Partially Serpentinized Mantle Peridotite in Newly Discovered Subduction Complex, southwest Arizona

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Discovery at Cemetery Ridge

The latest Cretaceous to early Paleogene Orocopia Schist records low-angle subduction of continental-margin supracrustal rocks beneath southwest North America (Grove et al., 2003; Jacobson et al., 2011). Heretofore, all known exposures of Orocopia Schist lay along the Chocolate Mountains anticlinorium (Haxel et al., 2002). This structure extends from the Orocopia Mountains (southern California) eastward to Neversweat Ridge, 65 km east of the Colorado River in southwest Arizona (Fig. 1). In December 2012, we discovered an additional exposure of Orocopia Schist significantly farther inland—at Cemetery Ridge (CR), 90 km east of the Colorado River and 90 km west of the outskirts of greater Phoenix (Fig. 1). This body of Orocopia Schist is extraordinary because it includes numerous blocks and fragments of partially serpentinized mantle peridotite (Fig. 2).

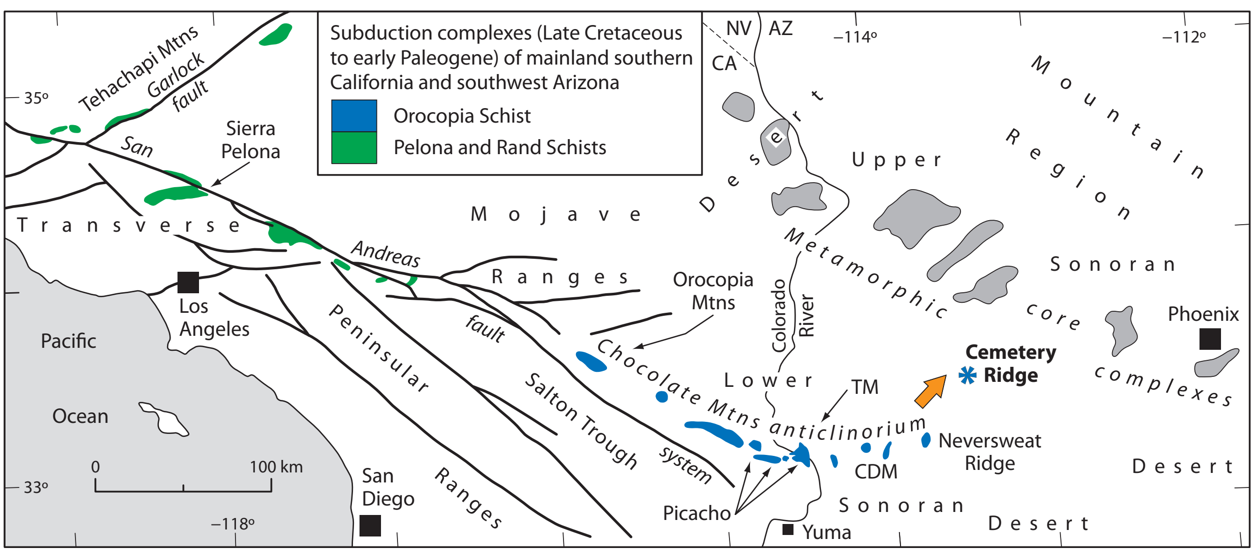


Figure 1. Distribution of the Orocopia Schist, and closely related Pelona and Rand Schists, southern California and southwest Arizona, showing location of the newly discovered exposure of Orocopia Schist at Cemetery Ridge relative to the Chocolate Mountains anticlinorium. Large arrow indicates inferred approximate direction (present coordinates) of subduction of Orocopia Schist beneath southwest Arizona, based upon the orientation of prograde metamorphic lineation (Fig. 2, inset). Before ≈ 300 km of late Neogene to Quaternary right slip on the San Andreas fault system, the Pelona Schist was adjacent to the Orocopia Schist; specifically, Sierra Pelona was directly west of the Orocopia Mountains (Crowell, 1962). CDM, Castle Dome Mountains; TM, Trigo Mountains. Map after Haxel et al. (2002); metamorphic core complexes after Spencer and Reynolds (1989, 1990).

