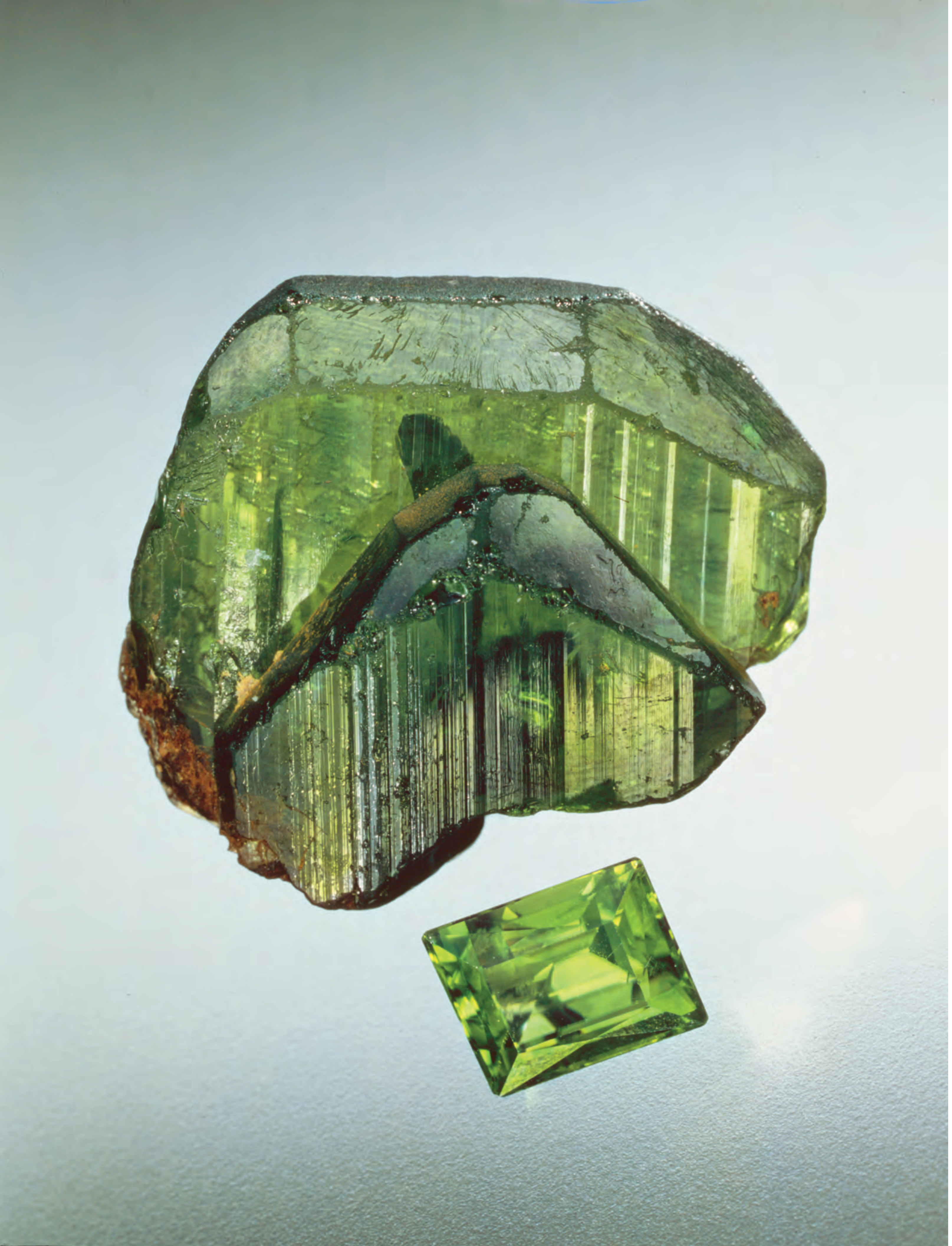

Peridot from Pyaung-gaung, Mogok Tract, Myanmar: Similarities to Sapat and Zabargad deposits

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PERIDOT IS THE ARABIC WORD for a grass green gem found on the Red Sea island of Zabargad (or Zebirget) that has been known since classical Antiquity. It is the gem variety of forsterite, the magnesian member of the olivine group of minerals and gives the name to and is a major constituent of the rocks of Earth's mantle: peridotite. In fact, most peridot is derived from a coarse, olivine-dominant peridotite known as dunite, in which grain size can exceed several centimeters. Examples of such sources are numerous, but the best known is a large field of volcanic rocks on the San Carlos Apache Reservation in New Mexico – dunite and other peridotites were carried up by volcanic eruptions that ended about one million years ago.

