fig. 3). The randomly distributed foliation attitudes and the mixed composition of xenoliths that are located next to one another indicate rotation (stoping), as also evident in an outcrop at the northern end of the pendant (Fig. 3). The abundance and size of the xenoliths decreases away from the pendant to the south where it gradually enters the more homogeneous biotite granite of the Yosemite Valley intrusive suite (Kyvg).

Kkc, Ktkc, Kehd, Kphd, Kcp—Tuolumne Intrusive Complex

The Tuolumne Intrusive Complex borders the east side of the Benson Lake pendant. Traversing the batholith perpendicular

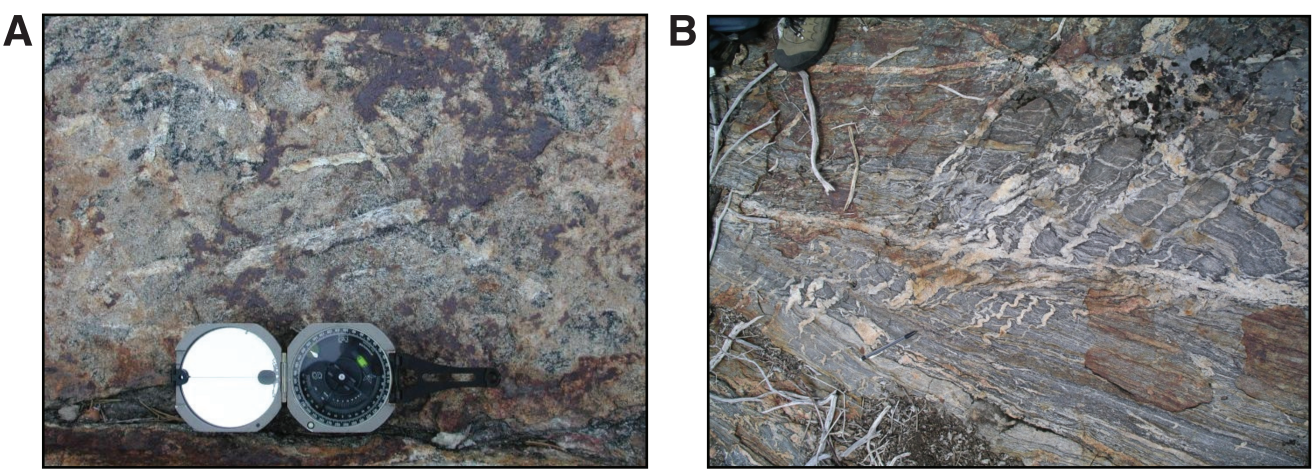

Figure 2. (A) Approximately 15-cm-long sillimanite crystals on foliation plane (S_2). (B) Migmatitic biotite schist from the southeastern part of the pendant; foot in upper left corner for scale.

