Spinel from Mogok, Myanmar—A Detailed Inclusion Study by Raman Microspectroscopy and Scanning Electron Microscopy

Myint Myat Phyo, Eva Bieler, Leander Franz, Walter Balmer and Michael S. Krzemnicki

ABSTRACT: Mineral inclusions within 100 gem-quality spinels from both primary marble and secondary alluvial mining sites within Myanmar's Mogok Valley were analysed using Raman microspectroscopy and scanning electron microscopy (including backscattered-electron imaging and energy-dispersive spectroscopy). The samples ranged from pink to red, orangey pink to orangey red, and grey to purplish grey. We identified a number of inclusions that are reported here for the first time in Mogok spinel: amphibole (presumably pargasite), anatase, baddeleyite, boehmite, brucite, chlorite, clinohumite, clinopyroxene, diaspore, geikielite, goethite, halite, marcasite, molybdenite, periclase and pyrrhotite. We also found several minerals that were previously known as inclusions in Mogok spinel, including anhydrite, apatite, carbonates (calcite, dolomite and magnesite), chondrodite, elemental sulphur, graphite, iron oxides or iron hydroxides, phlogopite and zircon. We further differentiated the occurrence of inclusions in spinel from different mining sites in Mogok to assess whether these mineral assemblages can enhance our understanding of the geological origin of these gems and whether the inclusions can help separate Mogok spinels from those of other marble-related deposits worldwide.

The Journal of Gemmology, **36**(5), 2019, pp. 418–435, http://doi.org/10.15506/JoG.2019.36.5.418

Since ancient times, gem-quality spinel (ideally $MgAl_2O_4$) has been appreciated for its range of colour and often exceptional clarity, and today spinel is the second most important and popular red gemstone after ruby (Cesbron *et al.* 2002; Pardieu *et al.* 2008). Spinel's significance is well illustrated by the famed 'Balas rubies'—which are actually spinels from historic mines in Badakhshan (i.e. Kuh-i-Lal, in what is today Tajikistan)—that were described and praised by the Persian scholar Al-Biruni (973–1048 AD). Exceptional pinkish red spinels were part of the Moghul imperial jewels, two of which were later integrated into British royal jewels (the Black Prince's 'Ruby' and the Timur 'Ruby'; see also Pardieu & Hughes 2008; Yavorskyy & Hughes 2010; Truong 2017).

Spinel may form by high-grade metamorphism in calc-silicate rocks and marbles (Balmer *et al.* 2017) or in skarns (contact zones between Ca-rocks and magmatic intrusions; Gorghinian *et al.* 2013), and is also found in secondary deposits (Thein 2008). It shows a wide variety of colours, mainly pink to red and purple, orange, violet to blue, green and even black. Although sometimes showing greyish or brownish hues, it may also display strong colour saturation, especially in the pink to red range. Moreover, the demand for and value of spinel have increased sharply in recent years. Although known from deposits throughout the world (Myanmar, Sri Lanka, Tanzania, Madagascar and Vietnam, to name a few), some of the finest spinels are found in the Mogok area of Myanmar (e.g. Figure 1). Mogok is one of the world's most eminent gem sources, renowned for producing exceptional rubies, sapphires and other popular stones, as well as rarities such as hibonite, jeremejevite, johachidolite, poudretteite and painite (Iyer 1953; Hughes 1997, 2017b; Themelis 2008).

Although the literature contains some information on inclusions in Burmese spinel (see, e.g., Gübelin & Koivula 1986; Hughes 1997; Themelis 2008; Malsy & Klemm 2010; Zhu & Yu 2018), most publications to date describe Burmese spinel in general (Themelis 2008; Peretti *et al.* 2015), or focus on specific gemmological features (Pardieu 2014; Vertriest & Raynaud 2017) or the oxygen isotope composition of these spinels (Giuliani *et al*. 2017). Several publications deal with inclusions in spinel from worldwide localities (Gübelin & Koivula 1986, 2005; Cooper & Ziyin 2014; Hughes 2017a).

In this study, we describe in detail the solid inclusions found in pink to red, orangey pink to orangey red and grey to purplish grey gem-quality spinels collected from various sites (and local gem markets) in the Mogok area. We found systematic variations in the inclusions related to the different mining sites, suggesting that such inclusion research may be applied to the origin determination of spinels and to separating them from their synthetic flux-grown counterparts (Krzemnicki 2008).

GEOLOGICAL SETTING AND MINING METHODS

Since the 15th century, the Mogok area of Myanmar has been known as a major source of rubies and other gems (Iyer 1953). Often referred to as the 'Mogok Stone Tract' (La Touche 1913; Fermor 1931; Chhibber 1934; Iyer 1953), this gem-rich area is located within the central part of the Mogok Metamorphic Belt. This assemblage is composed of Palaeozoic and Mesozoic high-grade metasediments and intrusive rocks (Searle & Haq 1964; Barley *et al.* 2003; Searle *et al.* 2007; Thu *et al.* 2016; Phyo *et al.* 2017) and forms part of the Mogok-Mandalay-Mergui belt (Figure 2), which extends for more than 2,000 km, north to south, along the western margin of the Shan-Thai (or Sibumasu) terrane, from the Himalayan syntaxis to the Andaman Sea (Bender 1983; Zaw 1990, 2017; Zaw *et al.* 2015). The Mogok Stone Tract is mainly composed of gneiss, marble, calc-silicate rocks and quartzite, which were intruded by various felsic to mafic igneous rocks (Iyer 1953).

Ruby, sapphire, spinel and other gems are mined from primary deposits (calc-silicate rocks and marbles, with spinel only forming in the latter) and from secondary

Figure 1: The spinels in this photo are all from Mogok, Myanmar. The faceted stones range from approximately 7 to 35 ct (not shown to scale). Composite photo by V. Lanzafame, © SSEF.

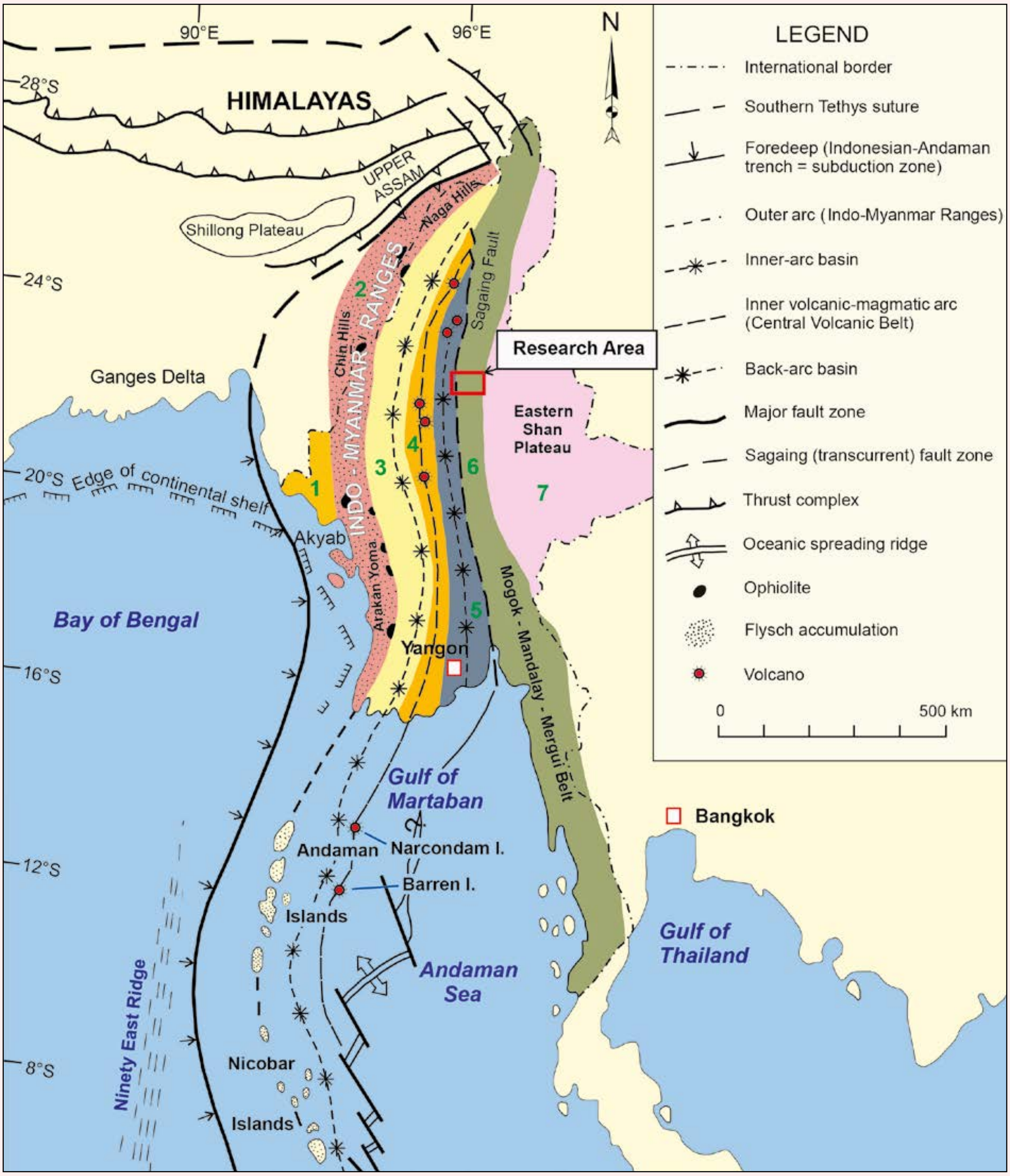


Figure 2: The Mogok research area is indicated on this regional map of Myanmar, which shows the main tectonic domains (numbered 1–7 from west to east) and fault structures (after Bender 1983; Zaw *et al.* 1989, 2015; Zaw 1990). The domains are: (1) Arakan (Rakhine) Coastal Strip, (2) Indo-Myanmar Ranges, (3) Western Inner-Burman Tertiary Basin, (4) Central Volcanic Belt (or Central Volcanic Line), (5) Eastern Inner-Burman Tertiary Basin, (6) Mogok-Mandalay-Mergui Belt and (7) Eastern Shan Highlands.