The most prized peridot gems are the large ones exceeding 50 carats from two historic deposits on

Figure 1a (facing page): A large twinned peridot crystal measuring 41 mm across and a faceted peridot (10.92 ct, 14 mm across), both from the classic locality of Zabargad Island in the Red Sea. Cat. nos. 42888 and 104653, American Museum of Natural History, New York. Courtesy of the American Museum of Natural History. Photo by Harold and Erica Van Pelt.

Figure 1b (above): Large faceted peridots; top stone is 164.16 ct from Pyaung-gaung, Mogok Stone Tract, Myanmar and the two lower stones, weighing 95.19 and 61.55 ct, are from Zabargad Island, Egypt. Purer green color is visible in the Myanmar stone. Cat. nos. 44789, 42739, 42740, American Museum of Natural History, New York. Courtesy of the American Museum of Natural History. Photo by Harold and Erica Van Pelt.

Figure 2: Peridot crystals from the ancient mine on Zabargad Island *(foreground)*(collected by J.A. Harrell), the classic peridot locality in the Red Sea 50 km from Ras Banas on the coast of Egypt; a deeply etched, sharp terminated crystal on calcite-rich marble matrix with magnetite concretions *(back left)* from Sapat Gali, Kohistan District, Khyber Pakhtunkhwa Province, Pakistan (coll. L. Thoresen); and a deeply etched, perfectly terminated tabular crystal *(middle)* measuring 18.2 x 26.4 x 8.6 mm from Pyaung-gaung, Bernardmyo, Myanmar (Pala International). Photo by Lisbet Thoresen.

Zabargad Island, Egypt, and in the Mogok Stone Tract of Myanmar (Burma)(Figures 1a,b), and a more recently discovered source at Sapat Gali, Kohistan District, Khyber Pakhtunkhwa, Pakistan (Figures 2, 15a,b). These deposits produce large fragments and well-formed crystals from pockets within peridotites. From a geological perspective this is really odd, because at the conditions of great depth and pressure of Earth's mantle, cavities filled with fluid in solid rock such as those found in gem pegmatite cannot survive, as the fluid will be quickly expelled upward and the cavity collapsed and crushed. Research in the last 30 years has shown that the olivine crystals from Zabargad and Sapat did not form at mantle depths, but are the result of recrystallization with the help of fluid from the Earth's tectonic activity (Kurat et al. 1993; Bouilhol et al. 2012; for a different interpretation see: Takla et al. 1997). However, because of the isolation of Myanmar from much modern geological research, particularly in the sensitive Mogok region, virtually nothing has been published on the geological origin of peridot there over the last 50 years, leaving one to rely on Iyer (1953: 82) (Figure 3), Bender (1983), and mostly Themelis (2007).

My first visit to Mogok was with Bill Larson in 1997, and the incredible diversity of minerals and unusual occurrences literally blew my mind. Since that time I have focused on acquiring specimens from the Mogok Stone Tract for the mineral and gem collection at the American Museum of Natural History, as well as carried out two expeditions (but short of Mogok) and studied some of the specimens we have acquired. Consequently, when the change in government in Myanmar started to show signs that westerners might be allowed to visit the Mogok Stone Tract in 2013, I jumped at the chance to get there, in part, to visit a peridot mine. Ted Themelis' splendid book from 2007 on Mogok geology, minerals and gems suggested that peridot cavities formed from some "mother liquid," but

Peridot: Gem form of forsterite, Mg_2SiO_4, which forms a solid solution with Fe2SiO4 to form the major constituents of the olivine group of minerals: $(Mg,Fe,Ni,Mn)_2SiO_4$

Crystal Symmetry:	Orthorhombic
Hardness:	7
Cleavage:	Imperfect in two directions: {010}, {100}
Specific Gravity:	3.22 – 3.29
Refractive Index:	1.635 – 1.690
Color:	Grass green to yellow-green and brownish green; the off color is generally attributed to ferric iron (Fe3+) oxidation of constituent ferrous iron (Fe2+)

Peridotite: A rock of basically igneous origin composed by a majority of olivine. Three types are common: dunite is >90% olivine; harzburgite contains olivine (> 40%), orthopyroxene ((Mg,Fe) SiO3) and less than 5% clinopyroxene (Ca(Mg,Fe)Si2O6), and lherzolite contains olivine (> 40%), orthopyroxene, and clinopyroxene generally above 5%. Chromite is a minor constituent of peridotites. Because of the extraordinary abundance of magnesium and iron (ferrum), these rocks are also called "ultramafic."