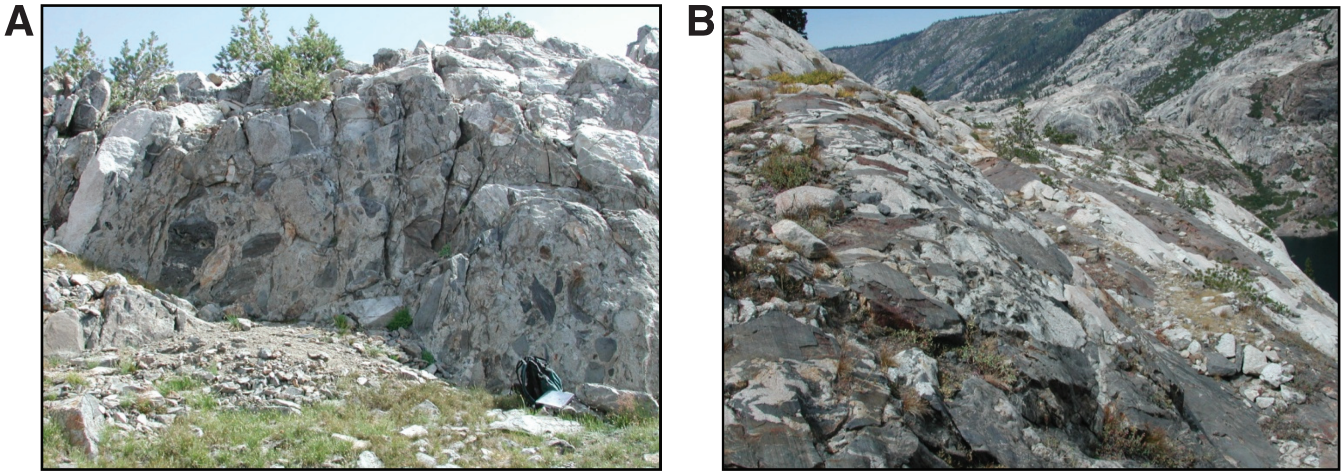

Figure 3. (A) Outcrop at the northern end of pendant where a variety of metasedimentary blocks are engulfed by the Yosemite Valley granite; 70-cm-tall backpack for scale. (B) Red-brown, metapelitic xenoliths in granite of the Kyvx unit south of the pendant, ~0.5-m-tall pine trees for scale.

to the northwest-striking units, and starting from the pendant in the southwest, three major units are distinguished: (1) the 50–800-m-wide Kuna Crest unit (Kkc), which is composed of medium-grained granodiorite with abundant cm–dm-size mafic enclaves; (2) the 500- to 1800-m-wide outer, equigranular (Kehd) and inner, porphyritic (Kphd) Half Dome granodiorite units, which differ from the Kuna Crest unit by containing <1-cm-long, euhedral hornblende and biotite, and abundant, <1 cm euhedral titanite (Kehd), as well as K-feldspar phenocrysts in the inner unit (Kphd); and (3) the Cathedral Peak unit that varies from granodiorite to granite and contains characteristic K-feldspar phenocrysts, which range in size from 1 to 10 cm, and local accumulations of K-feldspar phenocrysts. Transitional hybrid zones of ~50–200-m in width occur between these three major units and show characteristics of their neighboring units. One hybrid unit is present between the Kuna Crest (Kkc) and equigranular Half Dome granodiorite (Kehd), here referred to as the transitional Kuna Crest/Half Dome granodiorite (Ktkc), and the second unit occurs between the equigranular Half Dome granodiorite (Kehd) and the Cathedral Peak unit (Kcp), which is also known as the porphyritic Half Dome granodiorite (Kphd). The contacts between all of these units vary from gradational to knife-sharp, which suggests magmatic interactions and hybridization between the different Tuolumne units and local magmatic erosion during intrusion of the younger units, respectively (Memeti, 2009). It is particularly interesting to note that the nature of the contacts changes along strike (see geologic map). All units contain enclaves, enclave swarms, tubes, troughs, etc. (see also Paterson, 2009, describing these structures), which decrease in abundance toward the interior of the batholith. The Kuna Crest granodiorite generally contains fewer metasedimentary xenoliths in comparison to the granites of the Yosemite Valley intrusive suite, but like the latter, the Kuna Crest granodiorite has abundant xenoliths near the contact to the pendant. No mingling or mixing was observed between the Kuna Crest and the significantly older units of the Yosemite Valley intrusive suite, but Kuna Crest granodiorite sheets and cumulates have locally intruded the mingled zone and the east and southeast side of the pendant.

GEOCHRONOLOGY

Detrital Zircon Ages

Memeti et al. (2010) dated detrital zircons from two samples of the pendant, collected from the white quartzite unit on opposite sides of Benson Lake, with U/Pb zircon geochronology using laser ablation ICPMS. Both samples revealed zircon age peaks at 1150 Ma, 1360–1400 Ma, 1460–1520 Ma, 1815–1830 Ma, and 2500–3300 Ma, suggesting that the zircon age spectra are generally similar to passive margin strata in California and Nevada (e.g., Stewart et al., 2001) and do not have to be directly derived from the Victorville area in the Mojave desert, as Lahren and Schweickert (1989) and Grasse et al. (2001) suggested. The closest correlations based on detrital zircon age spectra are with the Neoproterozoic to Cambrian Wood Canyon Formation and Zabriskie Quartzite of the Death Valley facies passive margin deposits (Memeti et al., 2010).