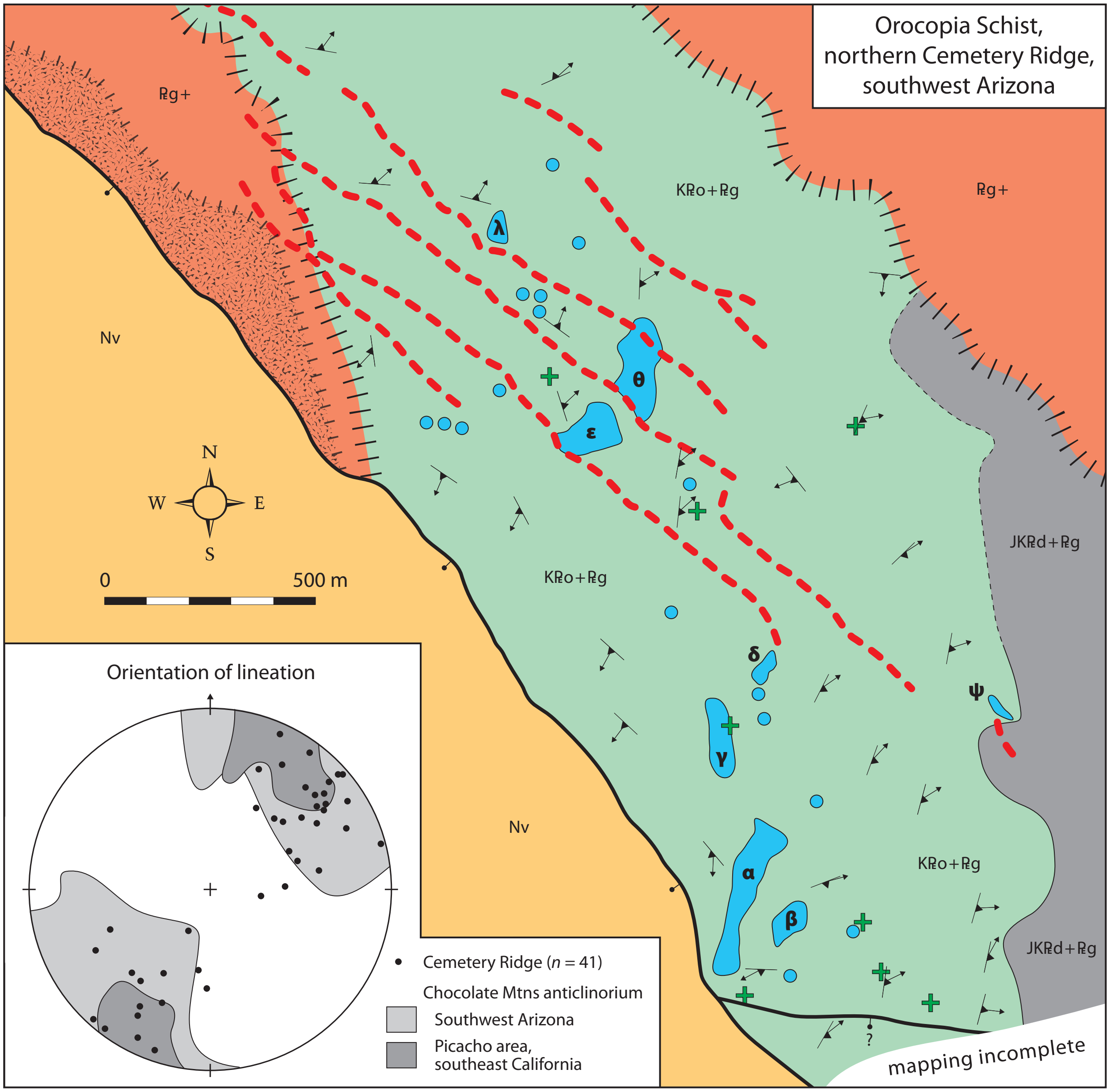
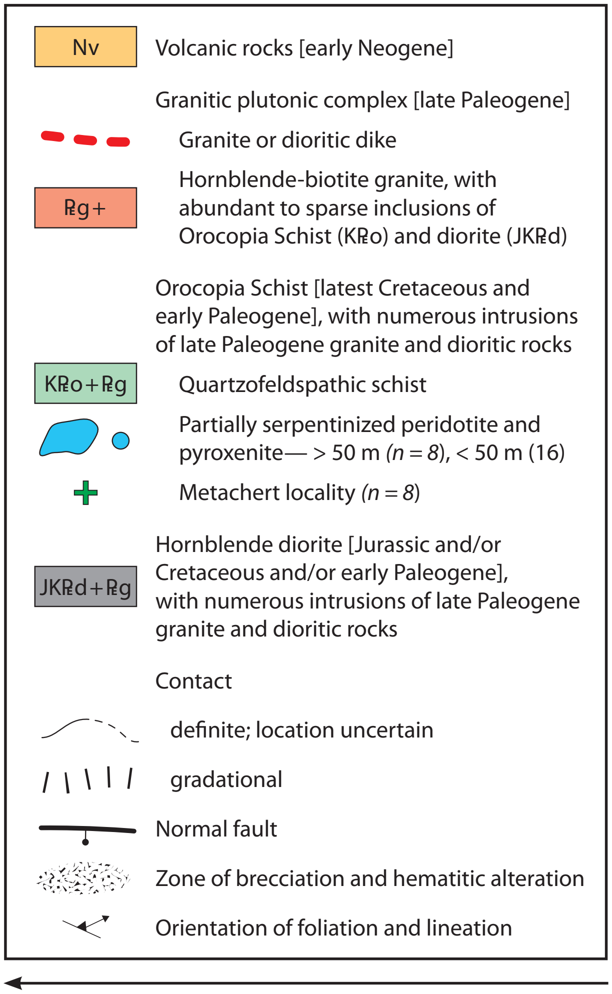


