

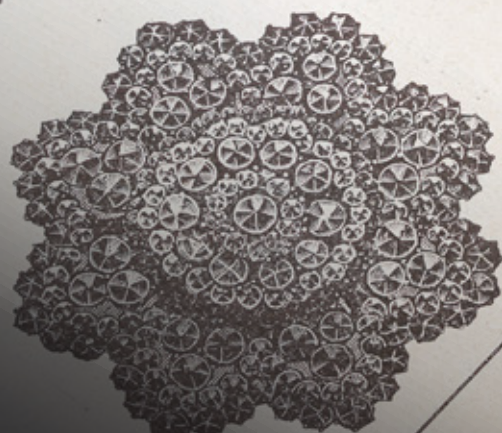


The Journal of Gemmology

Volume 39 / No. 3 / 2024



ých českých granátů.
e též zvlášť.



Cobalt-blue Spinel
from Canada
and Elsewhere

Bohemian
Garnet from the
Czech Republic

Brown Olivine
from Southeast
Vietnam

Unusually
Coloured Type
IIb Diamonds



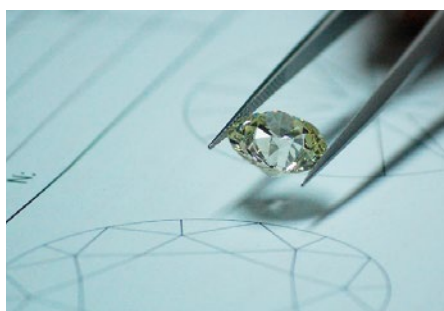
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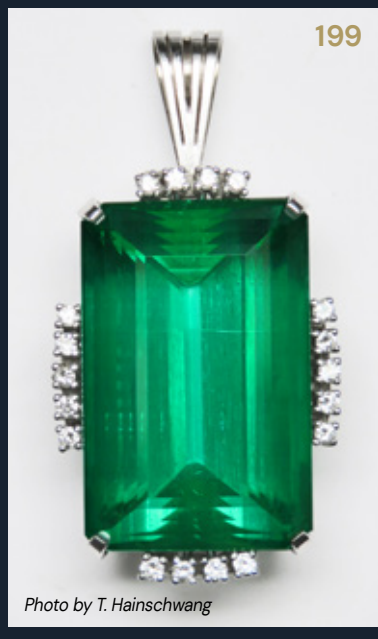
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Cover photo: Red Cr-bearing pyrope from the Czech Republic, known as Bohemian garnet, is reviewed in an article on pp. 242–258 of this issue. The foil-backed Bohemian garnet jewellery on the cover was made in Bohemia in the mid-nineteenth century. The bracelet has a diameter of 7 cm, and the brooch—set with Czech river pearls and a large almandine in the centre—is approximately 7 x 7 cm. The rough pieces of Bohemian garnet are about 5 mm in diameter. Also shown are two brass cups from the beginning of the nineteenth century, which were used by merchants for handling pre-sized rough or cut garnets. From a private collection; photo by Pavel Škácha.



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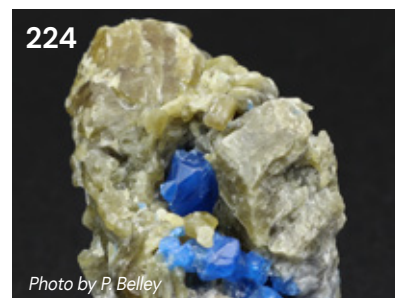
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The Journal of Gemmology is published by Gem-A in collaboration with SSEF.



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DESIGN & PRODUCTION

Zest Design, London. <https://www.zest-uk.com>

PRINTER

Park Communications Ltd, London.
<https://www.parkcom.co.uk>



© 2024 Gem-A (The Gemmological Association of Great Britain)
ISSN 1355-4565 (Print), ISSN 2632-1718 (Online)



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What's New

NEWS AND PUBLICATIONS

Gemmological Society of Japan 2024 Annual Meeting Abstracts

The 2024 Annual Meeting of the Gemmological Society of Japan was held 13–14 July in Tokyo, celebrating its 50th anniversary. Abstracts of the presentations are now available online at https://www.jstage.jst.go.jp/browse/gsj/46/0/_contents/-char/en. The 16 abstracts cover a variety of topics, such as melee-size fancy-colour synthetic diamonds, identifying colour-treated diamonds, geographic origin determination of emerald, separating green jade from Guatemala and Myanmar, using artificial intelligence to detect and classify inclusions, pearl culturing in Vietnam, X-ray fluorescence analysis of pearls, and more. The abstracts are in Japanese, but are accompanied by a brief English synopsis.

Abstract of Papers Presented at Annual Meeting of the Gemmological Society of Japan

GIT Report on a Large Natural Freshwater Blister

In July 2024, the Gem and Jewelry Institute of Thailand's Gem Testing Laboratory reported on a large (223 ct) natural freshwater blister. It was light brown with slight pink and purple overtones, and a baroque shape. Raman spectroscopy revealed a typical aragonite spectrum. X-radiography confirmed its natural origin, and the lack of a radial pattern or onion-like spherical ring structures indicated it was a natural blister rather than a blister pearl. EDXRF chemical analysis pointed to a freshwater origin. Download the report at <https://git.or.th/en/information-service/27/76/detail/3175>.



The Goldsmiths' Company Review 2023–2024

The Goldsmiths' Company, London, has released a review of its activities for the past year, with information about its personnel, its annual impact report, and articles about unusual jewellery, *objets d'art*, designers and manufacturing techniques, both traditional and innovative. While the Company's focus is on gold, the review also features work with silver and gemstones. The 92-page report is available as both a flip book and a downloadable PDF at <https://www.thegoldsmiths.co.uk/company-news/the-goldsmiths-review-23-24>.



International Kimberlite Conference Abstracts and Field Trip Guides

Extended abstracts from the 12th International Kimberlite Conference—held 8–12 July 2024 in Yellowknife, Northwest Territories, Canada—are now available online at <https://ikcabstracts.com/index.php/ikc>. The 170+ abstracts are available as individual PDF files covering an extensive range of topics pertaining to diamond and its host rocks, including prospecting and mining developments, geological origin, inclusions, research methods, age dating and updates on commercial diamond mines. Also available are four field trip guidebooks, including Trip 01 to Northwest Territories diamond mines (Diavik, Gahcho Kué and Ekati), which can be downloaded at <https://12ikc.ca/downloads>.