Figure 3: The main tunnel at the Kyauksaung mine in central Mogok provides an example of spinel extraction from primary (marble) host rocks. Photo © S. Hänsel, 2016.

deposits such as alluvial and eluvial placers, as well as karstic sinkholes and caverns (Thein 2008). To extract the gems from the primary rocks and associated karstic deposits, an extensive network of tunnels (e.g. Figure 3) has been excavated by drilling and blasting. For the secondary deposits, traditional mining methods are used such as *twinlon* (digging shafts in the soil/gravel with a maximum depth of ~30 m), *myawdwin* (hydraulic mining along hillsides; Figure 4) and *ludwin* (mainly used in sinkhole and cavern excavations). In the alluvial plains of the Mogok area, the gem-bearing gravel is usually reached at approximately 6–7 m below the surface (Iyer 1953). Detailed descriptions of the traditional mining methods used in the Mogok area are given in numerous reports (e.g. Gordon 1888; Halford-Watkins 1932a, b, c; Ehrmann 1957; Gübelin 1965; Keller 1983).

MATERIALS AND METHODS

For this study, we collected and analysed 87 pink to red, orangey pink to orangey red and grey to purplish grey gem-quality spinel samples from six mining sites in the Mogok area (Yadanar Kaday Kadar, Bawlongyi, Kyauksin, Kyauksaung, Pyaungpyin and Mansin; see Figure 5) and 13 samples bought in local gem markets. A list of the samples is shown in Table I.

We polished the surface of each spinel to provide a clear view of the interior and then used a standard gemmological microscope (Cambridge Instruments) at 10×–70× magnification to observe mineral inclusions in the samples. Photomicrographs of the inclusions were taken with a Nikon D7000 digital camera attached to a System Eickhorst GemMaster microscope using 16×–80× magnification.

Raman microspectroscopy was performed on the inclusions in each sample using one of two different setups: a Renishaw inVia Raman system coupled with a Leica DM2500 M microscope, using an argon-ion laser at 514.5 nm wavelength; and a Bruker Senterra Raman spectrometer coupled with an Olympus microscope, using a solid-state Nd-YAG laser at 532 nm or a direct diode laser at 785 nm. Raman spectra were mostly collected in the range of 1400–100 cm^{-1}, except for graphite (1600–100 cm^{-1}) and apatite (4000–100 cm^{-1}, to detect water peaks). Maximum exposure time per scan was 10 seconds and 10–50 scan accumulations were collected. Remarkably, there was only minor interference with the fluorescence of spinel. However, we were not able to identify very tiny inclusions with Raman

Figure 4: Hydraulic mining of gem-bearing gravels at Mansin in north-eastern Mogok demonstrates how spinels are obtained from secondary deposits. Photo © M. M. Phyo, 2016.

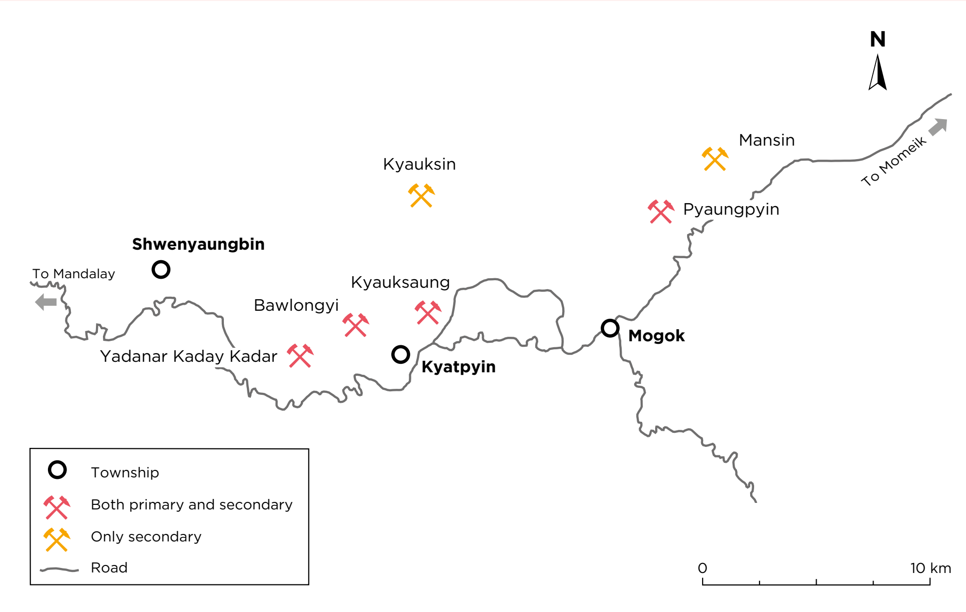
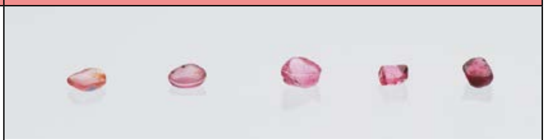
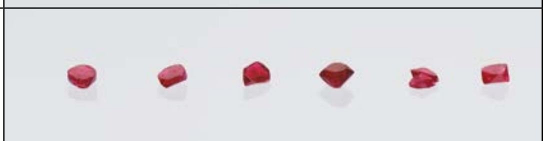


Figure 5: The mining locations from which spinel samples were obtained for this study (the 'research area' shown in Figure 2) are plotted on this map of the Mogok area.

Table I: Mogok spinel samples investigated for this study.

Location*	Coordinates	No. samples	Weight range	Colour	Photo
Yadanar Kaday Kadar	22°54′18.54″N 96°22′38.18″E	5	0.18–0.35 ct	Orangey pink, light pink to red	
Bawlongyi	22°54′53.59″N 96°23′53.09″E	19	0.16–2.21 ct	Light pink to red, dark red, orange to orangey red, grey, purplish grey	
Kyauksin	22°57′26.51″N 96°25′31.63″E	17	0.45–1.24 ct	Light orange to orange, purplish grey	
Kyauksaung	22°55′20.08″N 96°25′55.44″E	10	0.10–0.62 ct	Light orange to orange, grey to purplish grey	
Pyaungpyin	22°57′13.53″N 96°31′10.63″E	6	0.45–0.67 ct	Intense red	
Mansin	22°58′28.64″N 96°32′23.57″E	30	0.05–2.59 ct	Light pink to strong pink, red to dark red	
Market	–	13	0.54–8.65 ct	Light pink to dark red, grey	

* Sample locations (top to bottom) are arranged from west to east. Photos by M. M. Phyo.

microspectroscopy due to their small size. In addition, some inclusions produced Raman spectra of superposed combinations of two or more minerals, while others did not reveal a conclusive spectrum (probably because their weak Raman signal was dominated by the signal from the host spinel).

Scanning electron microscopy (SEM) was used to gain more information about selected mineral inclusions by visualising their shape and paragenetic intergrowths. In addition, SEM with energy-dispersive X-ray spectroscopy (EDS) was used to analyse their chemical composition. To accomplish this, the samples were carefully polished to expose the inclusions at the surface, and were then analysed at the Nano Imaging Lab of the University of Basel using a REM-FEI Nova NanoSEM 230 unit equipped with an energy-dispersive spectrometer and both secondary-electron (SE) and backscattered-electron (BSE) imaging modes. This system employed an in-lens detector for producing secondary-electron images and an Octane Elite detector for EDS analysis. With this setup, we were able (in principle) to detect elements ranging from carbon to uranium as long as they were above the instrumental detection limit. We used an accelerating voltage of 15 kV, with magnifications of 50×–2,500× and a working distance of 4.0–12.5 mm.

RESULTS

The solid inclusions that we identified in the Mogok spinels are listed in Table II, along with those identified

Table II: Alphabetical list and abundance of solid inclusions in Mogok spinels documented in the present study and compared with previously published work and other localities.

Mineral	Mogok area		Other localities				
	Present study[1]	Previous studies[2]	Vietnam	Tajikistan	Tanzania	Madagascar	Sri Lanka
Amphibole (presumably pargasite)	xxx	—	—	—	—	—	—
Anatase	x	—	—	—	—	—	—
Anhydrite	x	3	—	—	—	—	—
Apatite	xxx	1, 2, 3, 6, 7	1, 3	—	1	1	1, 7
Baddeleyite	x	—	—	—	—	—	—
Boehmite	x	—	—	—	—	—	1
Brucite	x	—	—	—	—	—	—
Calcite	xxxxx	3, 6, 7	3	—	—	—	1
Chlorite	x	—	—	—	—	—	—
Chondrodite	xxxxx	3	—	—	—	—	—
Clinohumite	x	—	—	—	—	—	—
Clinopyroxene	xxx	—	—	—	—	1	—
Diaspore	x	—	—	—	—	—	1
Dolomite	xxxxx	1, 3, 6	3	—	—	—	1
Geikielite	xxx	—	—	—	—	—	—
Goethite	x	—	1	—	—	—	—
Graphite	x	1, 3	3	—	—	—	1
Halite	x	—	—	—	—	—	—
Ilmenite	—	1	—	—	1	—	—
Magnesite	xxx	3	3	—	—	—	—
Marcasite	x	—	—	—	—	—	—
Molybdenite	x	—	—	—	—	—	—
Olivine (forsterite)	x	1	—	—	1	—	1
Periclase	x	—	—	—	—	—	—
Phlogopite	xxx	1	—	—	1	—	1
Potassium feldspar	—	3	3	—	—	—	1
Pyrite	—	1	—	—	—	—	1
Pyrrhotite	x	—	—	—	—	—	1
Quartz	—	1	—	—	—	—	1
Rutile	—	1	—	—	1	1	1
Sulfur	xxxxx	4, 5, 7	—	—	—	—	—
Titanite	—	1	3	—	—	—	1
Uraninite	—	1	—	—	1	—	1
Zircon	x	2	3	3	—	—	1

[1] Abbreviations: xxxxx = frequently seen; xxx = sometimes encountered; x = rarely found; — = not found.
[2] References: 1 = Gübelin & Koivula (1986, 2005); 2 = Themelis (2008); 3 = Malsy & Klemm (2010); 4 = Pardieu *et al.* (2016); 5 = Peretti *et al.* (2017); 6 = Zhu & Yu (2018); 7 = www.lotusgemology.com (accessed June 2018).

by other researchers in the published literature for spinels from Mogok and various deposits worldwide. The Raman spectra of representative inclusions that we identified are available in the Appendix at the end of this article, and photomicrographs and BSE images of the inclusions are shown below. Mineral abbreviations in these images are from Whitney & Evans (2010).

In general, most of the inclusions formed anhedral grains, although some of them (such as amphibole and phlogopite) showed subhedral to euhedral shapes. Inclusion sizes commonly ranged from 1 μm to several millimetres. Their wide range of composition is reflected in the presence of several mineral groups (silicate, oxide, hydroxide, carbonate, phosphate, sulphate, sulphide and native element).

Figure 6: An example of carbonate inclusions observed in the Mogok spinel samples is shown here by magnesite (Mgs). Photomicrograph by M. M. Phyo.