Figure 2. ***Explanation on next page.*** **Preliminary geologic map of part of the Orocopia Schist (Figs. 3, 4) at northern Cemetery Ridge, southwest Arizona (Fig. 1), emphasizing the distribution of bodies of partially serpentinized peridotite (Figs. 5–7). The eight mappable (> 50 m) peridotite bodies are designated by Greek letters—α, β, γ, δ, ε, θ, λ, and ψ. Orocopia Schist extends northwest at least 3 km beyond the northern border of the map. Only the largest of innumerable dikes and other small intrusions of granite are shown. Inset lower-hemisphere equal-area projection shows the orientation of prograde metamorphic lineation in Orocopia Schist at CR and along the Chocolate Mountains anticlinorium in southwest Arizona and in the Picacho area of southeasternmost California (Fig. 1; Dillon et al., 1990; Haxel et al., 2002).**



Geologic Setting

The Orocopia Schist at CR (Figs. 2–4) is a roof pendant within or above a stock of late Paleogene granite (Wilson, 1933; Gilbert and Spencer, 1992). No single or small number of discrete contacts separate Orocopia Schist and granite. Rather, two broadly gradational contacts delineate a central area that is largely schist and flanking areas that are mostly granite. The schist contains innumerable dikes and other small intrusions of granite and related dioritic rocks; the granite contains abundant to sparse inclusions of schist.

Orocopia Schist

The schist at CR possesses six hallmarks of Orocopia Schist in general (Fig. 4). It is mostly gray, flaggy, quartzofeldspathic schist (metasandstone) (1), with common porphyroblasts of bluish-gray to black graphitic albite (2). The schist contains thin, scattered layers of amphibolite schist (metabasalt) (3), Fe-Mn metachert (4), and siliceous marble (5); and abundant pods of coarse-grained actinolite rock (6). At CR as elsewhere, these rocks types attest to the marine, continental-margin origin of the protolith of the Orocopia Schist (Haxel et al., 1987, 2002; Dawson and Jacobson, 1989).

Partially Serpentinized Peridotite

The Orocopia Schist at CR includes at least 24 blocks of partially serpentinized mantle peridotite and pyroxenite (hereafter collectively called peridotite) (Fig. 2). These blocks, 200–400 m to < 30 m in length, are aligned in a diffuse trend ≈ 2 km long. They are probably dispersed fragments of a single peridotite slab, originally ~ 1 km long and a few hundred meters thick. As it is closely associated with metachert, the peridotite very likely represents oceanic (rather than continental) mantle. Field relations indicate the peridotite was partially serpentinized but otherwise unmetamorphosed when emplaced into the sandstone protolith of the schist. The peridotite was subsequently metamorphosed with the schist, but some parts of some blocks were only slightly affected. Here premetamorphic minerals, textures, and fabrics are partially preserved.