OTHER RESOURCES

MGJC 2024 Lecture Recordings



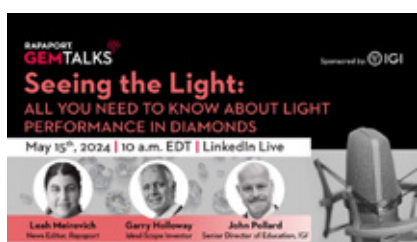
The 2024 Mediterranean Gemmological and Jewellery Conference was held 7–11 May in Italy and Slovenia. Recordings of its lectures and workshops are now available online at <https://www.brankogems.com/shop/product-category/conference-recordings>. Topics include identification and screening of natural and laboratory-grown diamonds, geographic origin determination of major coloured stones, spectroscopy of diamonds and coloured stones, inclusions in quartz, historic jewellery, responsible sourcing and in-depth discussions of individual coloured stones (tourmaline, coral, opal, emerald, corundum and spinel). Some recordings are available for free, but most require purchase.

Paul Zimnisky Diamond Analytics Podcasts

Diamond-industry analyst Paul Zimnisky (New York, New York, USA) hosts podcasts in which he interviews industry leaders to discuss diamond and jewellery topics. As of this writing, the most recent podcast, from 22 July, features retired De Beers executive Charles Stanley, who recounts the marketing strategies of the 1990s and explores the future impact of laboratory-grown diamonds on the natural diamond market. This is the 66th of Zimnisky's podcasts, which began in 2019, all of which can be accessed at <https://www.paulzimnisky.com/podcast>.



Rapaport GEMTalks Podcasts



The Rapaport Group has posted videos from its 2024 LinkedIn Live series of GEMTalks at <https://tinyurl.com/bdhyh9sj>. Featuring various experts from the diamond industry, they include 'How Not Screening Diamonds is Exposing You to Risk', 'Determining Diamond Origins: Scientific Challenges and Industry Requirements' and 'Seeing the Light: All You Need to Know about Light Performance in Diamonds'.

What's New provides announcements of new instruments/technology, publications, online resources and more. Inclusion in What's New does not imply recommendation or endorsement by Gem-A. Entries were prepared by Carol M. Stockton unless otherwise noted.

Gem Notes

COLOURED STONES

Large Aquamarine Overgrown by Synthetic Emerald

Hydrothermal synthetic emerald overgrowth on natural beryl is nothing new. It is a well-known product from the Lechleitner company in Austria, which produced these hybrid natural/synthetic gems for more than two decades, beginning in 1959. In the Lechleitner method, a faceted natural beryl (typically colourless or pink) was used as the seed, over which a thin layer of synthetic emerald with very high Cr content was grown to impart a more-or-less intense green colour (Nassau & Nassau 1980; Schmetzer *et al.* 1981). Today, such hybrid natural beryl/synthetic emerald gems are very rarely encountered in the trade, because Lechleitner produced limited quantities and ceased production in the 1980s. The specimens produced by this method were usually rather small (typically <5 ct).

In 2022, a pendant with a large green stone (with an estimated weight of 75 ct) declared as emerald was submitted to GGTL Laboratories in Liechtenstein for testing (Figure 1). Although Fourier-transform infrared (FTIR) spectroscopy clearly identified it as beryl without any apparent clarity enhancement, the details of the spectrum were unusual for natural emerald, and looked much more like beryl of another colour (e.g. aquamarine). In addition, the size, clarity and colour of the specimen made it highly suspicious. A closer look at minor details of the FTIR spectrum revealed small absorption features attributed to deuterated water (D₂O or HDO) in the 2830–2550 cm⁻¹ region, as well as many other minor spectral features that resemble those known for aquamarine from various sources, rather than any of the signatures known for natural emerald.

Viewed with a microscope, we noted various natural-appearing inclusions (mostly fluid- and gas-filled growth tubes parallel to the optic axis), as well as fine crazing within a thin surface layer on the specimen (Figure 2a). Such features are highly characteristic of Lechleitner ‘hybrid’ products (Schmetzer *et al.* 1981). Immersion in alcohol revealed a thin, intense green surface layer present on the pavilion facets



Figure 1: The 75 ct specimen in this pendant, surrounded by diamonds, was submitted as a natural emerald. Photo by T. Hainschwang.

(Figure 2b). The FTIR spectroscopic identification of the sample as beryl, combined with these microscopic features, unambiguously identified it as a natural beryl overgrown by synthetic emerald.

To investigate the colour of the underlying beryl

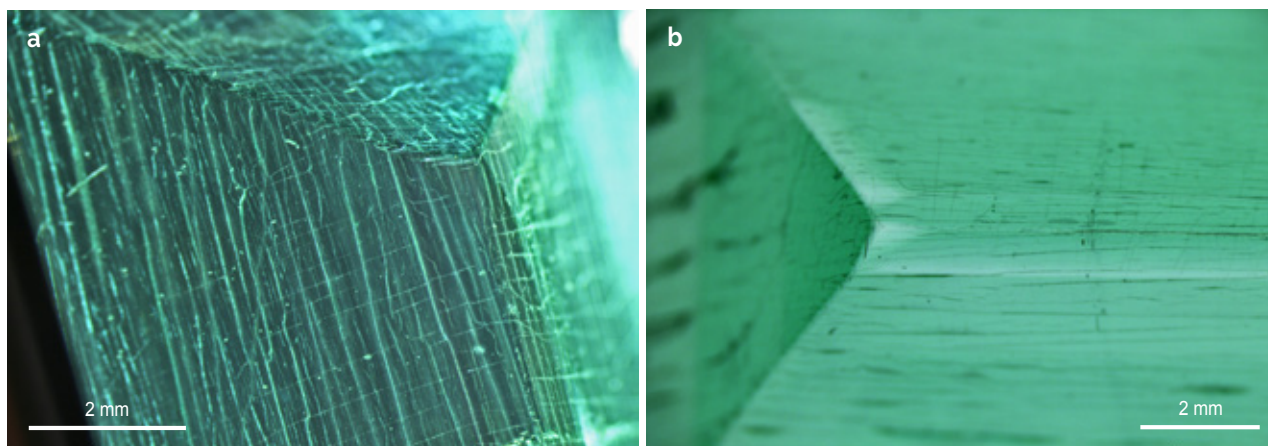


Figure 2: (a) Under magnification, abundant fine cracks with very little penetration depth were visible on the pavilion of the specimen. Such cracks are highly characteristic of epitaxial overgrowth of synthetic emerald on natural beryl. (b) Immersion in alcohol revealed the darker green layer of synthetic emerald, part of which had been removed when the specimen was repolished, resulting in irregular areas of lighter colouration. Photomicrographs by T. Hainschwang.

and verify our assumption that it was an aquamarine, we recorded polarised ultraviolet-visible-near infrared (UV-Vis-NIR) spectra of the sample (Figure 3). The spectra were characterised by distinct Cr absorptions, very strong Fe-related bands and intense water peaks attributed to H_2O overtone and combination bands.