Optical Microscopy and Raman Analysis

Since Mogok spinels formed in marbles, it was not surprising to find abundant carbonates (i.e. calcite, dolomite and magnesite; e.g. Figure 6) in most of the samples. They were typically present as colourless, irregularly shaped (partially resorbed) inclusions. Raman microspectrometry further revealed that carbonates sometimes also occurred as filling substances in octahedral negative crystals (similar to calcite and dolomite found by Zhu & Yu 2018).

A range of Ca- and Mg-bearing silicates was found in the investigated spinels. The humite-group minerals chondrodite [$(Mg,Fe^{2+})_5(SiO_4)_2(F,OH)_2$] and clinohumite [$Mg_9(SiO_4)_4F_2$] were the most abundant Mg-silicates in our samples (Figure 7). A colourless, short-prismatic Ca-Mg amphibole (presumably pargasite; Figure 8a) and clinopyroxenes (diopside and augite) were found in spinels from both Kyauksin and Mansin. Figure 8b reveals a colourless clinopyroxene inclusion with distinct cleavage that is associated with minute yellow elemental sulphur and black marcasite grains in a spinel from Mansin. In accordance with Gübelin & Koivula (2005), we also found forsterite, the Mg end member of the olivine group, as colourless rounded crystals (Figure 8c) in a few Mogok spinels. However, we did not find titanite and feldspar in our samples, both of which were mentioned by Gübelin & Koivula (2005) in spinel from Mogok. Zircon, although a common inclusion in sapphires and rubies from Mogok, was found only as tiny accessory inclusions in a few spinels from Kyauksin and Kyauksaung.

Oxides were commonly present as accessory phases in the studied spinels. We found yellow, rounded anatase (TiO_2) and yellow, prismatic baddeleyite (ZrO_2) inclusions, both surrounded by tension cracks (Figure 9a, b). Interestingly, using SEM-EDS we identified geikielite ($MgTiO_3$) as tiny needles/lamellae in spinel from Yadanar Kaday Kadar (western Mogok; Figure 9c). They were oriented along {111} lattice planes and

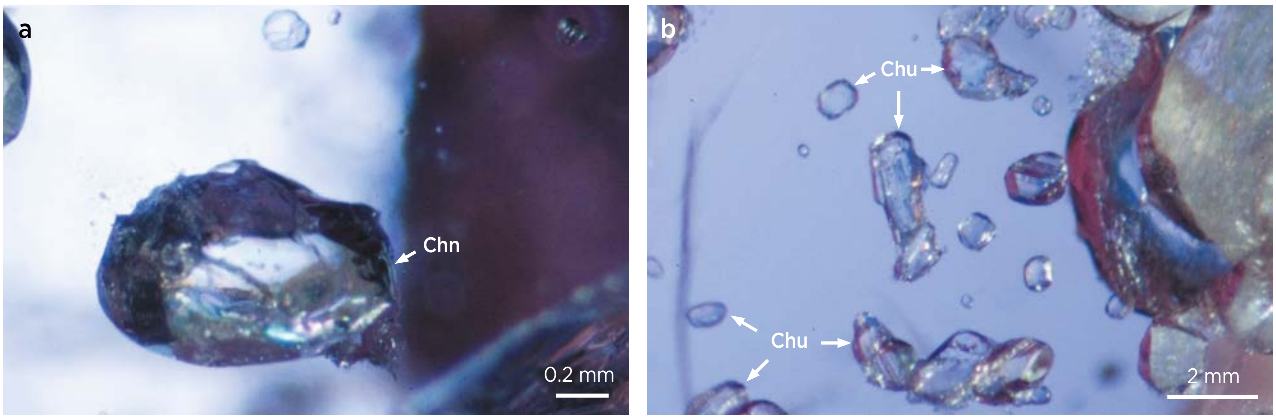


Figure 7: Among the silicate inclusions that were identified, humite-group minerals were common in some of the spinels: (**a**) anhedral chondrodite (Chn) and (**b**) a cluster of subhedral clinohumite (Chu) crystals. Photomicrographs by M. M. Phyo.

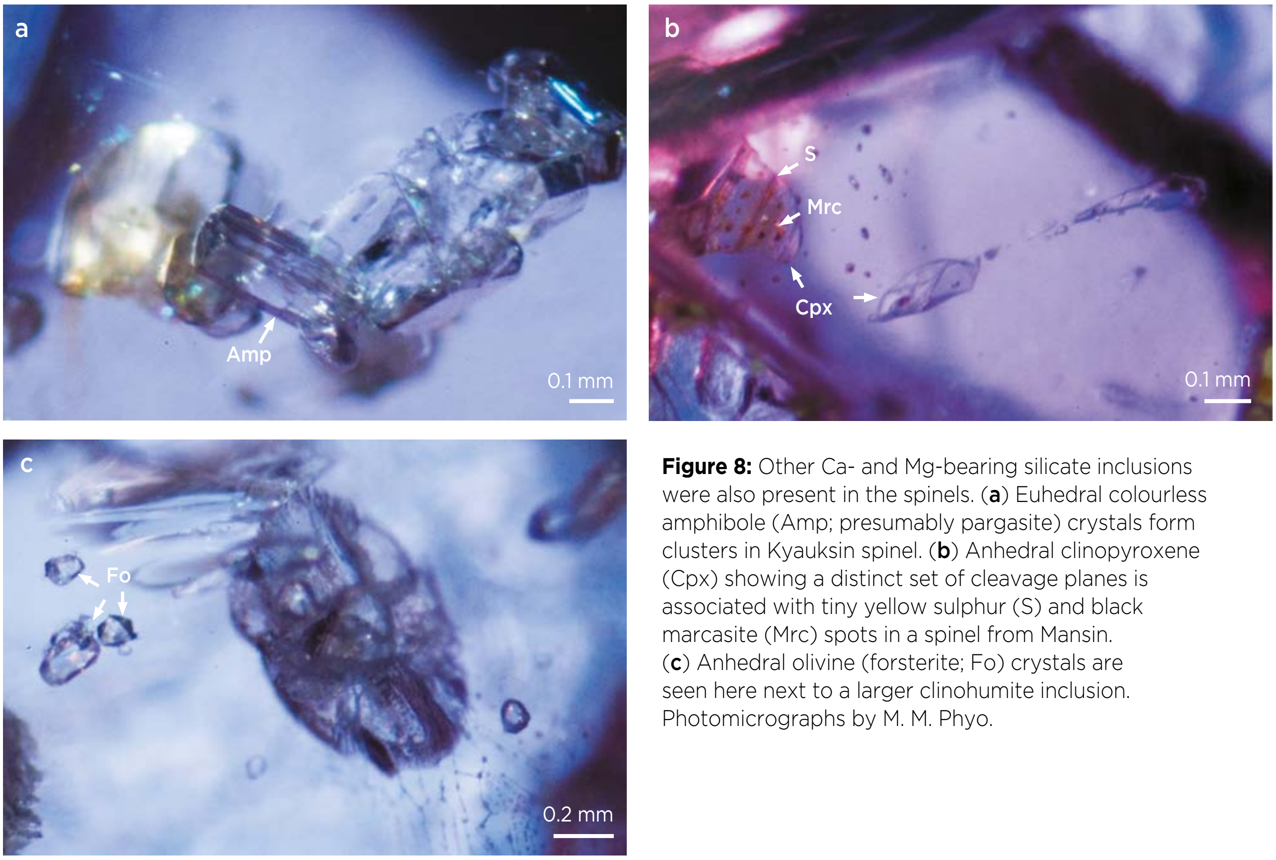


Figure 8: Other Ca- and Mg-bearing silicate inclusions were also present in the spinels. (**a**) Euhedral colourless amphibole (Amp; presumably pargasite) crystals form clusters in Kyauksin spinel. (**b**) Anhedral clinopyroxene (Cpx) showing a distinct set of cleavage planes is associated with tiny yellow sulphur (S) and black marcasite (Mrc) spots in a spinel from Mansin. (**c**) Anhedral olivine (forsterite; Fo) crystals are seen here next to a larger clinohumite inclusion. Photomicrographs by M. M. Phyo.

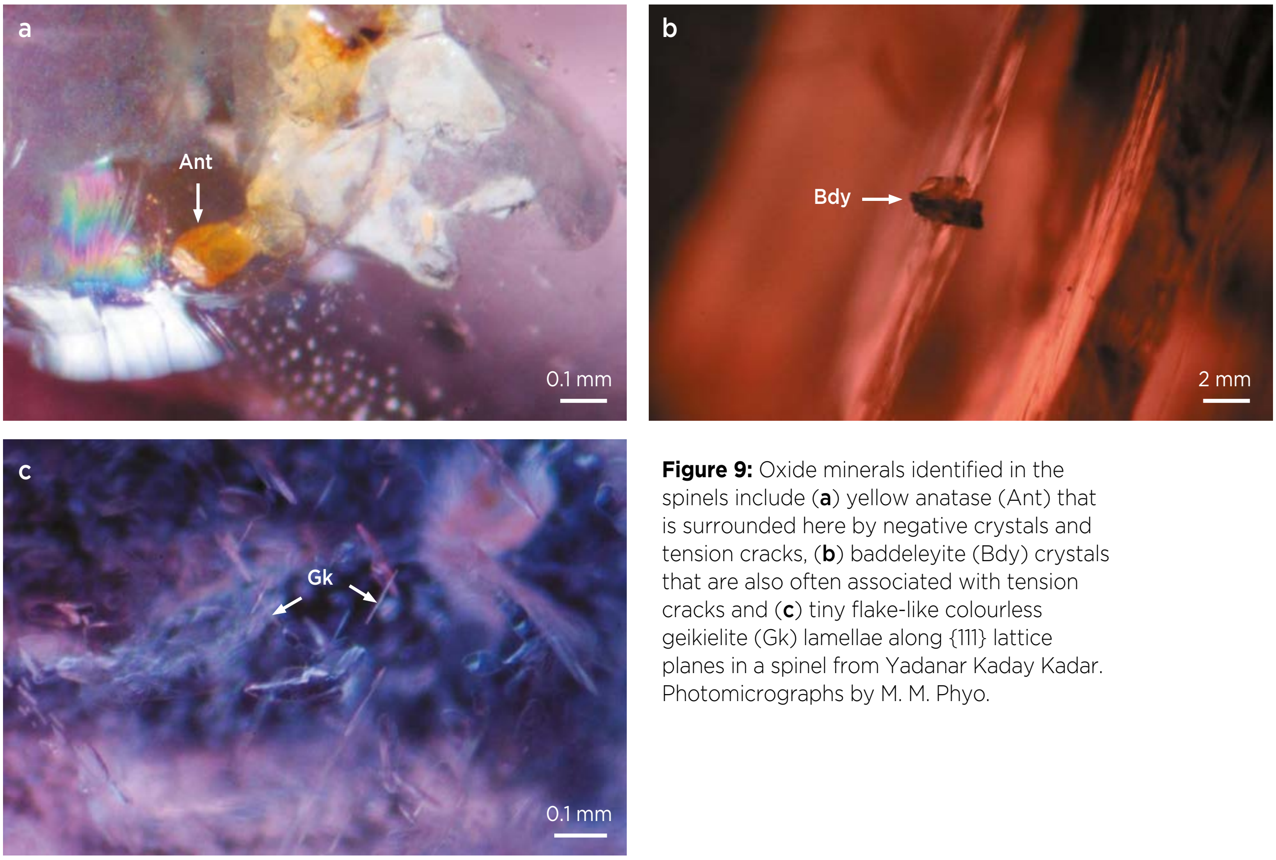


Figure 9: Oxide minerals identified in the spinels include (**a**) yellow anatase (Ant) that is surrounded here by negative crystals and tension cracks, (**b**) baddeleyite (Bdy) crystals that are also often associated with tension cracks and (**c**) tiny flake-like colourless geikielite (Gk) lamellae along {111} lattice planes in a spinel from Yadanar Kaday Kadar. Photomicrographs by M. M. Phyo.

presumably formed by epigenetic exsolution, similar to geikielite-rich ilmenite exsolution lamellae seen in chromite-chrome spinel from metacarbonates in Austria (Mogessie *et al.* 1988). To our knowledge, this is the first time such geikielite exsolution lamellae have been reported in gem-quality spinel.