In partially serpentinized but minimally metamorphosed peridotite, the most prominent feature is large (½–3 cm), reddish-brown-weathering aggregates of orthopyroxene, in a compact, black to bluish-black matrix (Figs. 5A,

Figure 3. Late Paleogene to early Neogene (Spencer et al., 1995) igneous rocks and Orocopia Schist at Cemetery Ridge (Fig 2): subvertical granite dikes intrude the schist, and gently dipping volcanic rocks overlie it. Mesa (Deadman Mountain) is 2.5 km distant. Note faint 1920s miners' trail at lower right.

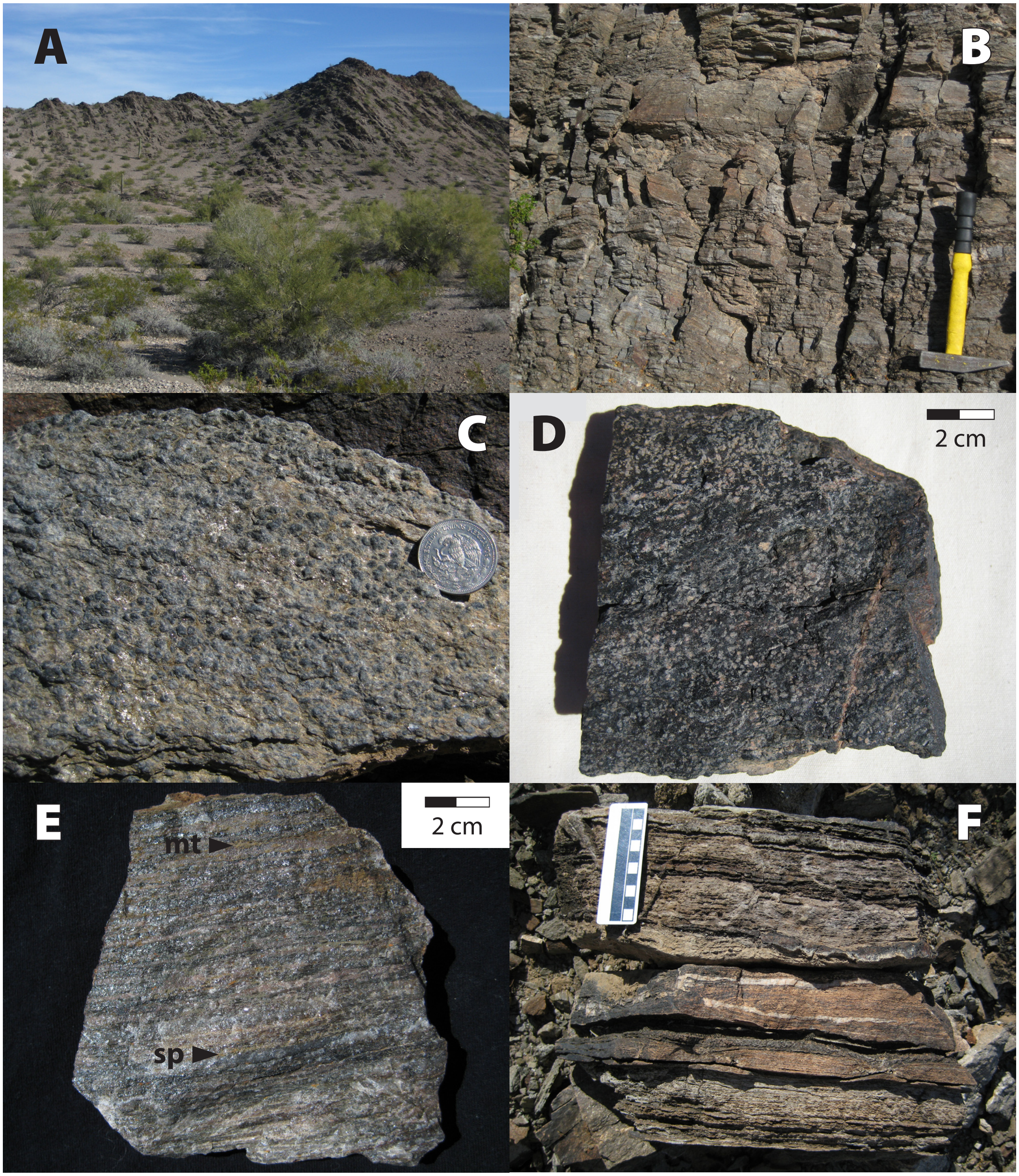


Figure 4. Hallmarks of Orocopia Schist, at Cemetery Ridge. (A) Moderately dipping layers of quartzofeldspathic schist. (B) Layered quartzofeldspathic schist. (C) Porphyroblasts, 1–3 mm diameter, of bluish-gray graphitic albite, on foliation surface of quartzofeldspathic schist. (D) Metabasalt—amphibolite schist comprising black hornblende needles and white porphyroblasts of sodic plagioclase. (E) Fe-Mn metachert, mostly quartz with thin layers of yellowish spessartine (sp) and magnetite (mt; largely altered to limonite). (F) Siliceous marble (two loose slabs placed side-by-side).

B; 6). These large objects resemble bastites, but in thin section most are seen to still be orthopyroxene, slightly serpentinized. In thin section the matrix is a mixture of serpentine (+ brucite?) + magnetite ± talc, derived from olivine. Relict olivine is fairly common. These rocks were originally intergradational orthopyroxene-rich harzburgite and subordinate olivine orthopyroxenite (hereafter collectively called harzburgite). Most comprise subequal proportions of olivine and orthopyroxene (Fig. 7), but some (not represented in Fig. 7) have surprisingly high modal orthopyroxene (Fig. 6), as much as ~ 70 percent. This partially serpentinized harzburgite is cut by numerous dikes and veins of more completely serpentinized dunite (Fig. 5A, C, D). This combination—harzburgite with dunite dikes and veins—is the single most common variety of peridotite at CR.