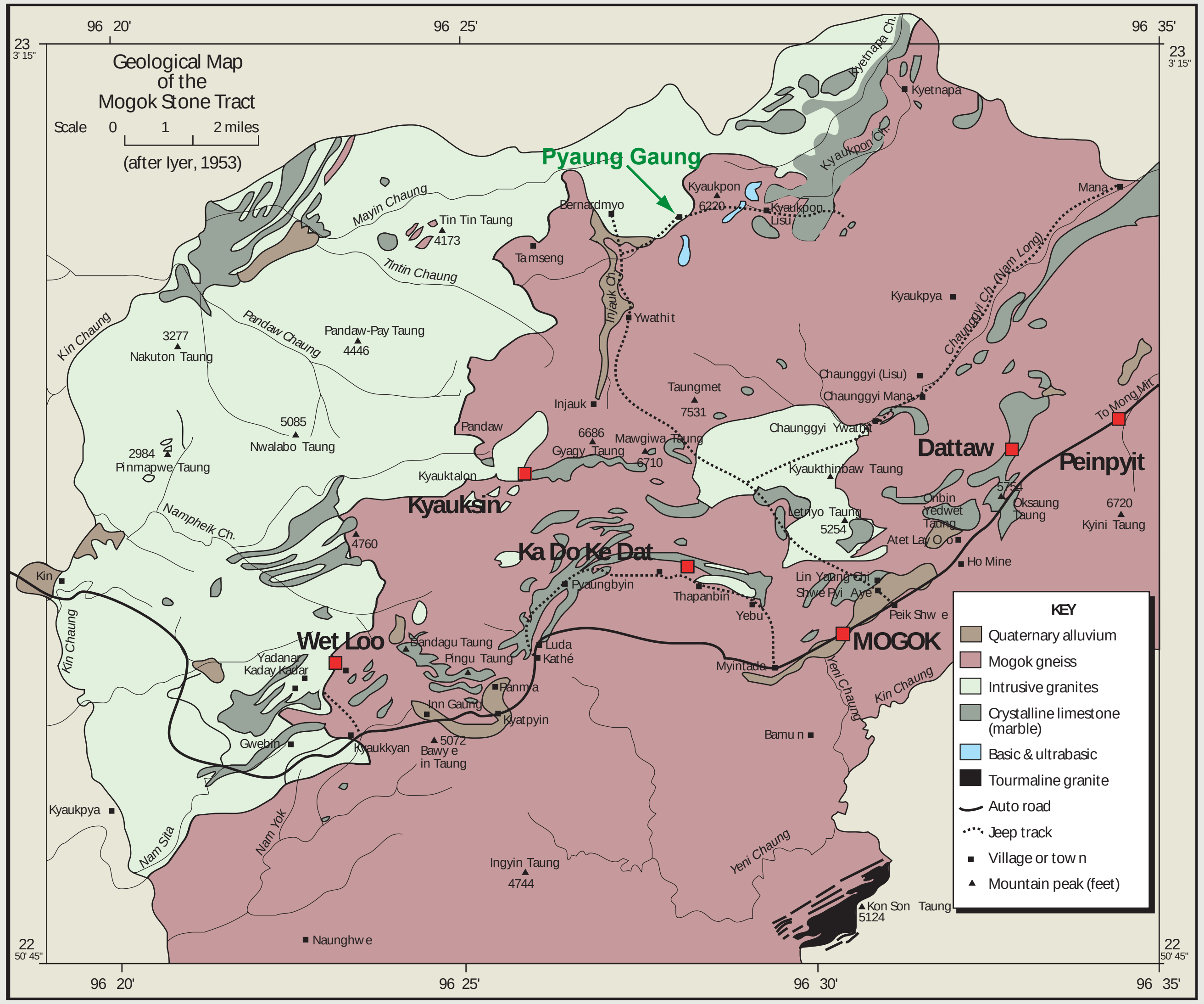


Figure 3: Map showing Pyaung-gaung mining areas, close to Bernardmyo at the northern edge of the Mogok Stone Tract, Mandalay Division, Myanmar. Map courtesy of Richard Hughes, after map by Iyer (1953).

he left the impression that the process was magmatic, involving liquid rock. Moreover, I had never been able to acquire samples suitable for answering the origin question, as I needed rocks more than beautiful crystals.