We also found several hydroxides in our spinels, including diaspore [α-AlO(OH)], boehmite [γ-AlO(OH)], brucite [$Mg(OH)_2$] and goethite [α-$Fe^{3+}O(OH)$]. They probably formed as retrograde phases, and were present in secondary inclusion trails (boehmite) or associated with phlogopite (brucite) or pyrrhotite (goethite).

Additional accessory inclusions in our spinels included anhydrite ($CaSO_4$, also known from Mogok rubies; Smith & Dunaigre 2001), apatite [$Ca_5(PO_4)_3$(F,Cl,OH)], sulphides (marcasite, molybdenite and pyrrhotite), graphite (C) and elemental sulphur (S_8). Apatite was seen as transparent to semi-transparent, anhedral to subhedral crystals (Figure 10). As for the elemental sulphur, its presence within fluid inclusions and as solid inclusions (Figure 11) seems to be highly characteristic for spinels from Mansin (Pardieu *et al.* 2016; Peretti *et al.* 2017). Less commonly, we also found elemental sulphur in the spinels from Kyauksaung and Pyaungpyin.

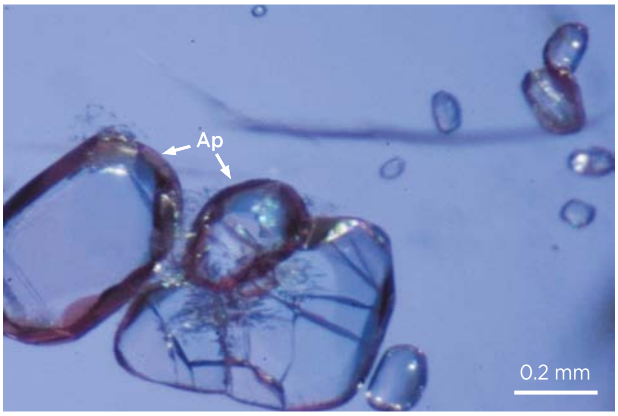


Figure 10: Rounded anhedral apatite (Ap) inclusions are present in this Mogok spinel. Photomicrograph by M. M. Phyo.

Figure 11: Solid inclusions of elemental sulphur (S) are seen here with multiphase fluid inclusions (probably containing liquid and sulphur) in a spinel from Mansin. Photomicrograph by M. M. Phyo.

SEM Imaging and EDS Analysis

Using SEM-EDS, it was possible to visualise and identify for the first time the complex intergrowth of multiphase inclusions (some containing small fluid cavities) within spinel from Mogok. These assemblages consisted of various minerals such as calcite ($CaCO_3$), dolomite [$CaMg(CO_3)_2$], halite (NaCl), phlogopite [$KMg_3(AlSi_3O_{10})(F,OH)_2$], apatite and/or anhydrite of sugary texture (Figure 12). They were similar to the inclusions containing residues of molten salts described by Giuliani *et al.* (2015) in rubies from Mogok.

SEM-EDS also revealed other inclusion features in the spinels. A euhedral amphibole inclusion contained

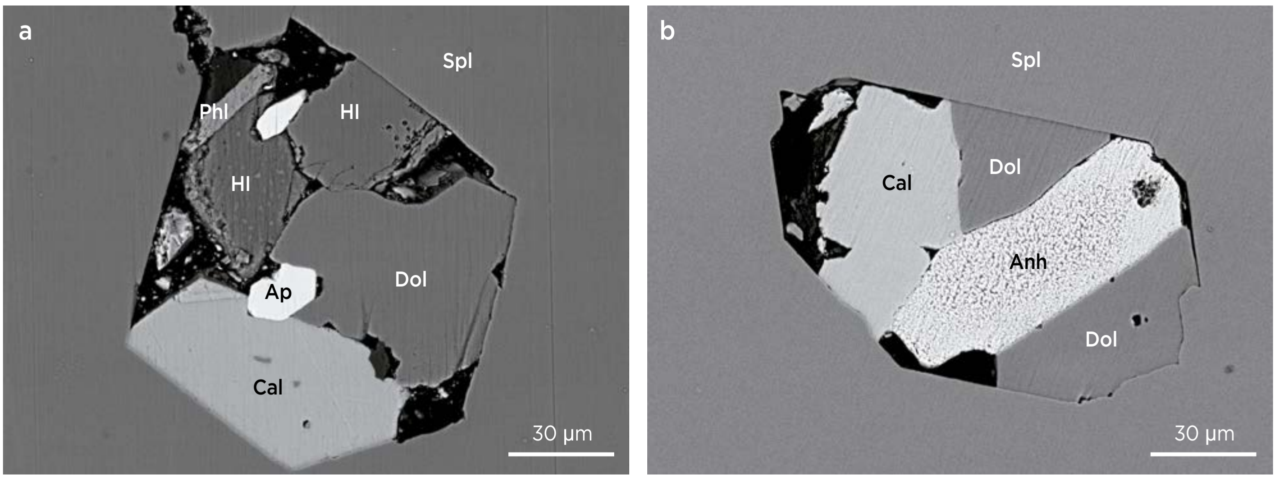


Figure 12: BSE images reveal the contents of multiphase inclusions in Mogok spinel (Spl): (**a**) calcite (Cal), dolomite (Dol), halite (Hl), phlogopite (Phl) and apatite (Ap); and (**b**) calcite, dolomite and anhydrite (Anh).

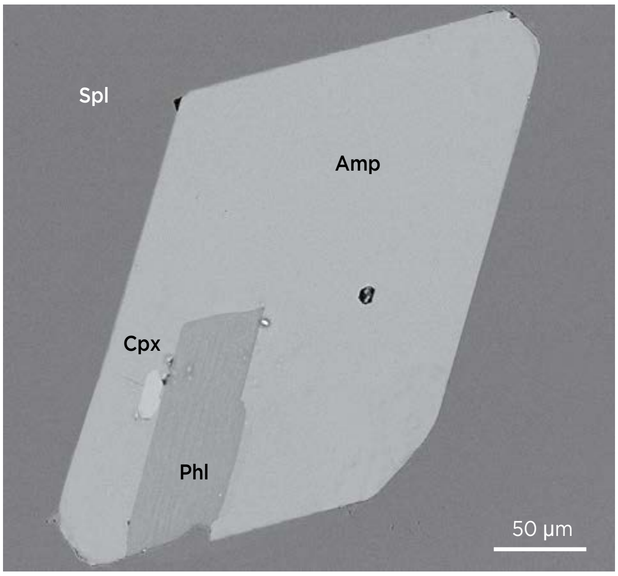


Figure 13: BSE imaging shows that a euhedral amphibole (Amp) inclusion in a spinel from Kyauksin contains inclusions of phlogopite (Phl) and clinopyroxene (Cpx).

clinopyroxene and phlogopite domains in a spinel from Kyauksin (Figure 13). We also imaged some phases that presumably exsolved from their hosts: dolomite blebs in certain calcite inclusions (Figure 14a) and the geikielite lamellae in spinel (Figure 14b) that were mentioned above. Furthermore, rare accessory inclusions of baddeleyite (also mentioned above) were easily visible with the SEM (Figure 15).

Various secondary mineral inclusions were identified with SEM-EDS, such as chlorite and brucite together with a phlogopite inclusion (Figure 16a), and a bright red powder-like substance that proved to be an iron compound (e.g. an Fe oxide or hydroxide, probably goethite) that formed an epigenetic encrustation along the cleavages and boundaries of a phlogopite inclusion (Figure 16b).

DISCUSSION

In the present study, we not only confirmed the presence of most inclusions previously described in the literature for Burmese spinel, but also identified for the first time 16 new solid inclusions in our samples from Mogok: amphibole (presumably pargasite), anatase, baddeleyite, boehmite, brucite, chlorite, clinohumite, clinopyroxene, diaspore, geikielite, goethite, halite, marcasite, molybdenite, periclase and pyrrhotite (see Table II).

Interestingly, we did not observe in our study any 'belly button' apatite inclusions that are considered typical for spinel from Mogok (Gübelin & Koivula 1986, 2005). These inclusions are characterised by a tiny black graphite or ilmenite platelet attached to rounded apatite. As previously described by Malsy & Klemm (2010), we only observed in our samples subhedral to anhedral colourless apatite crystals as individuals or clusters.

We also documented for the first time in gem-quality spinel multiphase inclusions (Figure 12) with small fluid cavities, which may be interpreted as residues of molten salts (Giuliani *et al.* 2003, 2015, 2018; Peretti *et al.* 2017, 2018). Their assemblages are reflective of paragenetic relationships within the host rock (e.g. calcite-dolomite-phlogopite-apatite). Some of the spinel inclusions also demonstrate mineral exsolution (e.g. oriented geikielite lamellae in Figures 9c and 14b) and retrograde transformations after spinel formation (e.g. the breakdown of phlogopite to chlorite, brucite and Fe oxides/hydroxides; see Figure 16; Yau *et al.* 1984).