To demonstrate the spectral effect of overlaying synthetic emerald on aquamarine, we acquired polarised spectra of both a hydrothermal synthetic emerald and an aquamarine (Figure 4a), and then combined the two spectra; that is, we added the ordinary ray spectrum of the aquamarine to the ordinary ray spectrum of the synthetic emerald, and we added the extraordinary ray spectrum of the aquamarine to the extraordinary ray spectrum of the synthetic emerald. The resulting spectra (Figure 4b) resembled those we obtained from

the 75 ct sample described here.

Chemical analyses by energy-dispersive X-ray fluorescence (EDXRF) spectroscopy were recorded for an area of the pavilion coated with synthetic emerald and for the table of the sample, which lacked any visible coating. The coated pavilion yielded 30,000 ppm Cr, while the Cr content of the table, where the overgrowth had been completely removed when the sample was repolished, was below the detection limit of the instrument. The very high Cr content of the coated area, which is significantly greater than the highest measured values of natural emerald, is consistent with the Cr contents published for Lechleitner synthetic emerald overgrowth (Schmetzer *et al.* 1981).

To the authors' knowledge, this is the largest documented Lechleitner-type hybrid natural beryl/

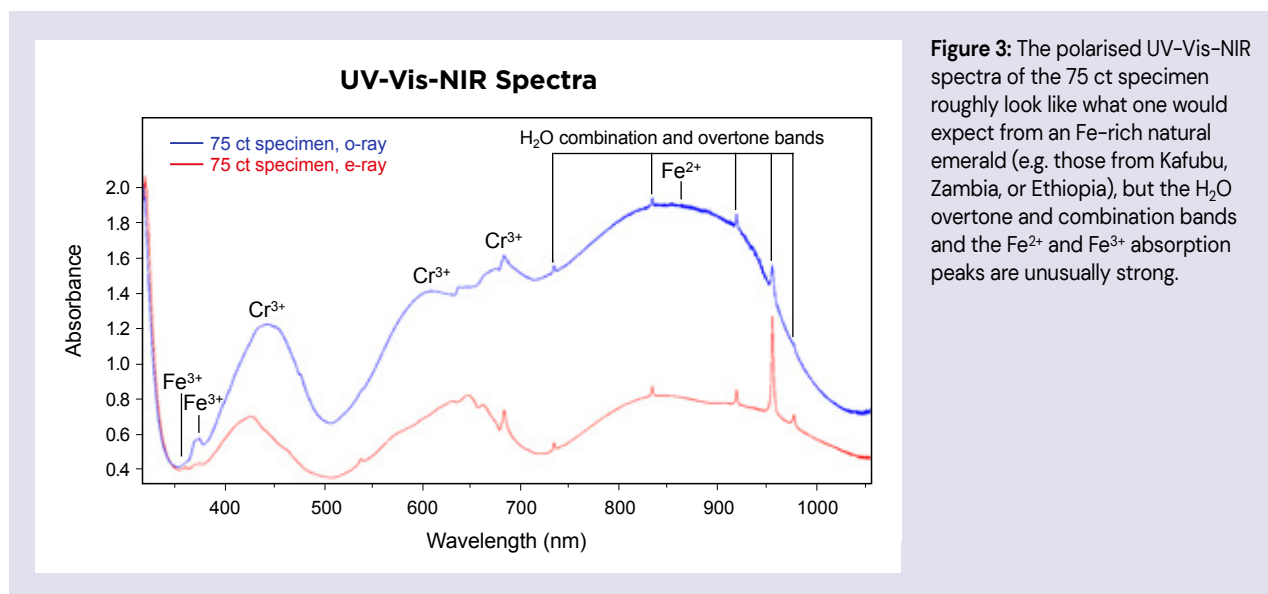


Figure 3: The polarised UV-Vis-NIR spectra of the 75 ct specimen roughly look like what one would expect from an Fe-rich natural emerald (e.g. those from Kafubu, Zambia, or Ethiopia), but the H_2O overtone and combination bands and the Fe^{2+} and Fe^{3+} absorption peaks are unusually strong.