In the winter of 2013, my colleague Jim Webster and I applied for a grant through the Museum to the Stavros Niarchos Foundation to support an expedition to Mogok. It was funded in the spring of 2013, so the planning commenced. With the incredible assistance of Kyaw Thu, a geologist who did his Ph.D. research in Mogok and who has become an important dealer of gems and minerals from the area, we visited Mogok for nine days in November (Figure 4), stopping at many of its mines and outcrops, including the important peridot mining area of Pyaung-gaung.

Visiting Pyaung-gaung requires driving north from Mogok town, over a ridge on the side of the tallest mountain in the Mogok Tract, Taung Me (Figure 5), where we encountered the pagodas at Shwe-Lay-Bauk (and found spinels in the roadside marble: Figure 6). This area exposes several narrow bodies of partially serpentinized peridotite that are aligned along minor faults connecting to the major E-W trending Momeik fault, which bounds the north side of the Mogok Tract. We visited one active mine, Mya-sein-taung, that uses a sub-horizontal tunnel to reach into the ultramafic rock body (Figure 7). We were invited to inspect the tunnel, but the combination of recent blasting and non-existent safety precautions stifled our enthusiasm. Instead, we surveyed the large area of exposed ultramafic rocks and mine tailings. It quickly became apparent that the peridotites exhibited a shear fabric (planar layering resulting from shear deformation), which was probably the result of strain while still at great depth and was cross-cut by several directions of younger fractures. The surfaces of these fractures are coated with a mixture of talc and microscopic carbonate minerals (probably calcite and dolomite: Figure 8). Another conspicuous feature is veins or fractures filled with coarsely crystallized brown enstatite (some crystals >10cm: Figure 9); miners told us that these veins were used prospecting for peridot, as these enstatite veins typically lead to peridot pockets (Figure 10). Another vein mineral described by the locals is brown phlogopite, which we have observed in parts of returned samples. This feature also is associated with finding peridot pockets. Before we departed the mining area we were shown some better (but non-commercial) samples showing the characteristic pocket mineralogy with centimeter-sized peridot crystals—a couple were given to us.

During our time in Mogok, we collected about 140 kilograms of samples, again mostly rocks, which we were able to ship back via air to the United States, again, with the superb assistance of Kyaw Thu. We were concerned that the existing sanctions against the former Burmese government, explicitly the Tom Lantos Block Burmese JADE (Junta's Anti-Democratic Efforts) Act of 2008, might strand our shipment, if the U.S. Customs officials believed that there might be contraband jade or rubies (the target of the Act) in the shipment. For whatever reason, the Museum destination of the package, our good karma, or the grace of God, our five boxes arrived at the Museum not long after our return shortly before Thanksgiving. Since then, we have had a little time to analyze samples recovered from the Mya-sein-taung mine at Pyaung-gaung, and these early results are reported below.

To understand the origin of the peridot, it is important to understand the geologic history of the hosting peridotites and their partial serpentinization. As the primary constituent of Earth's upper mantle, which lies 20 to 50 km below the surface of Earth's crust, peridotite typically exists at temperatures greater than 800ºC. One can interpret the conditions

Figure 4: East entrance to Rubyland (Mogok), with our "crew": from left to right Prof. Hla Kyi, George Harlow, Jamie Newman, Jim Webster, and Kyaw Thu. Photo by a guide.

Figure 5: View of Taung-Me, the tallest mountain in the Mogok Stone Tract; elevation 1743 meters (5718 feet). Photo by George E. Harlow.

that a peridotite experienced from the composition of coexisting minerals using thermodynamic data and tools. A peridotite sample we have examined is a harzburgite and consists of comminuted olivine ($Fo_{92\text{-}93}$), brown orthopyroxene ($En_{92\text{-}93}$), chromian magnetite ($Mgt_{61}Pcm_{18}Cm_{10}Sp_{9}$) and minor phlogopite with lizardite serpentine coating all grain boundaries. Dunite samples consist of olivine ($Fo_{92\text{-}93}$) and spinel ($Mgt_{65\text{-}70}Cm_{20\text{-}22}Pcm_{8}Sp_{4}$), again, with an intergranular coating of lizardite. Dunite appears to be the rock adjacent to peridot pockets (Themelis 2007), but we did not get to see good examples during our visit. Both rock types are cut by shear zones with the surfaces coated by shiny (soapy) lizardite and veins of magnetite-rich spinel or snow-flake talc ± lizardite.