We observed carbonate inclusions in our spinels from all mining locations sampled in the Mogok area. Some of these carbonate inclusions did not occur as a single mineral phase but were present within multiphase inclusions (Figure 12) and possibly as exsolved assemblages

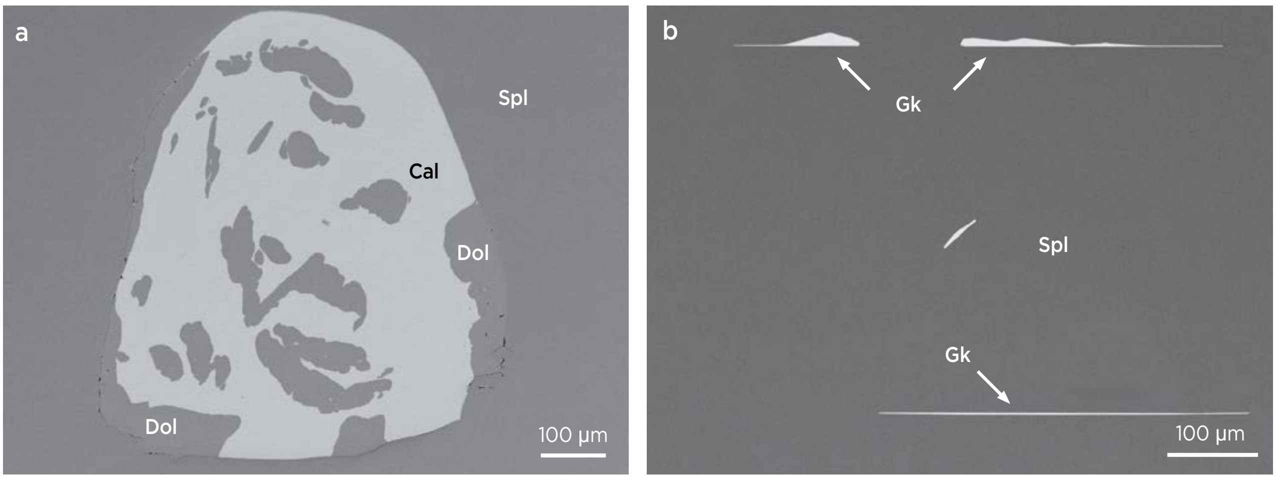


Figure 14: Evidence of exsolved mineral phases in Mogok spinels is seen in these BSE images of (**a**) dolomite (Dol) blebs in a calcite (Cal) inclusion and (**b**) oriented geikielite (Gk) lamellae.

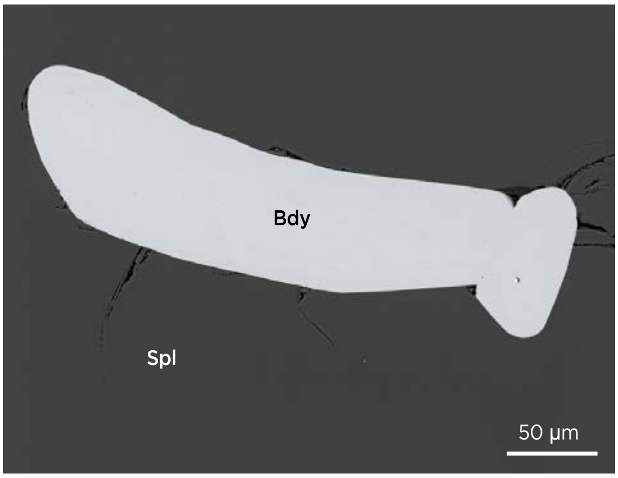


Figure 15: A baddeleyite (Bdy) inclusion with tension cracks shows high contrast against the host spinel in this BSE image.

(Figure 14a). In a few cases, such carbonates were also found in negative-crystal cavities. Moreover, the presence in spinel of various silicates such as amphibole (presumably pargasite), chondrodite, clinohumite and zircon—similar to the carbonate inclusions—reflects the compositional range of the host-rock marbles with interlayered calc-silicates in which these spinels from the Mogok area were formed.

The complex metamorphic evolution of the Mogok Stone Tract during the Himalayan orogeny is connected to and influenced by several magmatic events (Barley *et al.* 2003; Searle *et al.* 2007). Geographically and geologically, all of the spinel localities that were sampled for this study (primary marbles and secondary deposits) were found in close proximity to granite intrusions (Thu 2007). Mineral inclusions such as anatase, olivine, clinopyroxene, periclase and chondrodite could have formed either during granulite-facies regional metamorphism (Thu 2007; Phyo *et al.* 2017; Thu & Zaw 2017) or by contact metamorphism from the nearby intrusions. Remarkable is the prevalence of elemental sulphur and graphite in spinel from Mansin (Gübelin & Koivula 2005; Pardieu 2014; Vertriest & Raynaud 2017), which points to highly reducing conditions. Moreover, the multiphase inclusions with small fluid cavities that we observed in our Mogok spinels showed similarities to hypersaline fluid inclusions in Mansin spinel (Peretti *et al.* 2017, 2018) and to the residues of molten salts found in Mogok ruby (Giuliani *et al.* 2015).

We also sought to investigate whether it is possible to separate spinels from different locations within the Mogok Stone Tract based on their inclusions (see Figure 17; see also the sample locations in Figures 5 and 18). Although the number of samples (87, not including those obtained from local markets) and inclusions (about 400) that were analysed might not be sufficient, we can still report meaningful results. Similar to Themelis (2008) and Malsy & Klemm (2010), and as expected for marble-related spinels, we observed an abundance of carbonate inclusions in spinels from all of the studied localities. Closely related are impurities in the marble host rock—graphite, apatite and phlogopite—which were present in spinels from nearly all of the localities, although in distinctly smaller quantities. Additional inclusion phases were observed in spinel from a few localities, such as elemental sulphur (most prominently from Mansin but also from Pyaungpyin and Kyauksaung), anatase (Yadanar Kaday Kadar, Kyauksin and Kyauksaung) and chondrodite (Bawlongyi, Kyauksaung and Mansin). In contrast, a number of inclusions were found only in samples from one locality, such

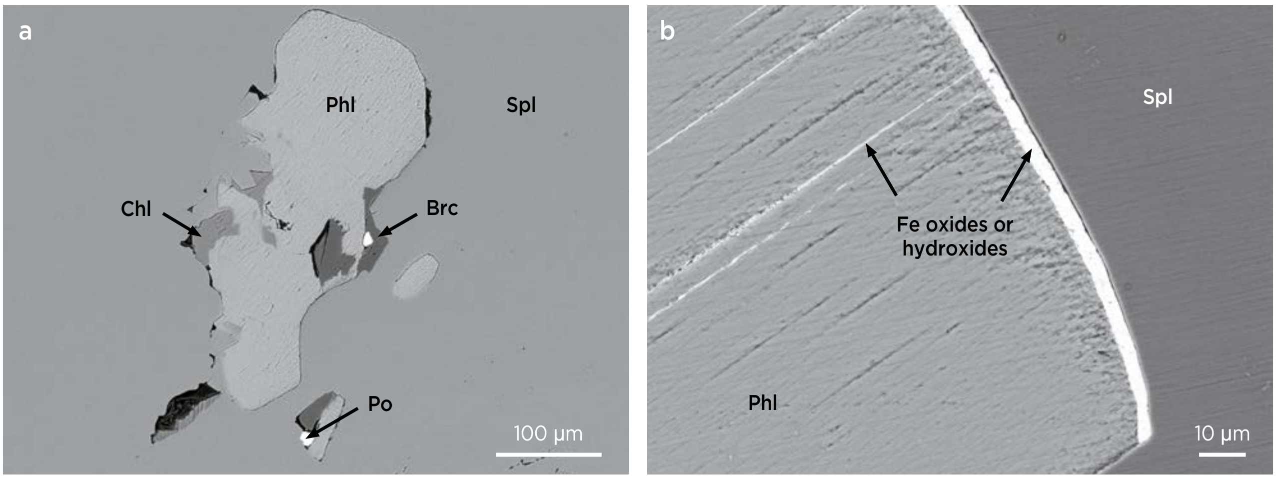


Figure 16: BSE imaging showed various secondary mineral assemblages associated with phlogopite (Phl) in Mogok spinel. (**a**) Phlogopite inclusions with tiny pyrrhotite (Po) grains are intergrown with the secondary minerals brucite (Brc) and chlorite (Chl). (**b**) Secondary Fe oxides or hydroxides are seen as bright areas along the rim and within cleavages in this phlogopite inclusion.

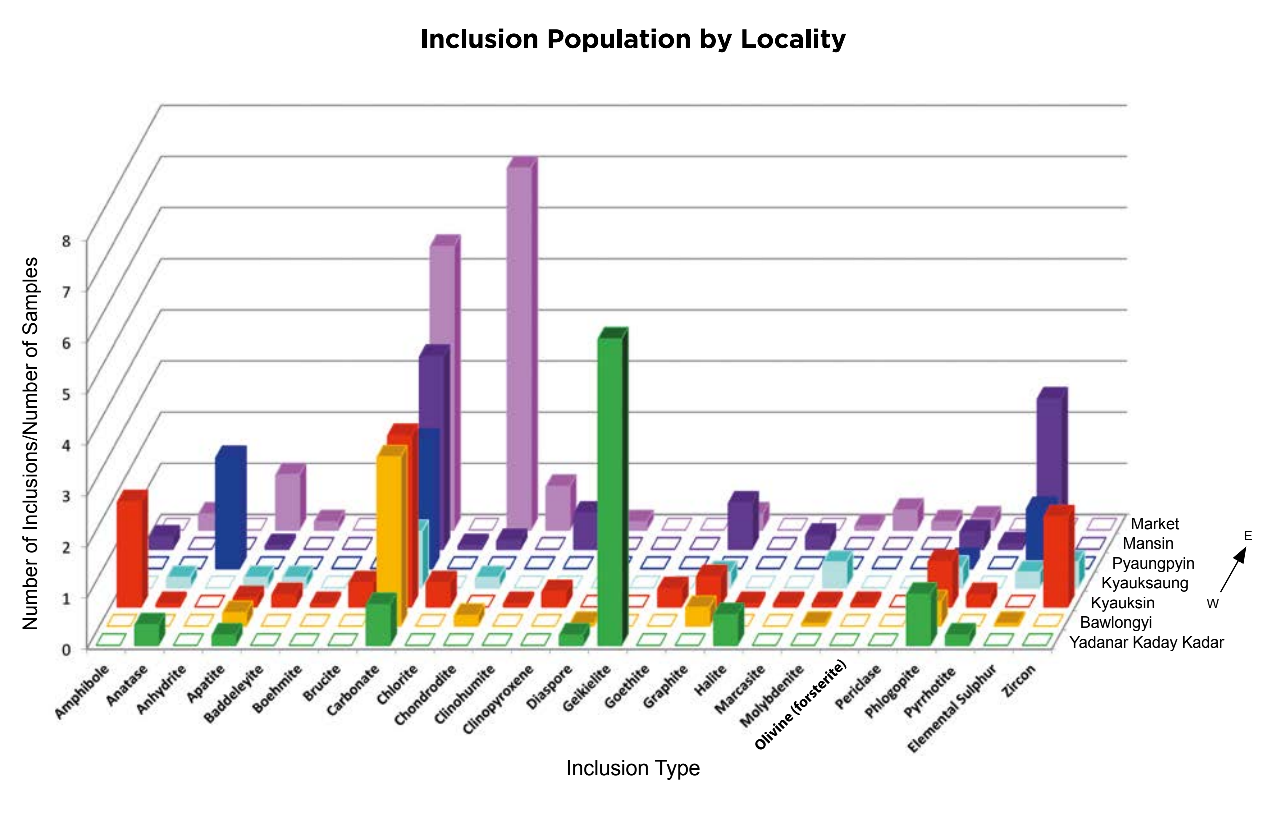


Figure 17: To express the relative amount of inclusions found in spinel from various mining sites (and local markets) in the Mogok region of Myanmar, the total number of observed inclusions was divided by the number of samples from that location. The distribution of the different inclusion types suggests that, with further research, they could be helpful for distinguishing spinels from certain localities.