Magma Crystallization Ages

The El Capitan granite, located ~2 km southwest of the Benson Lake pendant, has a U/Pb zircon age of ca. 102.5 Ma. The Tuolumne Intrusive Complex units in a transect perpendicular to the strike of the units at the southeastern termination of the Benson Lake pendant yielded the following U/Pb zircon ages: 92.8 ± 0.4 Ma for the Kuna Crest granodiorite, 91.5 ± 0.1 Ma for the equigranular Half Dome granodiorite, 88.1 ± 0.9 Ma for the porphyritic Half Dome granodiorite, and 87.3 ± 0.2 Ma for the

Cathedral Peak granodiorite. These zircon ages were all determined using the chemical abrasion ID-TIMS method. Ar-Ar cooling ages on hornblende and several size fractions of biotite revealed a 550–300 °C cooling age of 86–87 Ma in all units. All ages were determined by J. Matzel and R. Mundil at the facilities of the Berkeley Geochronology Center (Matzel et al., 2006).

STRUCTURE OF THE BENSON LAKE PENDANT

The Benson Lake pendant preserves evidence of at least five deformation phases that are represented by five sets of crosscutting structures. While the older phases are best preserved in the quartzitic units, the younger structures are more apparent in the weaker, metapelitic rocks. Primary, sedimentary structures in the Benson Lake pendant are evident in thick alternating beds of quartzite and metapelites as well as the local presence of cross-bedding and erosional, trough-like structures. Bedding (S_0) and a bedding-parallel foliation (S_1) were isoclinally folded and are now observed in layers of white quartzite as rootless, isoclinal folds of cm to m scale. During this event, strong rheological differences between the quartzites and metapelites produced layers of metapelites that, in map view, appear to thicken and thin, then end abruptly. The transposing, axial planar foliation associated with this first event of folding is the main foliation in the pendant (S_2). S_2 was refolded into open, upright to inclined, fairly cylindrical folds (F_3) with mm- to 100s-of-m-scale wavelengths and shallow to moderate, NW-plunging fold axes and crenulation lineations having an average orientation of 24/321 (Fig. 1). The pendant-scale fold (F_3) on the geologic map is attributed to this generation of folding (see antiform axis in geologic map with 30° plunge based on average fold axes orientations). While the F_3 folds in quartzite are the dominant structure and have box-fold symmetries, the more pelitic layers are more tightly folded, show crenulations at dm to mm scales and quite commonly a transposing S_3 foliation. Some of the axial planar S_3 foliation in the quartzite is associated with granitic melt and ductile shear with small offsets or is expressed as a spaced fracture cleavage. Foliation S_3 was subsequently folded into very open, upright, m-scale F_4-folds or corrugations perpendicular to F_3 causing an undulation of the S_3 foliation. In places, particularly in quartzite south of Benson Lake, mm to m scale box folds and a spaced fracture cleavage (S_4) with an average orientation of 068/81 with local mm to cm scale offsets along box-fold hinges were developed. Rarely, mm-scale F_5 crenulation and cm-wide, granite veins were folded into recumbent folds and are only observed in the metapelites close to the western contact with the granites of the Yosemite Valley intrusive suite (Fig. 2). Small brittle faults occur locally in the mapped area, but major faulting could not be discerned.

STRUCTURE OF THE PLUTONIC UNITS

All plutonic rocks, including the Tuolumne Intrusive Complex units as well as granites and associated rocks of the Yosemite Valley intrusive suite, have dominantly preserved magmatic foliations and lineations.

The granites of the Yosemite Valley intrusive suite (Kyvg), including the complexly mingled rocks, preserve a variety of foliations ranging from weak to moderately strong, pure magmatic foliations to magmatic foliations that have a weak to strong subsolidus overprint. Generally steep foliations and lineations vary in strike and trend, respectively, between NW-SE to ENE-WSW orientations in different domains along the pendant margin. Solid-state overprint occurs locally in the granites of the Yosemite Valley intrusive suite south of the metasediments and west of the southern part of the “tail” containing the mingled zone. Farther away from the contacts with the pendant and the mingled zone, the subsolidus overprint in the granitic units of the Yosemite Valley intrusive suite decreases. Local magmatic shear zones occur in the granites and the complex mingled zone. The high temperature solid-state foliation overprint and ductile shear zones are particularly apparent along segments near Rodgers Lake, where protomylonitic textures were developed.

The granodiorite units of the Tuolumne Intrusive Complex are characterized by steep lineations and steep, NW-SE and subordinate E-W–striking magmatic foliations. The magmatic fabrics generally crosscut the ~NW-trending internal contacts where at an angle (see also interpolated foliation traces in cross section). Magmatic shears of cm to dm scale are rarely found in Tuolumne rocks and are restricted to near the host rock contact.

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