Ol-Opx-Spinel thermometry for our sample Mogok13-34-3 yields an equilibration temperature of 730ºC ± 40 (OFM 2012; PTEXL2-2) and a permissible pressure of 20 kilobars or less. This should represent the last approach of this rock to chemical equilibrium and is well below melting temperatures. Clearly, the rock experienced lower temperature than mantle conditions, so we interpret this as the result of the exhumation process, i.e., uplift, probably related to motion along the Momeik fault. Another indication of this post-mantle history is the spinel composition in both the harzburgite and dunite, which rather than being dominated by chromite (Cm: $FeCr_2O_4$) is dominated by magnetite (Mgt: $Fe^{2+}Fe3^{+}{}_2O_4$). The high magnetite content suggests re-equilibration

Figure 6 (above): View of Shwe Lay Bauk pagodas. ***Overset:*** A sample of marble loaded with pink spinels found along the adjacent road. Photo by George E. Harlow.

Figure 7 (facing page): Entrance to underground mine at Pyaung-gaung with adjacent weathered outcrop of partially serpentinized peridotite. Rustiness indicates that there is still olivine in the peridotite that has not been reacted to become serpentinite. Photo by George E. Harlow.

Figure 8: Close-up of partially serpentinized peridotite (yellow-green) outcrop showing the sub-horizontal planar shear feature cut by fractures exposing surfaces partially coated with a mixture of talc and serpentine (white and brown). Photo by George E. Harlow.

Figure 9: Close-up of outcrop exposing a large vein of brown enstatite (it too is coated by talc and carbonate), running upper left to lower right through the chaotic exposure. FOV ca. 1 m w. Photo by George E. Harlow.

Facing page

Figure 10 (top): Close-up of a small area of pocket peridot surrounded by talc + carbonate (white) and interspersed enstatite exposed in a fragmented rusty peridotite. Photo by George E. Harlow.

Figure 11 (bottom): Two samples of a portion of a pocket showing peridot crystals (green), white pocket filling (a mix of calcite, pyroaurite—$Mg_6(Fe^{3+})_2CO_3(OH)_{16}\cdot 4H_2O$), talc, and lizardite serpentine), and graying serpentinized pocket host rock. These specimens were donated by the mine owner to the American Museum of Natural History, New York. Photo by George E. Harlow.