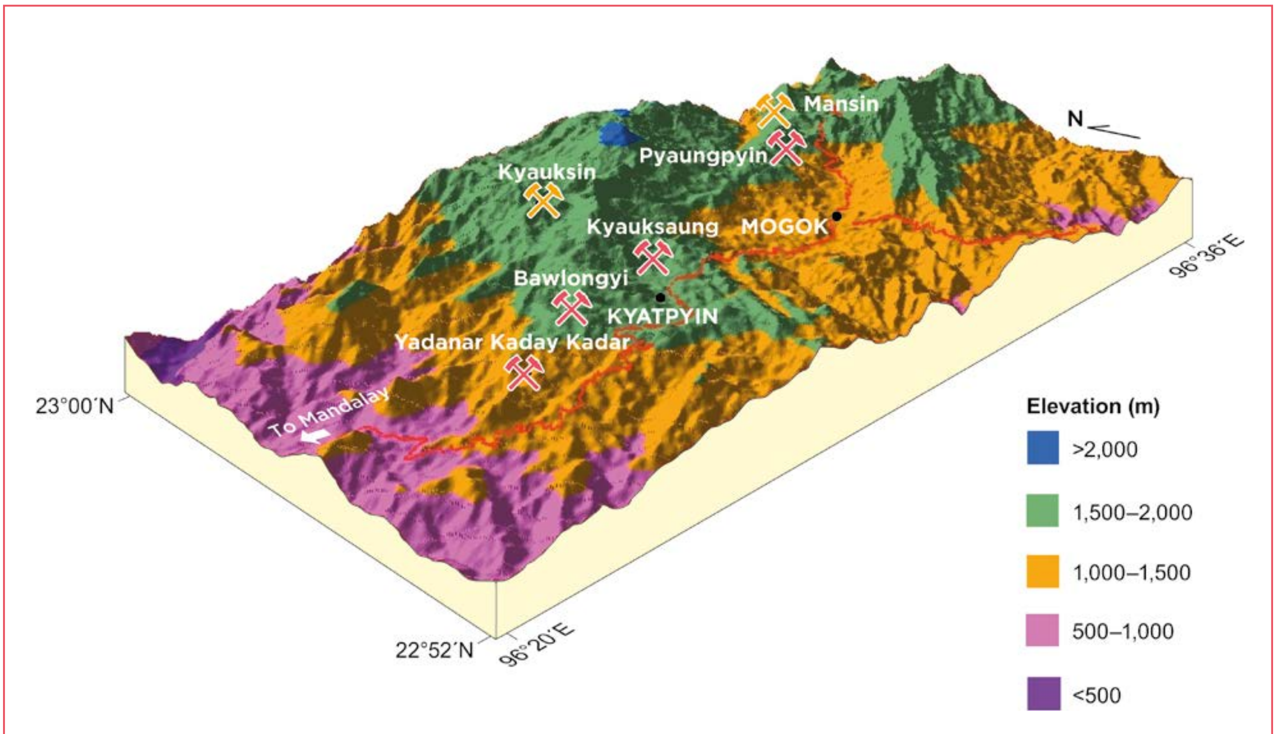


Figure 18: The mine sites sampled for this study are shown on this three-dimensional map of the Mogok area. Most of them are situated at elevations ranging from 1,500 to 2,000 m. The colouration of the mine symbols is explained in Figure 5. Spatial data are based on topographic maps of Northern Shan State and the Katha District (93 B-5 and 93 B-9, scale 1" = 1 mile, 1945).

as goethite (Kyauksin), anhydrite (Pyaungpyin) and geikielite lamellae (Yadanar Kaday Kadar). Whether these findings are truly specific to these locations or just the result of the limited sampling is presently unknown. Nevertheless, the assemblages documented in spinel from Mogok and elsewhere are clearly different from the inclusions seen in synthetic flux-grown spinel (Krzemnicki 2008), and therefore are useful for separating natural spinels from their synthetic counterparts.

CONCLUSION

This study presents the first detailed description of inclusions in spinel from Mogok, Myanmar. It documents several solid inclusions for the first time in these spinels, as well as multiphase assemblages (some containing small fluid cavities) that add to their complexity. All of the mineral inclusions are related to the local geology and geochemistry of the host rocks in the Mogok area. Spinel and its associated minerals such as ruby, diopside, olivine, chondrodite and clinohumite testify to granulite-facies metamorphic conditions in the Mogok Metamorphic Belt (Thu *et al.* 2016; Phyo *et al.* 2017). Elemental sulphur and graphite inclusions furthermore indicate highly reducing conditions during the formation of these spinels. The generation of gem-quality spinel by skarn-forming processes can be excluded due to the absence of typical skarn mineral inclusions (e.g. vesuvianite, pectolite or nephrite) in our samples.

Based on the data presented in this article, the authors feel that such inclusion studies can help distinguish Mogok spinels from those of other sources worldwide (e.g. Figure 19), and therefore contribute to the origin determination of spinels in gemmological laboratories. We expect that further studies of spinel inclusions in the future will add to this knowledge.

Figure 19: Detailed inclusion studies may be helpful toward geographic origin determinations of spinel from various world localities, such as those shown here. All of the crystals are from Mogok, and the cut stones are from Tanzania (7.31 ct pink oval), Tajikistan (5.90 ct pink cushion), Vietnam (all pear shapes, up to 3.22 ct) and Mogok (4.01 and 2.63 ct red cushions). Photo by Prasit Prachagool, Thai Lanka Trading Ltd Part., Bangkok, Thailand.

REFERENCES

Balmer, W.A., Hauzenberger, C.A., Fritz, H. & Sutthirat, C. 2017. Marble-hosted ruby deposits of the Morogoro region, Tanzania. *Journal of African Earth Sciences*, **134**, 626–643, https://doi.org/10.1016/j.jafrearsci.2017.07.026.

Barley, M.E., Pickard, A.L., Zaw, K., Rak, P. & Doyle, M.G. 2003. Jurassic to Miocene magmatism and metamorphism in the Mogok Metamorphic Belt and the India-Eurasia collision in Myanmar. *Tectonics*, **22**(3), article no. 1019, 11 pp., http://doi.org/10.1029/2002tc001398.

Bender, F. 1983. *Geology of Burma*. Gebrüder Borntraeger, Berlin, Germany, 295 pp.

Cesbron, F., Lebrun, P., Le Cléac'h, J.-M., Notari, F., Grobon, C. & Deville, J. 2002. Corindon et spinelles. *Minéraux & Fossiles,* Special Issue No. 15, 105 pp.

Chhibber, H.L. 1934. *The Geology of Burma*. Macmillan and Co. Ltd, London, 538 pp.

Cooper, A. & Sun, Z. 2014. Lab Notes: Spinel inclusion in spinel. *Gems & Gemology*, **50**(4), 293–301.

Ehrmann, M. 1957. Gem mining in Burma. *Gems & Gemology*, **9**(1), 2–30.

Fermor, L.L. 1931. General report for the Geological Survey of India, 1930. *Records of the Geological Survey India*, **65**, 445–456.

Giuliani, G., Dubessy, J., Banks, D., Hoàng Quang Vinh, Lhomme, T., Pironon, J., Garnier, V., Phan Trong Trinh, Pham Van Long, Ohnenstetter, D. & Schwarz, D. 2003. CO_2–H_2S–COS–S_8–AlO(OH)-bearing fluid inclusions in ruby from marble-hosted deposits in Luc Yen area, North Vietnam. *Chemical Geology*, **194**(1–3), 167–185, http://doi.org/10.1016/s0009-2541(02)00276-0.

Giuliani, G., Dubessy, J., Banks, D.A., Lhomme, T. & Ohnenstetter, D. 2015. Fluid inclusions in ruby from Asian marble deposits: Genetic implications. *European Journal of Mineralogy*, **27**(3), 393–404, http://doi.org/10.1127/ejm/2015/0027-2442.

Giuliani, G., Fallick, A.E., Boyce, A.J., Pardieu, V. & Pham, V.L. 2017. Pink and red spinels in marble: Trace elements, oxygen isotopes, and sources. *Canadian Mineralogist*, **55**(4), 743–761, https://doi.org/10.3749/canmin.1700009.

Giuliani, G., Dubessy, J., Ohnenstetter, D., Banks, D., Branquet, Y., Feneyrol, J., Fallick, A.E. & Martelat, J.-E. 2018. The role of evaporites in the formation of gems during metamorphism of carbonate platforms: A review. *Mineralium Deposita*, **53**(1), 1–20, http://doi.org/10.1007/s00126-017-0738-4.

Gordon, R. 1888. On the ruby mines near Mogok, Burma. *Proceedings of the Royal Geographical Society and Monthly Record of Geography*, **10**(5), 261–275, http://doi.org/10.2307/1801309.

Gorghinian, A., Mottana, A., Rossi, A., Oltean, F.M., Esposito, A. & Marcelli, A. 2013. Investigating the colour of spinel: 1. Red gem-quality spinels ("balas") from Ratnapura (Sri Lanka). *Rendiconti Lincei*, **24**, 127–140.

Gübelin, E. 1965. The ruby mines in Mogok in Burma. *Journal of Gemmology*, **9**(12), 411–425, http://doi.org/10.15506/JoG.1965.9.12.411.

Gübelin, E.J. & Koivula, J.I. 1986. *Photoatlas of Inclusions in Gemstones*. ABC Edition, Zurich, Switzerland, 532 pp.

Gübelin, E.J. & Koivula, J.I. 2005. *Photoatlas of Inclusions in Gemstones,* Vol. 2. Opinio Publishers, Basel, Switzerland, 829 pp.