The second most common type of peridotite is massive, mostly fine-grained, black to bluish-black serpentinized dunite and spinel dunite, which forms homogeneous bodies as much as tens of meters across. In thin section relict olivine is minimal to common, and serpentine + magnetite are sometimes accompanied by minor tremolite. Relations between harzburgite and massive dunite are as yet unclear.

Harzburgite in some places displays a coarse, gneissic fabric defined by crude alternating layers of olivine and orthopyroxene (Fig. 5B, E, F). This fabric is distinct in style and orientation from that of the enclosing quartzofeldspathic schist. We tentatively interpret this feature of the peridotite as relict mantle tectonite fabric (cf. Loney et al., 1971).

Actinolite Veins, and a Mystery Solved

Serpentinized peridotite at CR is cut by numerous actinolite veins, a few centimeters to nearly a meter thick (Fig. 5G). We presume that these veins were produced by interaction of the Mg-Fe-rich peridotite with Ca-bearing fluids from the enclosing schist (Harlow and Sorensen, 2005). In the 1920s prospectors seeking asbestiform amphibole dug at least 14 pits in actinolite veins at CR.

Throughout southern California and southwest Arizona, one of the hallmarks (and minor mysteries) of the Orocopia and related Schists (Fig. 1) is pods and layers of actinolite rock and actinolite schist (collectively, actinolitite). At CR, the origin of this enigmatic rock is revealed—its source is actinolite veins in serpentinized peridotite. During metamorphism of quartzofeldspathic schist and fragmentation of included peridotite blocks, pieces of vein actinolite were detached from their host peridotite and dispersed through the schist. Despite the ubiquity of actinolitite in the Orocopia and related Schists, other ultramafic rocks are rare (except at CR). Nonetheless, somewhere along their subduction path all of the schists must have come into contact with serpentinized peridotite, from which they acquired their actinolitite.