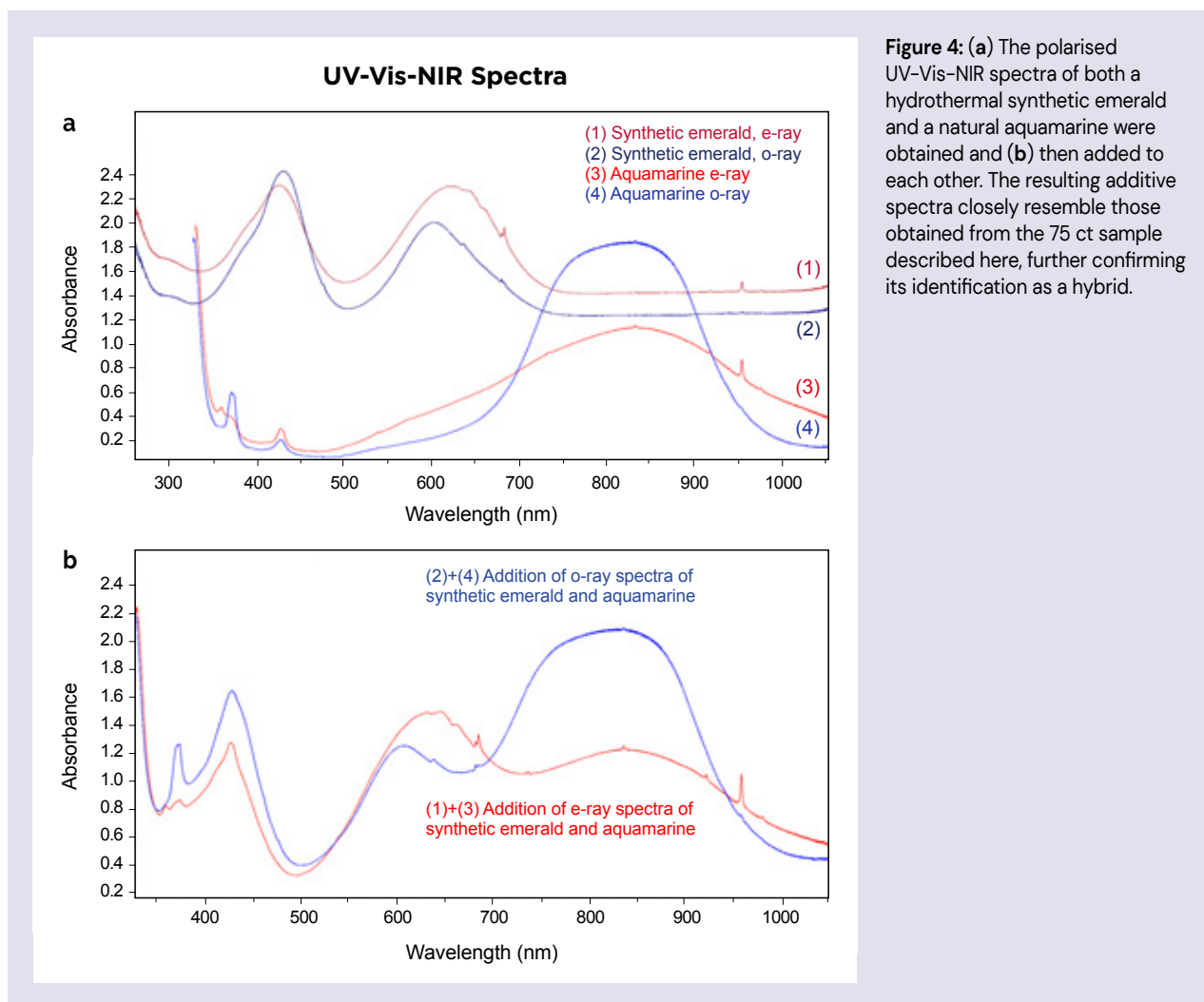


Figure 4: (a) The polarised UV-Vis-NIR spectra of both a hydrothermal synthetic emerald and a natural aquamarine were obtained and (b) then added to each other. The resulting additive spectra closely resemble those obtained from the 75 ct sample described here, further confirming its identification as a hybrid.

synthetic emerald. Whether it had originally been sold as a Lechleitner hybrid is unknown, but after being mounted in the jewel it was represented as natural emerald.

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Burbankite from Kola Peninsula, Russia

Burbankite is a rare-earth carbonate mineral with the chemical formula $(\text{Na,Ca})_3(\text{Sr,Ba,Ce})_3(\text{CO}_3)_5$. It ranges from colourless, greyish yellow, pale yellow, and pink to pale green, with a Mohs hardness of 3½–4 and fair cleavage on {1010} (<https://www.mindat.org/min-803.html>). Gem-quality material was initially reported by

Koivula *et al.* (1992a) from Mont St-Hilaire, Quebec, Canada. They described it as ‘a newcomer to the gem world, which shows a remarkable color change from greenish brown in fluorescent light to reddish brown in incandescent light.’ They further indicated that clean gemstones up to 6.62 ct had been faceted from

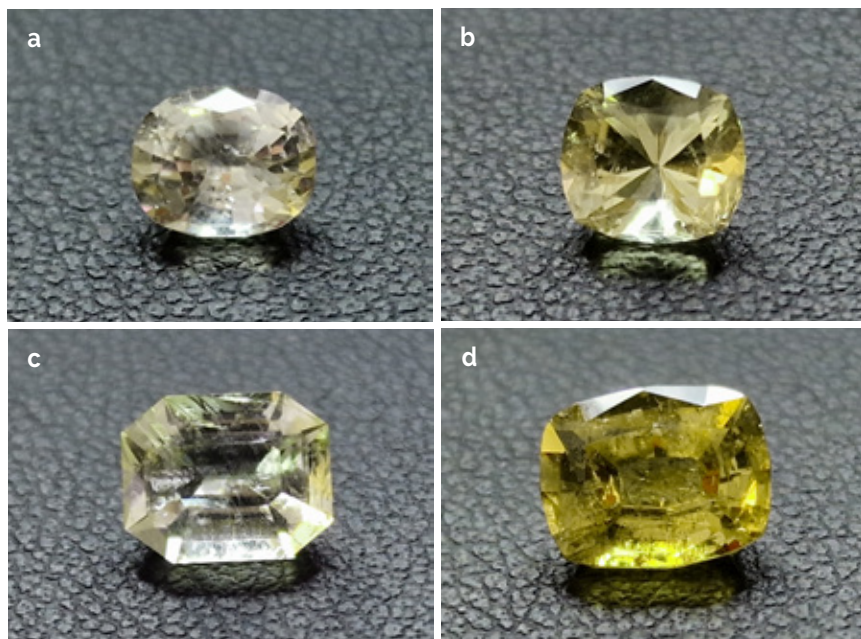


Figure 5: The burbankite gemstones examined for this report weigh (a) 0.85 ct, (b) 0.98 ct, (c) 1.51 ct and (d) 1.59 ct. Photos by D. Gravier.

that locality. Such material was described in more detail by Koivula *et al.* (1992b), but the 3.18 ct gem examined for that report (also from Mont St-Hilaire) turned out to be rémondite-(Ce), which is another mineral in the burbankite group with the formula $\text{Na}_3(\text{Ca,Ce,Na})_3(\text{CO}_3)_5$. They attributed its colour change—from very slightly greenish yellow in daylight to slightly yellowish orange in incandescent light—to the presence of Nd^{3+} .