Halford-Watkins, J.F. 1932a. The ruby mines of upper Burma: A short history of their working. *The Gemmologist*, **1**(9), 263–272.

Halford-Watkins, J.F. 1932b. Methods of ruby mining in Burma. *The Gemmologist*, **1**(11), 335–342.

Halford-Watkins, J.F. 1932c. Methods of ruby mining in Burma: Washing, grading and selling the stones. *The Gemmologist*, **1**(12), 367–373.

Hughes, E.B. 2017a. Beyond octahedra: Inclusions in spinel. *Journal of the Gemmological Association of Hong Kong*, **38**, 41–44, www.gahk.org/journal/GAHK_Journal_2017_v5.pdf.

Hughes, R.W. 1997. *Ruby & Sapphire*. RWH Publishing, Bangkok, Thailand, 511 pp.

Hughes, R.W. 2017b. *Ruby & Sapphire: A Gemologist's Guide*. RWH Publishing, Bangkok, Thailand, 816 pp.

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

Keller, P.C. 1983. The rubies of Burma: A review of the Mogok Stone Tract. *Gems & Gemology*, **19**(4), 209–219, http://doi.org/10.5741/gems.19.4.209.

Krzemnicki, M.S. 2008. Trade Alert: Flux-grown synthetic red spinels on the market. *SSEF Newsletter*, No. 14, October, 3 pp, www.ssef.ch/wp-content/uploads/2018/03/2008_Krzemnicki_Trade_Alert_-_Flux_grown_synthetic_red_spinels_again_on_the_market.pdf.

La Touche, T.H.D. 1913. Geology of the northern Shan States. *Memoirs of the Geological Survey of India*, **39**, Part 2, 379 pp.

Malsy, A. & Klemm, L. 2010. Distinction of gem spinels from the Himalayan mountain belt. *CHIMIA International Journal for Chemistry*, **64**(10), 741–746, http://doi.org/10.2533/chimia.2010.741.

Mogessie, A., Purtscheller, F. & Tessadri, R. 1988. Chromite and chrome spinel occurrences from metacarbonates of the Oetztal–Stubai complex (northern Tyrol, Austria). *Mineralogical Magazine*, **52**(365), 229–236, http://doi.org/10.1180/minmag.1988.052.365.09.

Pardieu, V. 2014. Hunting for "Jedi" spinels in Mogok. *Gems & Gemology*, **50**(1), 46–57, http://doi.org/10.5741/gems.50.1.46.

Pardieu, V. & Hughes, R.W. 2008. Spinel: Resurrection of a classic. *InColor*, No. 2, 10–18.

Pardieu, V., Sangsawong, S., Vertriest, W. & Raynaud, V. 2016. Gem News International: "Star of David" spinel twin crystal with multiphase inclusions from Mogok. *Gems & Gemology*, **52**(1), 100–101.

Peretti, A., Kanpraphai-Peretti, A. & Günther, D. 2015. World of magnificent spinel: Provenance and identification. *Contributions to Gemmology*, **11**, 293 pp.

Peretti, A., Mullis, J., Franz, L. & Günther, D. 2017. Spinel formation by sulphur-rich saline brines from Mansin (Mogok area, Myanmar). *15th Swiss Geoscience Meeting*, Davos, Switzerland, 17–18 November, 149–150.

Peretti, A., Mullis, J., Franz, L. & Günther, D. 2018. Spinel formation by sulphur-rich saline brines from Mansin (Mogok area, Myanmar). GRS GemResearch Swisslab AG, Lucerne, Switzerland, http://gemresearch.ch/spinel-formation-mansin, accessed 24 December 2018.

Phyo, M.M., Franz, L., de Capitani, C., Balmer, W. & Krzemnicki, M. 2017. Petrology and PT-conditions of quartz- and nepheline-bearing gneisses from Mogok Stone Tract, Myanmar. *15th Swiss Geoscience Meeting*, Davos, Switzerland, 17–18 November, 88–89.

Searle, D.L. & Haq, B.T. 1964. The Mogok belt of Burma and its relationship to the Himalayan orogeny. *22nd International Geological Congress*, New Delhi, India, 14–22 December, 132–161.

Searle, M.P., Noble, S.R., Cottle, J.M., Waters, D.J., Mitchell, A.H.G., Hlaing, T. & Horstwood, M.S.A. 2007. Tectonic evolution of the Mogok Metamorphic Belt, Burma (Myanmar) constrained by U-Th-Pb dating of metamorphic and magmatic rocks. *Tectonics*, **26**(3), article no. TC3014, 24 pp, https://doi.org/10.1029/2006tc002083.

Smith, C.P. & Dunaigre, C. 2001. Gem News: Anhydrite inclusion in a ruby from Myanmar. *Gems & Gemology*, **37**(3), 236.

Thein, M. 2008. Modes of occurrence and origin of precious gemstone deposits of the Mogok Stone Tract. *Journal of the Myanmar Geosciences Society*, **1**(1), 75–84.

Themelis, T. 2008. *Gems & Mines of Mogok*. Self-published, 352 pp.

Thu, K. 2007. *The igneous rocks of the Mogok Stone Tract: Their distributions, petrography, petrochemistry, sequence, geochronology and economic geology.* PhD thesis, Department of Geology, University of Yangon, Myanmar, http://m.palaminerals.com/mogok.

Thu, K. & Zaw, K. 2017. Gem deposits of Myanmar. *Geological Society, London, Memoirs*, **48**(1), 497–529, http://doi.org/10.1144/m48.23.

Thu, Y.K., Win, M.M., Enami, M. & Tsuboi, M. 2016. Ti-rich biotite in spinel and quartz-bearing paragneiss and related rocks from the Mogok Metamorphic Belt, central Myanmar. *Journal of Mineralogical and Petrological Sciences*, **111**(4), 270–282, http://doi.org/10.2465/jmps.151020.

Truong, A.R. 2017. A highly-important imperial Mughal spinel, India, dated 1024 AH/1615 AD and 1070 AH/1659 AD. www.alaintruong.com/archives/2017/03/23/35086977.html, accessed 24 December 2018.

Vertriest, W. & Reynaud, V. 2017. *G&G* Micro-World: Complex yellow fluid inclusions in red Burmese spinel. *Gems & Gemology*, **53**(4), 468.

Whitney, D.L. & Evans, B.W. 2010. Abbreviations for names of rock-forming minerals. *American Mineralogist*, **95**(1), 185–187, http://doi.org/10.2138/am.2010.3371.

Yau, Y.C., Anovitz, L.M., Essene, E.J. & Peacor, D.R. 1984. Phlogopite-chlorite reaction mechanisms and physical conditions during retrograde reactions in the Marble Formation, Franklin, New Jersey. *Contributions to Mineralogy and Petrology*, **88**(3), 299–306, http://doi.org/10.1007/bf00380175.

Yavorskyy, V.Y. & Hughes, R.W. 2010. *Terra Spinel: Terra Firma*. Ivy, New York, New York, USA, 203 pp.

Zaw, K. 1990. Geological, petrological and geochemical characteristics of granitoid rocks in Burma: With special reference to the associated W-Sn mineralization and their tectonic setting. *Journal of Southeast Asian Earth Sciences*, **4**(4), 293–335, http://doi.org/10.1016/0743-9547(90)90004-w.

Zaw, K. 2017. Overview of mineralization styles and tectonic–metallogenic setting in Myanmar. *Geological Society, London, Memoirs*, **48**(1), 531–556, https://doi.org/10.1144/m48.24.

Zaw, K., Acharyya, S.K. & Maung, H. 1989. Comments and reply on "Transcurrent movements in the Burma–Andaman Sea region". *Geology*, **17**(1), 93–98, http://doi.org/10.1130/0091-7613(1989)017<0093:carotm>2.3.co;2.

Zaw, K., Sutherland, L., Yui, T.-F., Meffre, S. & Thu, K. 2015. Vanadium-rich ruby and sapphire within Mogok gemfield, Myanmar: Implications for gem color and genesis. *Mineralium Deposita*, **50**(1), 25–39, http://doi.org/10.1007/s00126-014-0545-0.

Zhu, J. & Yu, X. 2018. Inclusions of spinel from Burma. *Journal of Gems and Gemmology*, **20**(Supp.), 18–23 (in Chinese with English abstract).

The Authors

Myint Myat Phyo and
Prof. Dr Leander Franz
Department of Mineralogy and Petrology,
Basel University, CH-4056 Basel, Switzerland
Email: myintmyat.phyo@unibas.ch

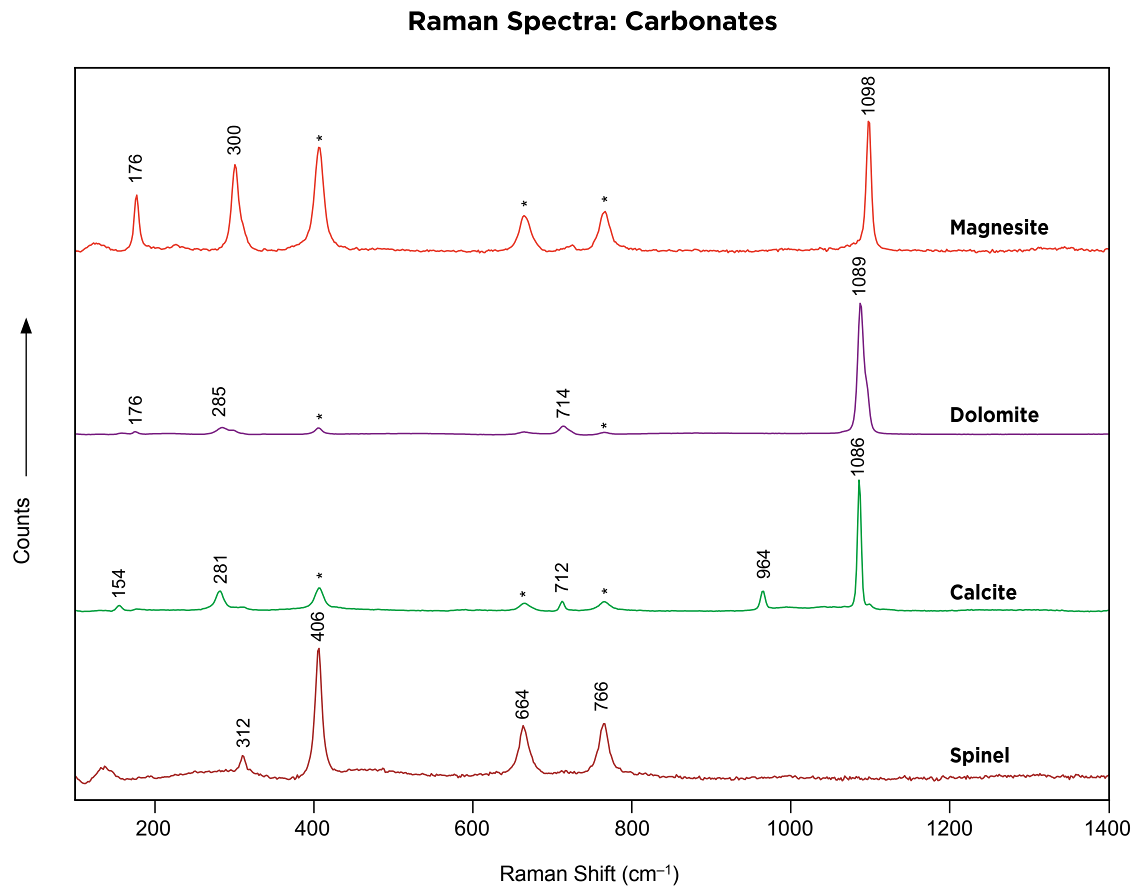
Eva Bieler
Swiss Nano Imaging Lab,
Swiss Nanoscience Institute,
Basel University, CH-4056 Basel, Switzerland