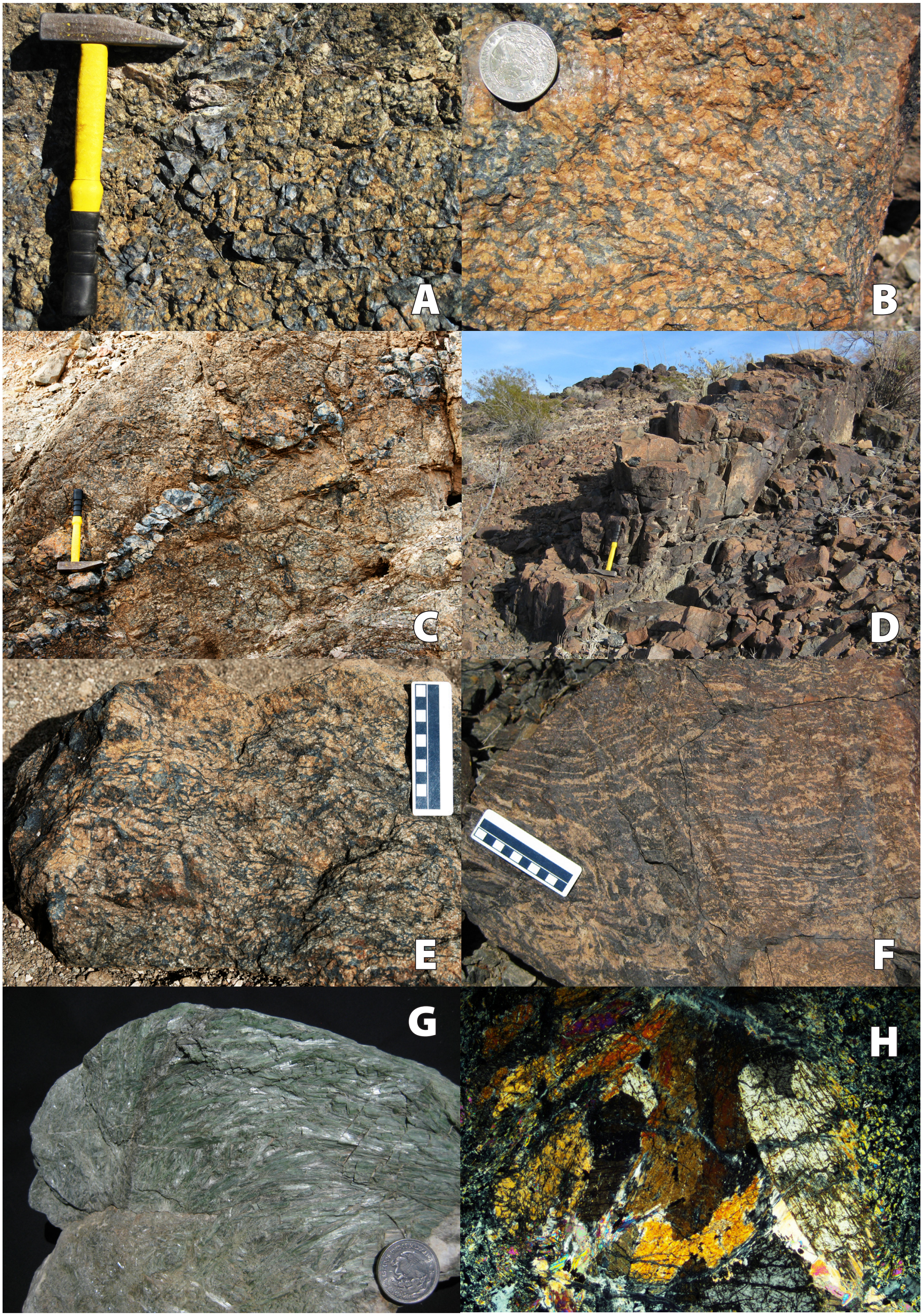
Origin of Peridotite at Cemetery Ridge

At this preliminary (five-month) stage of our investigation, only two observations constrain the origin and provenance of the CR peridotite: (1) It is associated with metachert. (2) Much of it is harzburgite unusually rich in orthopyroxene.

Metachert is unusually abundant at CR. Seven of eight metachert layers found so far lie within the same broad trend as the peridotite bodies (Fig. 2). In two places metachert and metaserpentinite are interfoliated. Evidently, chert and peridotite were introduced into the sandstone protolith of the Orocopia Schist together. The peridotite must have once been exposed on local submarine topographic highs where the dominant biogenic component of the chert could accumulate above the reach of clastic sedimentation by turbidites (Haxel et al., 1987).