Burbankite—but not rémondite-(Ce)—is also known from the Kirovskii apatite mine in the Khibiny (or Khibina) alkaline massif, Kola Peninsula, Russia (Zaitsev *et al.* 1998; see also <https://www.mindat.org/loc-2685.html>). Burbankite gemstones from this locality were displayed by author DG at the February 2024 gem and mineral shows in Tucson, Arizona, USA. The rough material first appeared in late 2022, and the author obtained a few pieces in November 2023, from which eight stones were cut. They weighed

0.67–3.67 ct and ranged from very light yellow to deep greenish yellow. None of the stones showed a colour change between daylight and incandescent light. Four samples were characterised by author DG for this report (Figure 5). Their RIs were $n_o = 1.620\text{--}1.627$ and $n_e = 1.606\text{--}1.612$ (birefringence = 0.014–0.015), and their hydrostatic SG was 3.55–3.57. They fluoresced orangey pink to long-wave UV radiation: very strong for the pale-coloured specimens and strong for the deeply coloured stone. Internal features consisted of partially healed fractures, iridescent thin films along fractures (e.g. Figure 6) and fine needle-like features consisting of strings of pinpoints. A handheld spectroscope yielded a clear apatite-like spectrum, with a group of lines in the 530 nm region and two doublets around 600 nm.

Burbankite is a collector's stone due to its rarity, low hardness and fair cleavage. Its future availability is uncertain.

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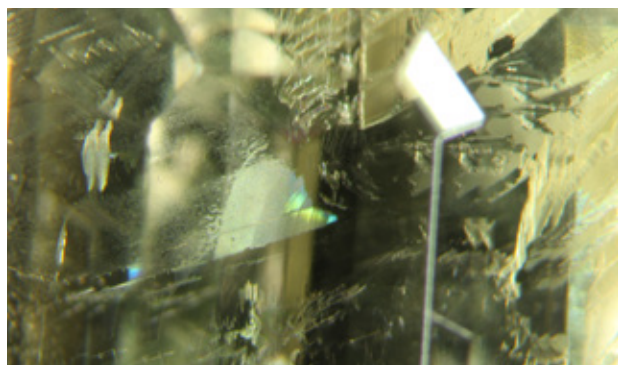


Figure 6: The main internal feature in the burbankite samples consisted of partially healed fractures, as seen here in the 1.51 ct stone. Associated thin films locally display iridescence. Photomicrograph by D. Gravier; image width 4.3 mm.

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Emerald Mining in Musakashi, Zambia

For the past two decades, Zambia has been considered the world's second-most-important source of gem-quality emerald (after Colombia and before Brazil). Most of Zambia's emerald production comes from the Kafubu area, located about 45 km south-east of Kitwe, in the Copperbelt Province of northern Zambia. Emeralds were initially found there towards the end of the 1920s, but production did not really start to grow until the beginning of the 1970s. In the early 2000s, emeralds were also discovered near Musakashi village in the Solwezi District of the neighbouring North-Western Province, about 150 km north-west of the Kafubu area (Zwaan *et al.* 2005). According to Manyepa and Mutambo (2021), emerald mineralisation there is associated with quartz-feldspar-magnetite/limonitic veins intruding shale host rocks.

Emerald production from Musakashi has been discontinuous, mainly due to legal issues linked with the mining licences (Zwaan *et al.* 2005; Klemm 2010; Pardieu *et al.* 2015). Nevertheless, for the past five years, gemmological laboratories have occasionally received emeralds from the Musakashi deposit (e.g. Figure 7), sometimes mixed with stones from Kafubu (Krzemnicki *et al.* 2021; Hennebois *et al.* 2022). Musakashi emeralds are commonly deep green with few to no fissures, and although faceted stones over 5 ct are rare, recently some exceeding 10 ct and one weighing about 20 ct were reported by gem dealers. Emeralds from Musakashi have completely different characteristics from those of Kafubu, and may be confused with stones from Colombia (Saeseaw 2014; Pardieu *et al.* 2015) or Afghanistan (Krzemnicki *et al.* 2021).

In early July 2024, the authors visited the Musakashi area to gain first-hand information on the

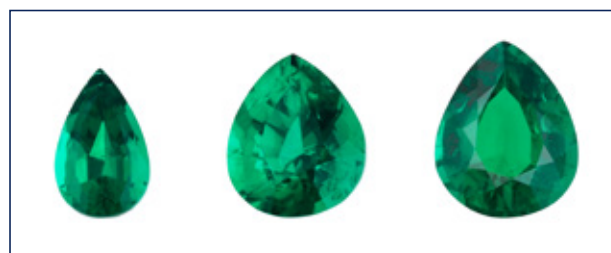


Figure 7: These faceted emeralds from Musakashi weigh 1.06, 3.17 and 4.13 ct. Courtesy of Berçot SAS, France; photo by Sandie Clain/LFG.

mining situation and obtain samples for research. We learned that in 2018 the legal problems with the mining licences were resolved, and a mechanised operation was initiated by Pridegems Mines Ltd. In mid-2023, Pridegems discontinued this work and moved their machinery to Kafubu, where they are mining emeralds in collaboration with Grizzly Mining Ltd. However, an agreement between Pridegems and the residents of Musakashi village allows the locals to use hand methods to rework the mine tailings. These activities mainly occur during the rainy season, when water is available on site.

For two days the authors witnessed the villagers' emerald mining activities (Figures 8–9) and obtained samples for the Laboratoire Français de Gemmologie (LFG) reference collection. More than 20 emerald specimens were procured from the miners on-site after witnessing them being recovered from the washing operation (Type B samples according to Pardieu 2020), and several hundred additional samples were purchased from local miners/dealers but were not witnessed being recovered (e.g. Figure 10). The latter research specimens (Types C and D according to Pardieu 2020) were obtained in Musakashi and also in Kitwe (about 200 km away, requiring a four-hour

Figure 8: Local residents wash and filter material collected from the tailings of the Musakashi emerald mine. Photo by V. Pardieu.





Figure 9: (a) The gravels are then washed on fine-meshed screens, and (b) the emeralds are removed by hand. This emerald (about 5 mm long) was acquired for the LFG reference collection after the authors witnessed its recovery by the miner. Photos by V. Pardieu.



Figure 10: These emeralds are some of the samples obtained from local stone dealers for the LFG reference collection. Photo by V. Pardieu; image width about 7 cm.

drive on unpaved and paved roads). In Kitwe, the authors saw some top-quality emeralds that were reportedly from Musakashi (or ‘Solwezi’), including a rough sample of about 2 g.