Walter Balmer and
Dr Michael S. Krzemnicki FGA
Swiss Gemmological Institute SSEF,
Aeschengraben 26, 4051 Basel, Switzerland

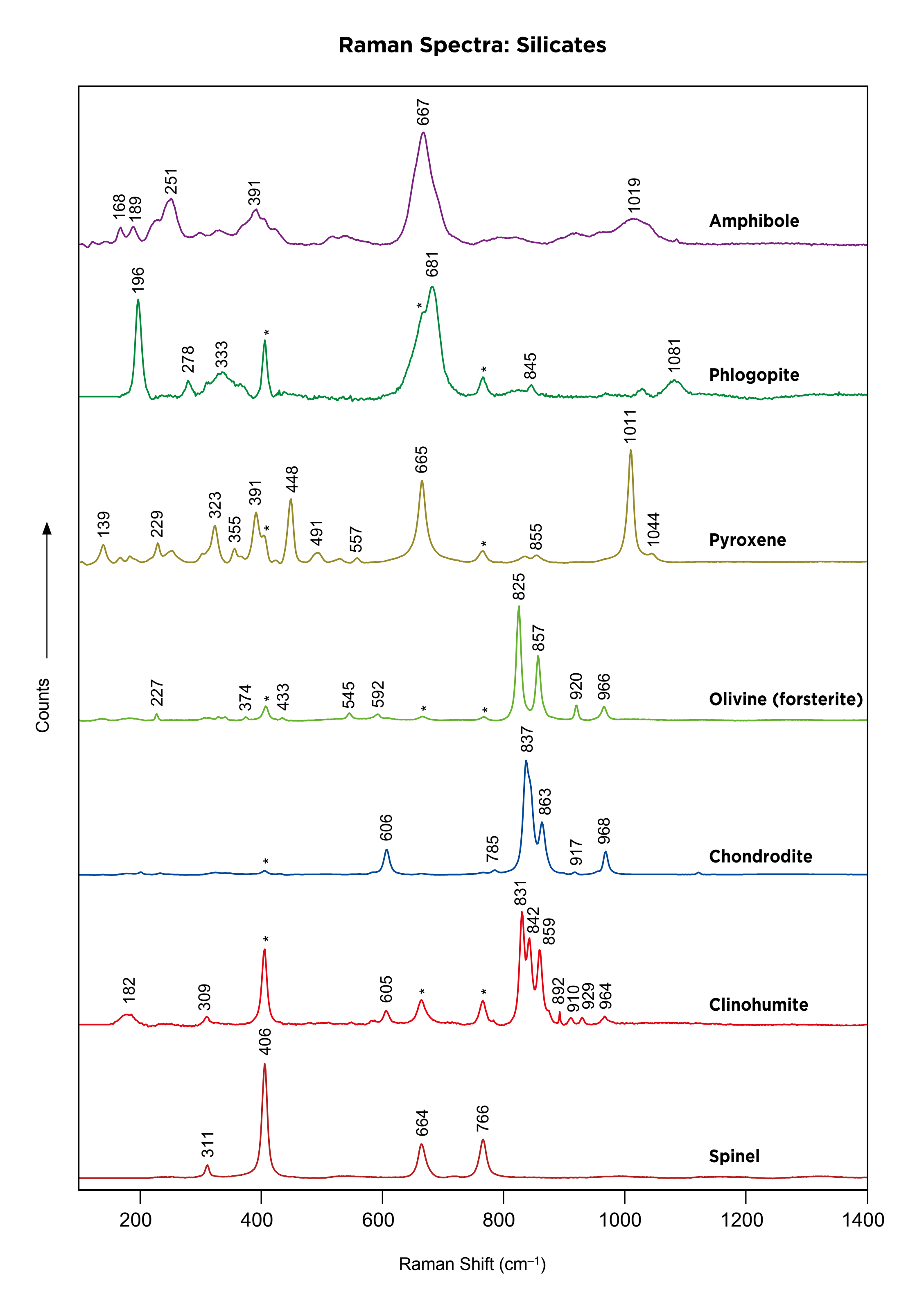
Acknowledgements

The authors thank Ma Mie, Ko Chu (Kyauksaung mine), Dr Takahito Mori, Ko Kyaw Swar and Ko Nay for all their support and for providing samples of gem-quality spinel and host rock. Further thanks to Sebastian Hänsel, U Aung Kyaw Htoon and Ko Ja Mu for their help with fieldwork. Special thanks to Ah Ba, Aunty Phyu and the local people and miners of the Mogok area for their kind encouragement during the fieldwork. Many thanks to Judith Braun, Dr Tashia Dzikowski and Dr Laurent E. Cartier FGA (all of the Swiss Gemmological Institute SSEF, Basel) for their help, advice and fruitful discussions on this paper. This study was financed by a grant from Kanton Basel (Stipendienkommission für Nachwuchskräfte aus Entwicklungsländern), by a research grant from FAG (Freiwillige Akademische Gesellschaft Basel) and by the Swiss Gemmological Institute SSEF. We also thank the three peer reviewers for their helpful suggestions and information.

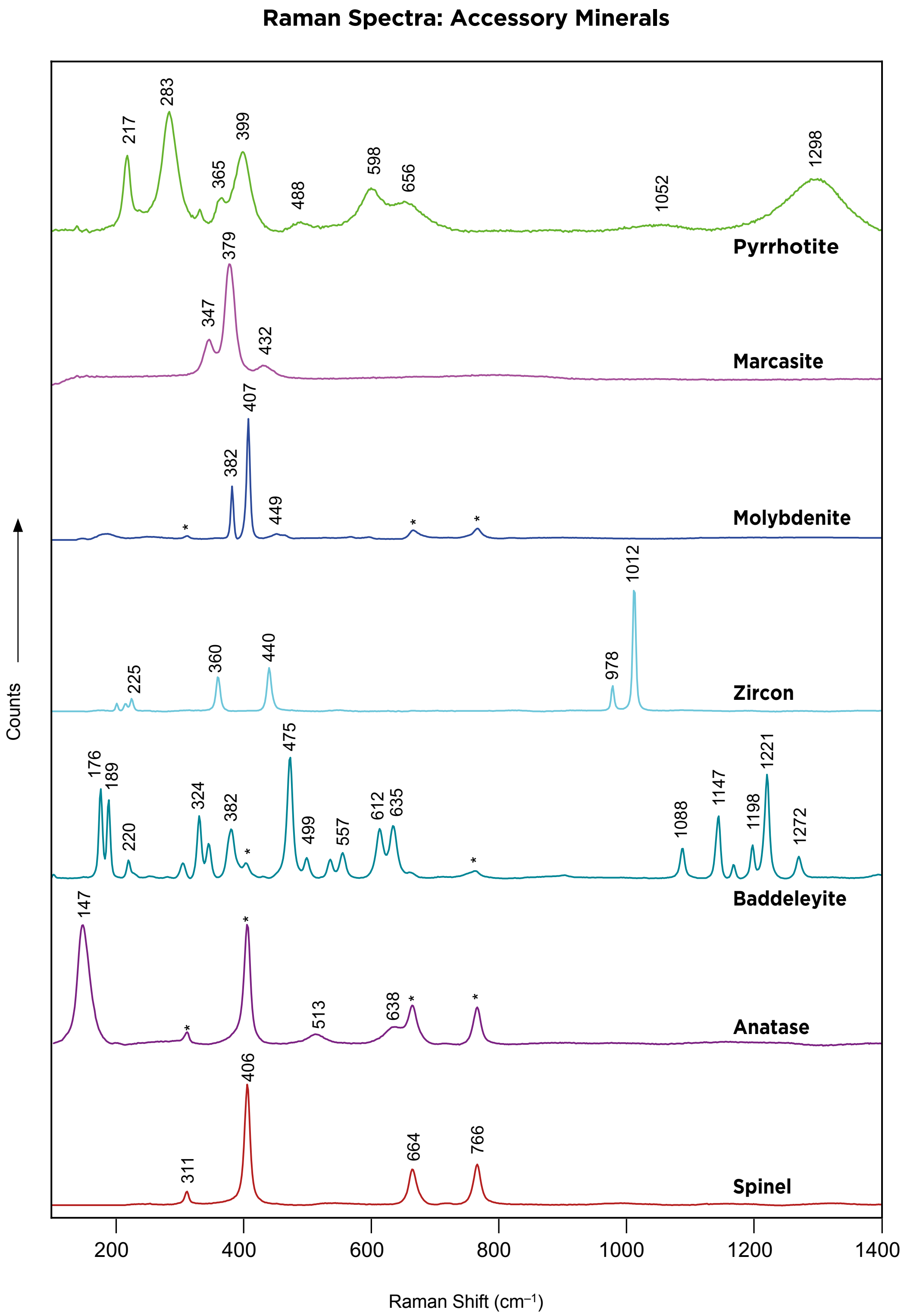
APPENDIX



Representative Raman spectra are shown for carbonate mineral inclusions analysed in our samples from Mogok, together with a spectrum of the host spinel. Peaks in the inclusion spectra that are marked with an asterisk are from the host spinel.



Representative Raman spectra are shown for various silicate mineral inclusions analysed in our samples from Mogok, together with a spectrum of the host spinel. Peaks in the inclusion spectra that are marked with an asterisk are from the host spinel.



Representative Raman spectra are shown for various accessory mineral inclusions analysed in our samples from Mogok, together with a spectrum of the host spinel. Peaks in the inclusion spectra that are marked with an asterisk are from the host spinel..