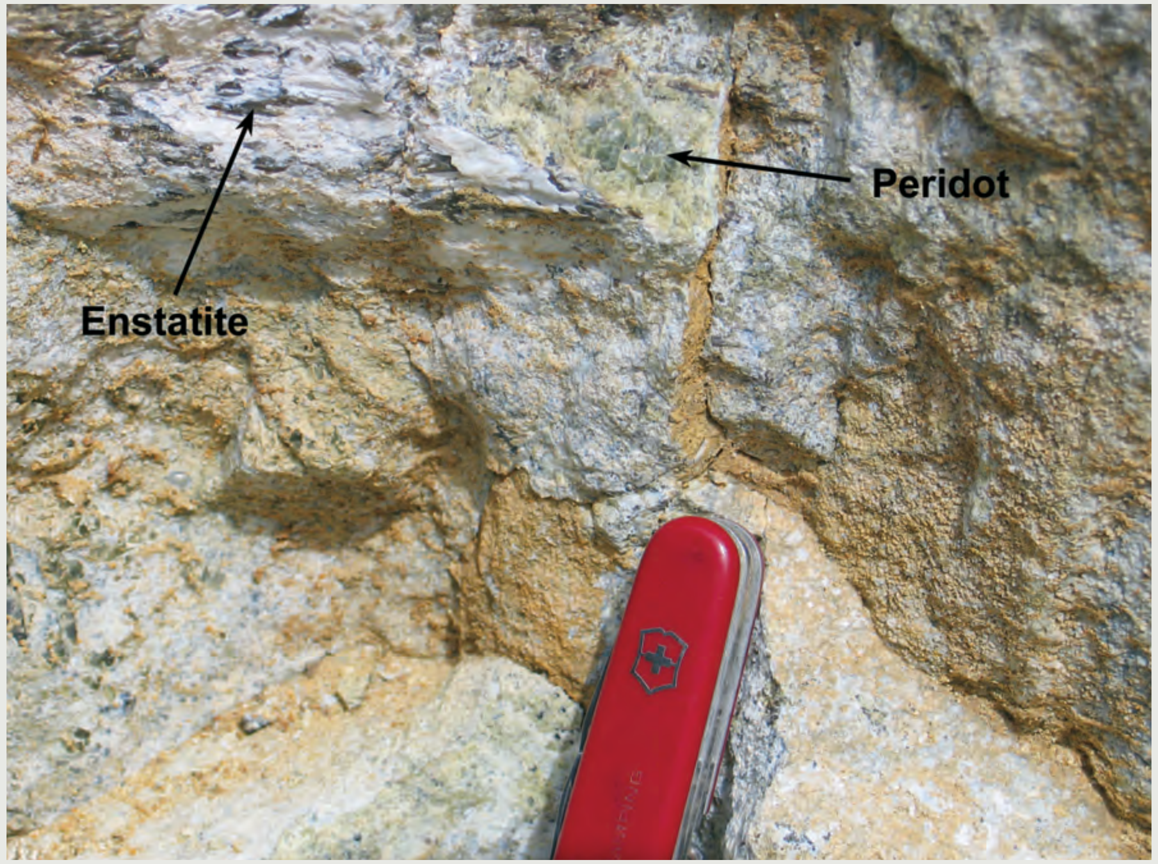
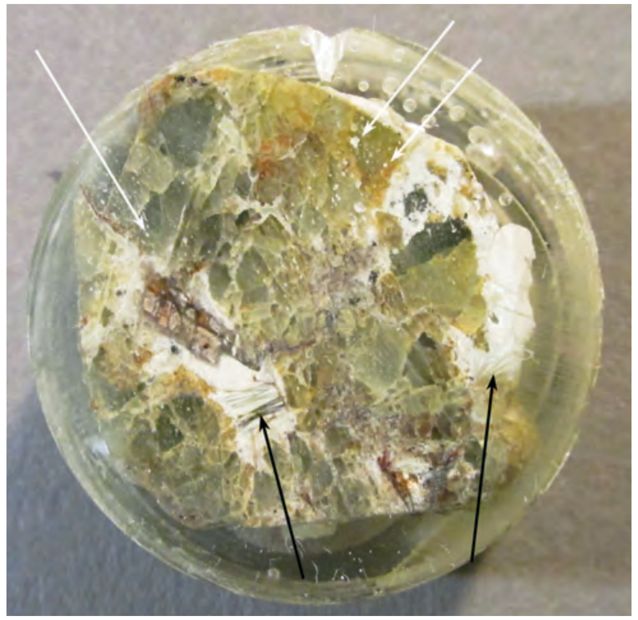
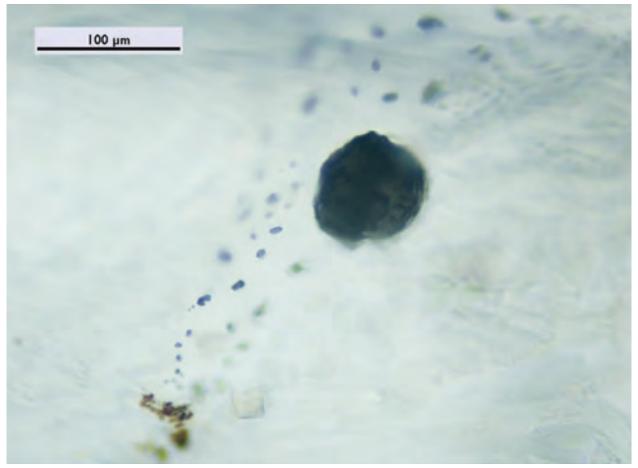