The LFG team is currently collecting data on the samples they acquired, and the results will be published in a future article.

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Ludlamite from Brazil

In early 2024, the author received a 0.31 ct faceted green ludlamite (Figure 11) selected from a parcel of five small gemstones (0.24–0.60 ct). The rough material reportedly came from the Cabeça do Cachorro claim, São Gabriel da Cachoeira, in north-western Amazonas State, Brazil (see <https://www.mindat.org/locentry-919724.html>). Mineral specimens of ludlamite (and vivianite) from this locality were displayed at the June 2024 Sainte-Marie-aux-Mines mineral and gem show. The ludlamite occurred as clusters of centimetre-size crystals on matrix, and the specimens typically had a maximum dimension of around 10 cm.

Ludlamite is a monoclinic hydrated iron phosphate, $\text{Fe}_3^{2+}(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$, and forms tabular crystals, sometimes in parallel groups. Although it occurs worldwide, ludlamite is relatively rare. Most ludlamite contains minor amounts of Mg and Mn^{2+} replacing Fe^{2+} , which explains why its formula is often expressed as $(\text{Fe}^{2+}, \text{Mg}, \text{Mn}^{2+})_3(\text{PO}_4)_2 \cdot 4\text{H}_2\text{O}$ (O'Donoghue 2006). It ranges from 'apple' green, green and 'olive' green to almost colourless (rarely blue), and is translucent or transparent (<https://www.mindat.org/min-2452.html>). Its Mohs hardness is only $3\frac{1}{2}$, and it has perfect cleavage on {001}, so faceting can be challenging. Cut gemstones have been reported from the Blackbird mine in Lemhi County, Idaho, USA (Fritsch *et al.* 2019).

The following gemmological properties were recorded for the 0.31 ct sample from Brazil: colour—slightly yellowish green; lustre—vitreous; diaphaneity—transparent; RIs—1.653–1.691; birefringence—0.038; optic character—biaxial positive; magnetism—picked up by an N52 neo-



Figure 11: The 0.31 ct (5.60 × 3.72 × 2.57 mm) ludlamite examined for this study is transparent with a slightly yellowish green colour. Photo by T. Cathelineau.

dymium magnet; Chelsea Colour Filter—emerald green with incandescent light; and fluorescence—inert to long- and short-wave UV radiation. The optical data mentioned above are consistent with those previously reported for ludlamite (O'Donoghue 2006). (The hydrostatic SG value could not be accurately determined due to the small size of the sample, but reportedly is 3.12–3.19; <https://www.mindat.org/min-2452.html>.) Microscopic examination did not reveal any notable internal features other than a profusion of clouds along with healed and partially healed fractures. The faceted surface showed a poor polish, with striations.

Raman spectroscopy (636.6 nm laser) showed an intense peak at 950 cm^{-1} , a weak shoulder at 916 cm^{-1} , two weak peaks at 1042 and 1074 cm^{-1} , and a second significant group of peaks composed of a moderate peak at 548 cm^{-1} with weaker ones at 463 , 497 , 597 and 636 cm^{-1} . This almost perfectly matched the Raman spectra of ludlamite in the RRUFF database (<https://rruff.info/ludlamite>). The dominant 950 cm^{-1} peak (related to the PO_4^{3-} symmetric stretching mode) also occurs in the Raman spectra of vivianite, but all other observed peaks were distinct, making it easy to separate the two species. Peak assignments for some of the Raman features are given by Frost *et al.* (2013).

Unpolarised Vis-NIR spectroscopy yielded a complex spectrum (Figure 12) in the visible range, with sharp lines at 389, 457, 477, 482 and 503 nm and weaker broad bands at 424, 440, 546 and 588 nm. The red-to-NIR region is characterised by broad, strong absorption bands extending over this spectral range. The overall pattern yields a transmission window between about 470 and 650 nm that produces the green to yellowish green colour. The 389, 457, 477, 482 and 503 nm bands are similar to those of Fe^{2+} in vivianite (positioned at 389, 454, 482 and 508 nm), which is another iron phosphate: $\text{Fe}_3^{2+}(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ (Faye *et al.* 1968; Taran & Platonov 1988). Fritsch *et al.* (2019) stated 'the colour is intrinsically due to Fe^{2+} but Mn^{2+} can modify it'. The present author speculates that the bands at 424, 440, 477, 482, 546 and 588 nm could be related to Mn^{2+} , based on his observations of Mn^{2+} absorptions in minerals such as willemite, rhodochrosite, etc.

Photoluminescence (PL) spectroscopy with various laser excitation sources (254, 310, 365, 405 and 447 nm) did not yield any luminescence spectra for this specimen.

Ludlamite gemstones have been rare up to now, but because of the mining activities in Brazil, they could

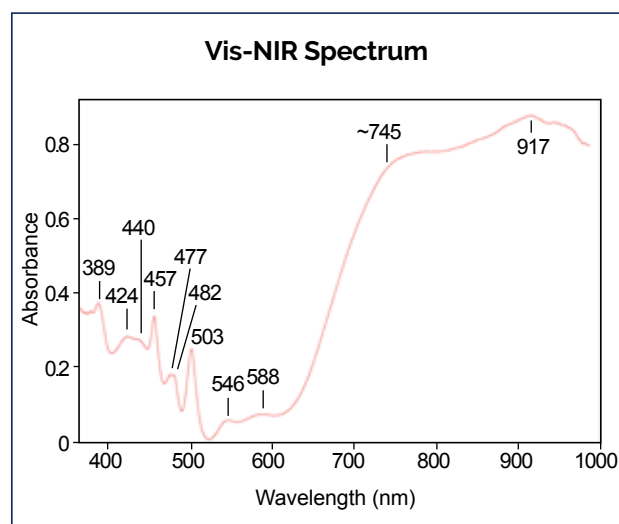


Figure 12: An unpolarised Vis-NIR absorption spectrum of the 0.31 ct ludlamite was collected with the beam travelling through the sample perpendicular to the table (path length ~2.5 mm).

become more readily available. However, despite its attractive colour, ludlamite will remain a collector's stone because of its low hardness combined with its perfect cleavage.