The most striking feature of CR peridotite is harzburgite with high modal abundance of orthopyroxene (Figs. 5–7). Orthopyroxene-rich peridotite in an oceanic setting suggests subarc mantle—the mantle wedge above a subduction zone—where olivine can be converted to orthopyroxene by interaction with siliceous aqueous fluid or silicic (boninitic) melt (review by Arai and Ishimaru, 2008). This secondary orthopyroxene displays several forms and textures, including "radial aggregates". Interestingly, in all four CR harzburgites examined in thin section, the large bastite-like objects (Figs. 5A, B; 6) are not single grains but clusters of ~ 10–30 intergrown orthopyroxene crystals (Fig. 5H). Selective serpentinization of olivine apparently has obscured any textural evidence that this orthopyroxene replaced olivine. The idea that the orthopyroxene-rich CR peridotite represents subarc mantle is intriguing, and worth evaluating.

We envision four tectonic settings where the CR peridotite might have originated (Fig. 8). The two constraints just outlined suggest that the most likely source is the leading corner of the mantle wedge (❸, Fig. 8), where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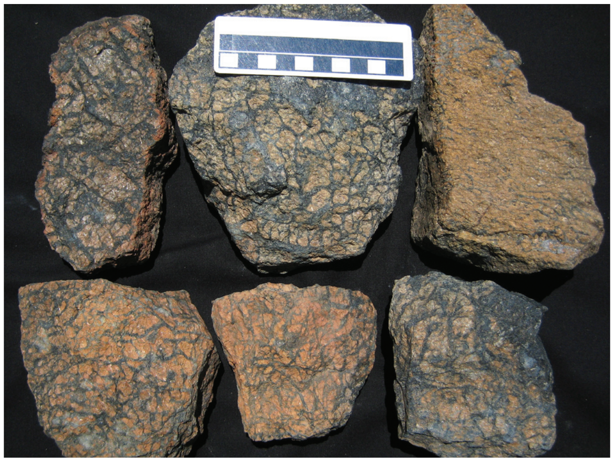

Figure 6. Cobbles of partially serpentinized harzburgite–olivine orthopyroxenite, illustrating typical orthopyroxene-rich character. Scale divisions 1 cm and 1 dm.

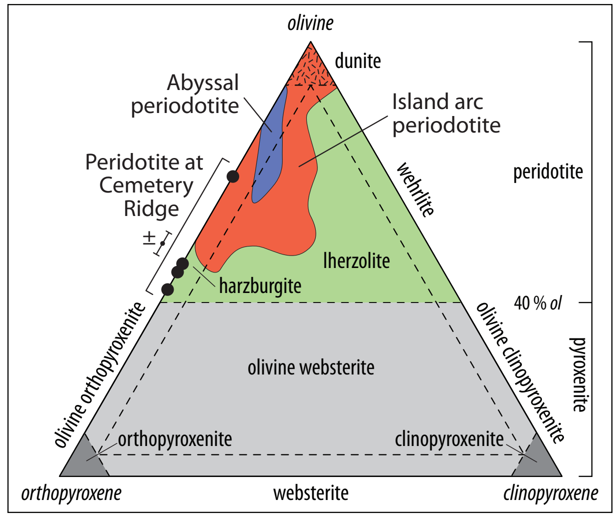

Figure 7. Estimated modal composition of four samples of partially serpentinized coarse-grained harzburgite at Cemetery Ridge (Figs. 5, 6), compared with those of abyssal peridotites and the majority of peridotite xenoliths and forearc mantle peridotites from island arcs of the western Pacific Ocean (Dick et al., 1984; Dick, 1989; Arai and Ishimaru, 2008). Accuracy of modal compositions for CR is limited because they were determined from thin sections of coarse-grained, serpentinized rocks. Estimated precision of *ol/(ol + opx)* ratio, based upon replicate analyses, is indicated by the error bar ("±"). Small grains of possible clinopyroxene, difficult to distinguish from relict olivine in these rocks, constitute no more than a few modal percent.

subarc mantle was exposed on the sea floor, thinly covered by continental-margin chert, detached from the leading corner of the mantle wedge by mass wasting or tectonic erosion (von Huene and Scholl, 1991; Stern, 2011), emplaced into the accretionary prism, and subducted. *Given the limited evidence available, this scenario is merely a preliminary hypothesis to highlight issues to be addressed by further work.*

Continuing Research

We plan to . . .

- Study the peridotite at Cemetery Ridge in much greater detail, through larger-scale geologic mapping, petrography, whole-rock geochemistry (e.g., Hattori and Guillot, 2007; Savov et al., 2007), and microprobe analysis of minerals.