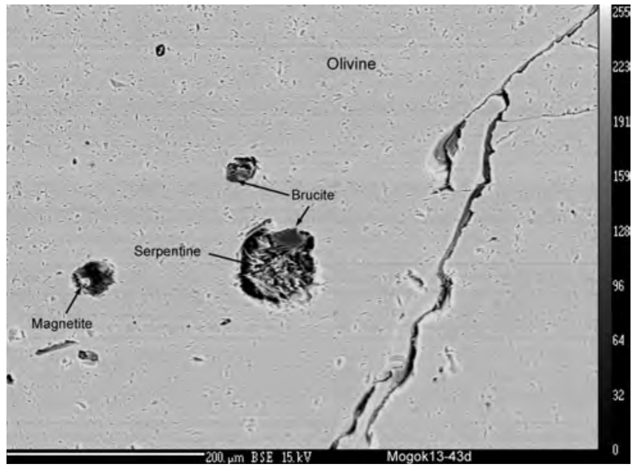
Figure 12 (right): Photomicrograph of Mogok13-43b2_PS, a one-inch diameter polished section of a peridot pocket sample (see: Figure 11). White arrows point to white inclusions in peridot; black arrows point to plates of lizardite that occasionally contain talc cores. Photo by George E. Harlow.

Figure 13 (below left): Photomicrograph of a peridot fragment in plane-polarized transmitted light. The dark "spherule" is an inclusion filled by a serpentine ball. Other much smaller inclusions decorate a healed fracture in peridot and appear to have the same contents as the larger inclusions.

Figure 14 (below right): Back-scattered electron image of an exposed inclusion in peridot from sample Mogok13-43b2_PS. Several inclusions are exposed on the section surface, and the contents of serpentine (antigorite), brucite, and magnetite are labeled. Very small, darker areas are the result of incomplete polishing.







at the sub-mantle temperature, probably due to some reaction with a fluid. Finally, the talc (Tc) and lizardite serpentine in fractures indicates addition of water relatively late and at much lower temperature (probably < 300ºC).

Peridot pockets have been described as being lined with peridot crystals that otherwise are filled with secondary but unidentified white material (Themelis 2007). Pocket samples we observed suggest this distribution, but they were generally too small or irregular to verify. Peridot compositions from cavities measured so far are very homogeneous – $Fo_{92\text{-}93}$ with NiO = 0.4-0.5 wt%. In addition to the white material filling the interstices of the peridot pockets are whitish inclusions in the base segments of peridot crystals adjacent to the cavity walls (Figure 11). A combination of X-ray diffraction and electron microprobe analysis shows that the white material around the peridot crystals in the pocket assemblage consists of a mixture of very fine-grained (cryptocrystalline) carbonate minerals (calcite, dolomite, and pyroaurite), and lizardite serpentine. Plates of lizardite can be observed in the white zones (Figure 11), which suggests that they crystallized in the cavity prior to the in-filling of fine-grained carbonate and serpentine. The white inclusions in peridot crystals generally consist of a crystal spray of a serpentine mineral (probably antigorite), crystals of magnetite and brucite ($Mg(OH)_2$), and open space (see: Figures 12–14). Some inclusions are bounded by a zone of olivine somewhat higher in iron content (Mg# = 0.943 vs 0.924), which suggests a re-equilibration between Mg-rich antigorite in the inclusion (Mg# = ~0.975) and host olivine at T < 600ºC (Evans 2010).

Figure 15a (above left): A peridot crystal (15.19 ct) from the classic locality of Zabargad Island, 50 km off of Egypt's coast in the Red Sea. Pala International. Photo by Mia Dixon.

Figure 15b (above right): The large dark green peridot crystal (44 mm h.) contains magnetite and antigorite inclusions and a profusion of curving, hair-like inclusions of Vonsenite-Ludwigite. The large blocky shape and crystal size, as well as inclusions are characteristic features of peridot from Pakistan; however, the color is not as common (Pala International). More typical of Pakistani material is the smaller yellow-green crystal *(front left)*(20.0 mm h.) with its sharp termination faces and deeply etched surfaces (coll. L. Thoresen, formerly Marin Mineral). The pair of tabular yellow-green color crystals *(front right)* from Myanmar exhibit characteristic deeply etched surfaces (Pala International). Photo by Lisbet Thoresen.