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Peridot from Tanzania

Peridot is mined from various localities, with Myanmar, China, Pakistan and the USA (Arizona) being some well-known sources. Peridot was documented from Tanzania by Stockton and Manson (1983), reportedly from alluvial deposits in the vicinity of the Usambara Mountains near the Tanzania-Kenya border. During the February 2024 Tucson gem and mineral shows, Steve Ulatowski (New Era Gems, Grass Valley, California, USA) introduced peridot from a relatively new find (in July 2023) in the Rubeho Mountains in central Tanzania. Ulatowski calls the material 'Gogo peridot' after the local Wagogo tribe living in that region. In total, about 6 kg of gem-grade rough was available from Ulatowski in Tucson, in sizes from below 2 g to around 11 g. Author CS obtained three pieces, and cut one of them into a 2.22 ct oval gemstone (Figure 13).

Standard gemmological properties were collected by author CS on the three samples. The material had a hydrostatic SG of 3.30 (average of ten

measurements on the three samples), as well as a biaxial positive character with RIs of 1.648–1.680 and a birefringence of 0.032 (obtained from the

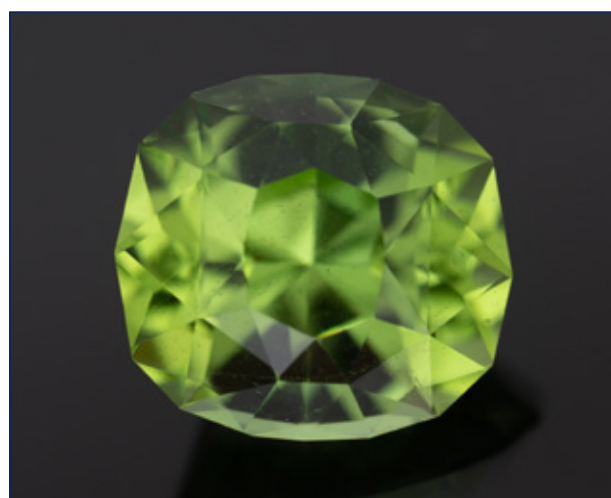


Figure 13: This 2.22 ct gemstone (8.0 × 7.3 mm) is one of the three peridot samples from Tanzania examined for this study. Photo by C. Schwarzingier.

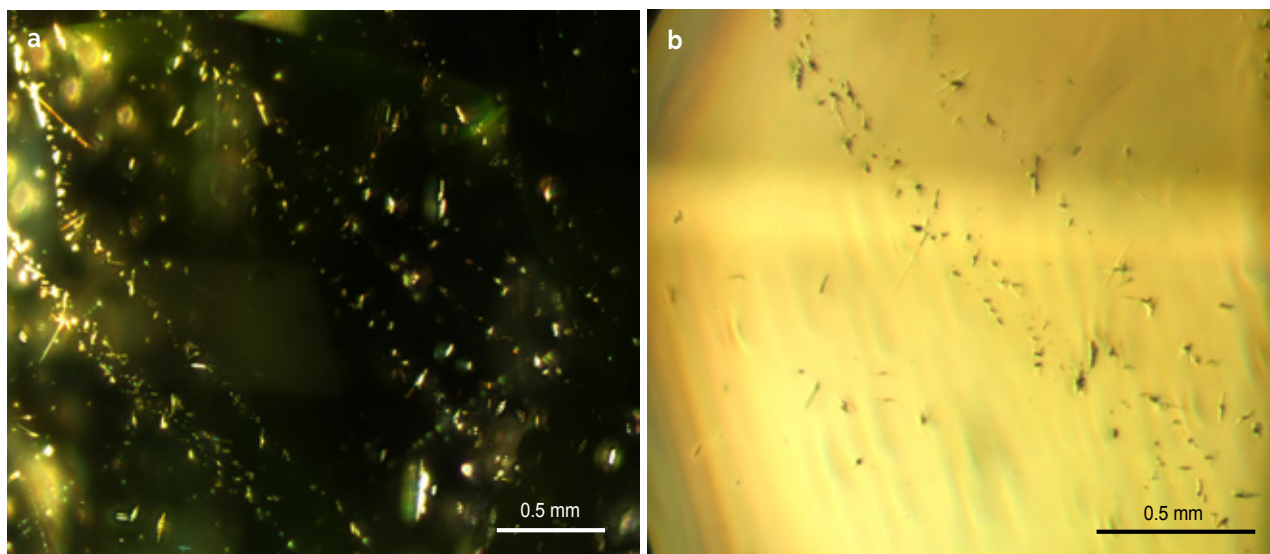


Figure 14: The Tanzanian peridot contains strings of colourless particles, as seen here in the faceted sample in (a) darkfield and (b) brightfield illumination. Photomicrographs by C. Schwarzsinger.

faceted stone). It was inert to long- and short-wave UV radiation. Microscopic examination revealed strings of tiny colourless particles, which were mostly seen in the faceted stone (Figure 14), while one of the rough pieces contained some tiny black crystals spread throughout the sample (Figure 15). Some of these seemed to be rounded, or at least not well formed, while others showed perfect octahedral shape. They were identified as chromite or magnetite by confocal Raman spectroscopy; due to the low signal-to noise-ratio, it was not possible to confirm the specific species present.

The UV-Vis spectrum (Figure 16) displayed strong absorption below 350 and above 840 nm,

and bands at around 380, 400, 447, 471, 494, 528 and 637 nm, which are all due to Fe^{2+} (Adamo *et al.* 2009; Seneewong-Na-Ayutthaya *et al.* 2021). Overall, the spectrum shows strong similarities to peridot from other localities.