- Consider relations of the CR peridotite to peridotites in the western Coast and Transverse Ranges of central California (Fig. 8 caption; Loney et al., 1971; Dickinson et al., 1996; Coleman, 2000; Choi et al., 2008; Hopson et al., 2008); and to ultramafic xenoliths probably related to low-angle subduction beneath the Colorado Plateau (Smith, 2013).

- Determine U-Pb depositional (detrital-zircon) and $^{40}Ar/^{39}Ar$ metamorphic and cooling ages for the Orocopia

Figure 5. Variably serpentinized peridotite and pyroxenite and associated rocks in Orocopia Schist at Cemetery Ridge (Fig. 2); rocks A–F named according to primary (pre-serpentinization) mineralogy. (A) Coarse-grained harzburgite, comprising orthopyroxene (red-brown) and serpentinized olivine (black). Note small dunite vein to right of hammer. (B) Coarse-grained olivine orthopyroxenite, comprising orthopyroxene (red-brown) and serpentinized olivine (black). (C) Dunite dike, ≈ 2 dm thick, in harzburgite. Bluish serpentine partially coats joints and fractures in dunite, for example to right of hammer. Outcrop is deeply weathered. (D) Dunite dike, 1–1.5 m thick, in olivine orthopyroxenite. (E, F) Relict mantle tectonite fabric in harzburgite–olivine orthopyroxenite. (G) Coarse-grained actinolite vein rock. (H) Cluster of ≈ 15 orthopyroxene crystals in harzburgite. Cluster is surrounded on left, top, and right by serpentine + magnetite derived from olivine. Orthopyroxene is cut by several serpentine veins. Image ≈ 6 mm wide; crossed polarizers.

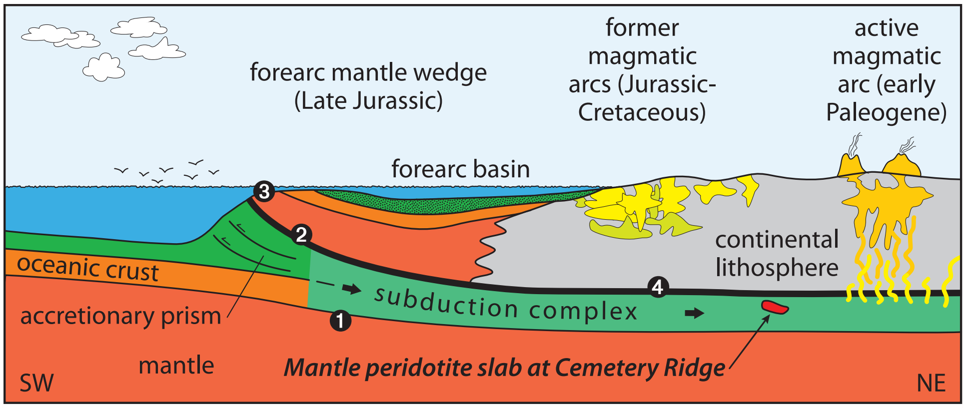

Figure 8. Sketch section (not to scale; vertically exaggerated) of low-angle continental-margin subduction system west of and beneath southern California and southwest Arizona, showing four tectonic settings where the mantle peridotite slab in the latest Cretaceous to early Paleogene Orocopia Schist subduction complex exposed at Cemetery Ridge might have originated. The forearc mantle wedge and former magmatic arcs are related to Jurassic and Cretaceous subduction system(s), not the early Paleogene active system. The Late Jurassic forearc mantle wedge, originally west of southern California, has been displaced northward along the late Neogene to Quaternary San Andreas fault, and now resides in the western Coast and Transverse Ranges of central California (Monterey to Santa Barbara). Igneous rocks of the Jurassic and Cretaceous magmatic arcs are widespread in the Mojave and Sonoran Deserts and Salinia block.

Schist at CR, in order to fit this farthest-inland exposure of schist into age patterns established for subducted terranes closer to the continental margin (Fig. 1; Jacobson et al., 2011).

Examine and date probable low-angle exhumation faults (Jacobson et al., 2002, 2007) overlying the Orocopia Schist at CR, in the northwest and southeast parts of the area of Figure 2.

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