The white inclusions in peridot can be interpreted as the result of the reaction:

Forsterite + H2O = Antigorite + Brucite

Thus, these inclusions are the relics of hydrous fluid inclusions and, based on the above reaction, require temperatures above 370ºC at a pressure of 2 kilobars and somewhat higher temperatures with increasing pressure. This is demonstrable proof that the peridot formation at Pyaung-gaung is the result of a hydrous fluid dissolving olivine and precipitating it within cavities. The cavities were probably produced by the same tectonic deformation that uplifted the fault slices of peridotite from the underlying mantle; in what are called tension gashes, as described by Bouilhol et al. in the peridot deposit at Sapat, Pakistan (2012). Consequently, it is clear that Pyaung-gaung peridot shares a similar origin to that of peridot from Sapat and Zabargad Island (Figures 15a,b).

How do these deposits of pocket peridot compare? All clearly show the influence of a hydrous fluid in producing well-formed crystals in pockets, but otherwise there are significant differences. At Zabargad, former fluid inclusions typically contain halite crystals, which have been interpreted as an indication that the fluids were hypersaline, perhaps related to evaporite or dewatered brines. No extant fluid was found in the inclusions. Further work is required on Pyaung-gaung samples to assess the presence of relic salinity, but we have not observed casts of halite in sections or halite crystals in unopened inclusions. At Sapat, borate and carbonate minerals have been found as inclusions and have been interpreted as evidence of fluids derived from subduction zone dewatering. Inclusions with a fluid inside were described but not identified. We have not observed either carbonate or borate minerals in the inclusions from Pyaung-gaung. These differences may reflect the different tectonic histories: rifting at Zabargad, subduction mantle wedge exhumation at Sapat, and lateral displacement and uplift along the Momeik fault. We continue our research on these samples to refine our observations and interpretations.

References

Bender, F. 1983. *Geology of Burma*. Berlin, Gebrüder Borntraeger.

Bouilhol, P., Burg, J-P., Bodinier, J-L.,Schmidt, M.W., and Bernasconi, S.M. 2012. Gem olivine and calcite mineralization precipitated from subduction-derived fluids in the Kohistan arc-mantle (Pakistan). *The Canadian Mineralogist* 50: 1291–1304.

Peridot from Mogok Stone Tract, Myanmar, 4.8 cm high. William F. Larson collection. Photo by Jeffrey A. Scovil.

Bouilhol, P., Burg, J-P., Bodinier, J-L.,Schmidt, M.W., and Bernasconi, S.M. 2012. Gem olivine and calcite mineralization precipitated from subduction-derived fluids in the Kohistan arc-mantle (Pakistan). *The Canadian Mineralogist* 50: 1291–1304.

Evans, B.W. 2010. Lizardite versus antigorite serpentinite: Magnetite, hydrogen, and life(?). *Geology* 38: 879–882.

Iyer, L.A.N. 1953. The geology and gem-stones of the Mogok Stone Tract, Burma. *Memoirs Geol. Surv. India* 82, 100p.

Girnis, A.V., Stachel, T., Brey, G.P., Harris, J.W., and Phillips, D. 1999. Internally consistent geothermobarometers for garnet harzburgites: Model refinement and application. In: *The J.B. Dawson Volume. Proceedings of the VIIth Intl. Kimberlite Conf.*, Capetown, pp. 247–254.

Kurat, G., Palme, H., Embey-Isztin, A., Touret, J., Ntaflos, T., Spettel, B., Brandstätter, F., Palme, C., Dreibus, G., and Prinz, M. 1993. Petrology and geochemistry of peridotites and associated vein rocks of Zabargad Island, Red Sea, Egypt. *Mineralogy and Petrology* 48: 309–341.

OFM Research Site. 2012. Calculate T, log10 fO2 at specified pressure. Available from <http://ctserver.ofm-research.org/Olv_Spn_Opx/index.php>.

PTEXL2_2 is an MS Excel® file including a number of popular mineralogical geothermometers and geobarometers for mantle peridotites: by Andrei Girnis and Thomas Koehler, see: Girnis et al. 1999.

Takla, M.A., Eldougdoug, A.A., Hussein, Abdel Aziz, A., and El-Eraky, F.Y. 1997. Petrogenesis of Zabargad ultramafic rocks and origin of peridot, Zabargad Island, Red Sea, Egypt. *Annals of the Geological Survey of Egypt* 20: 451–478. (These authors do not recognize the influence of a hydrous fluid in the peridot origin, which is inexplicable given the evidence in Kurat et al. 1993).

Themelis, T. 2007. *Gems and Mines of Mogôk: The Forbidden Land.* Bangkok, A&T Press.