The chemical composition of the three samples was determined by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS; instrumental details and operating conditions were as reported by Schwarzsinger 2022). Assuming one Si atom per formula unit, the calculated formula is $\text{Mg}_{1.83}\text{Fe}_{0.16}\text{SiO}_4$, corresponding to a mixture of 92% forsterite and 8% fayalite. The peridot also contained moderate amounts of Ni and Mn,

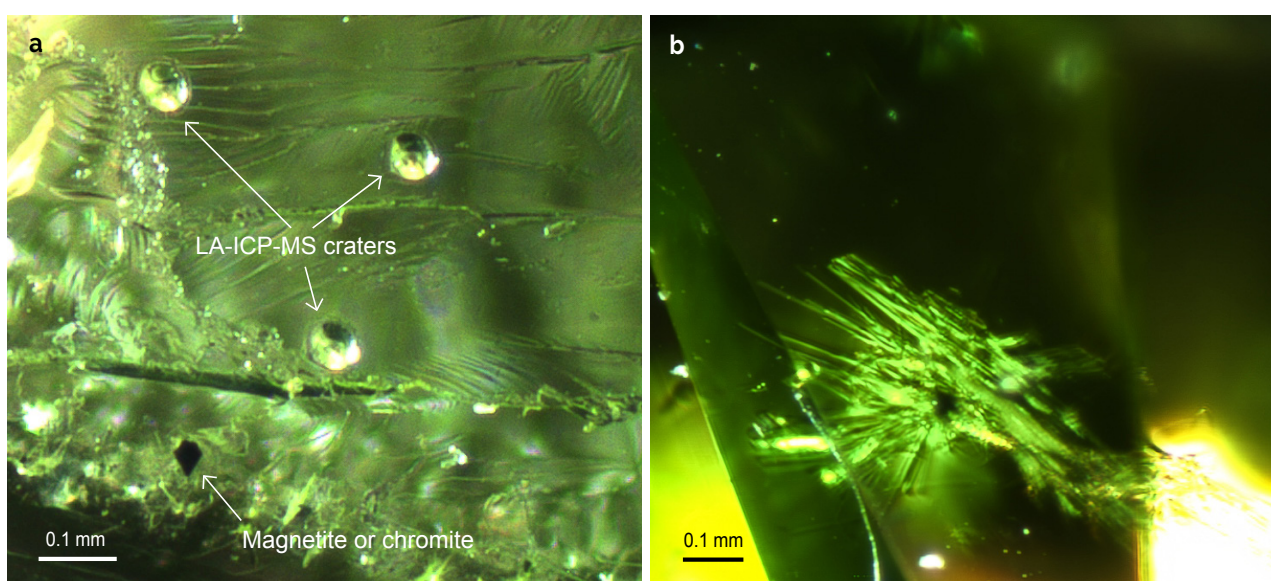


Figure 15: Also present in the Tanzanian peridot are solid black inclusions of magnetite or chromite, which (a) can show octahedral crystal form and (b) may be surrounded by swirl-like features. Photomicrographs by C. Schwarzsinger.

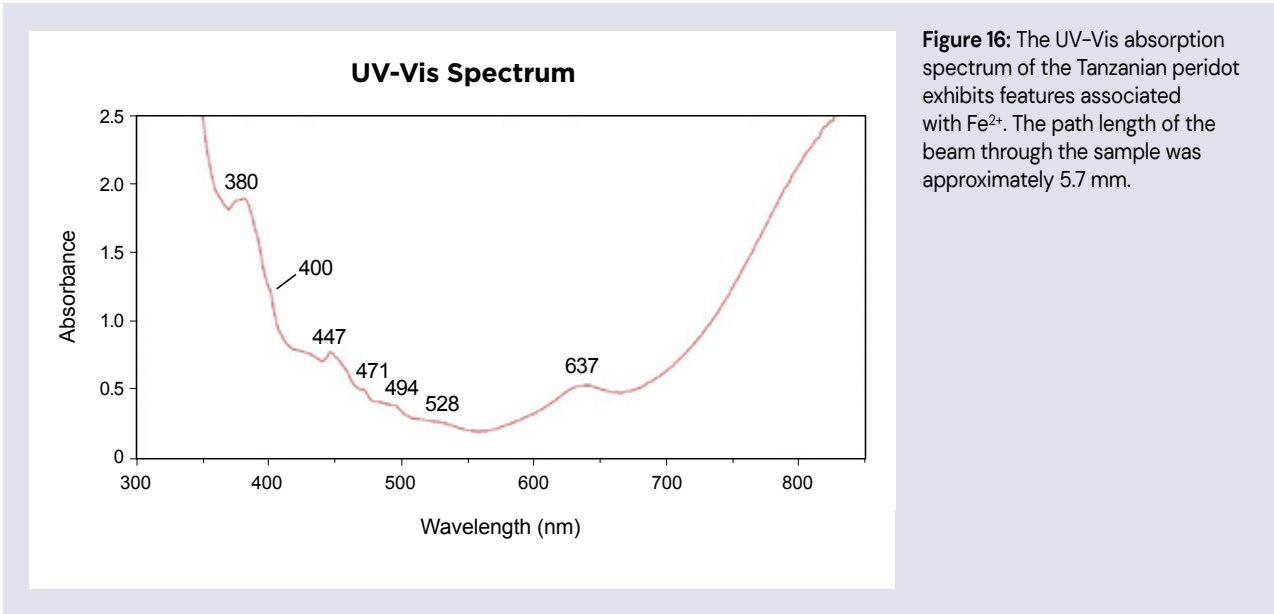


Table I: Chemical composition of the Tanzanian peridot determined by LA-ICP-MS.^a

Sample	Rough 1	Rough 2	Gemstone	Average (n = 9) ^b
Major elements (wt.%)				
Mg	31.38	29.56	31.58	30.84
Si	19.74	19.10	20.06	19.63
Fe	6.187	6.428	6.368	6.330
Minor and trace elements (ppmw)				
Al	21.88	53.34	10.68	29.00
Cr	24.11	9.392	21.65	18.00
Mn	1150	993	1080	1080
Co	105.0	135.4	124.5	122.0
Ni	3280	4060	3530	3620
Zn	15.60	27.81	19.06	21.00

^a Values shown for each specimen are averages of three spots analysed per sample.

^b Equivalent oxide values for the average major elements are 51.13 wt.% MgO, 42.02 wt.% SiO₂ and 8.14 wt.% FeO.

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Phenakite from Volodarsk-Volynski, Ukraine

Miarolitic granitic pegmatites in Ukraine's Volodarsk-Volynski region (renamed the Khoroshiv region in 2015) have been known for decades for producing spectacular gem crystals of beryl and topaz that are coveted by collectors. In addition, pegmatites in this region have occasionally produced gem-quality phenakite (Lyckberg *et al.* 2009), which is a beryllium silicate mineral (Be_2SiO_4) that crystallises in the trigonal system. The mineral is colourless to very pale pink or yellow, and has a Mohs hardness of $7\frac{1}{2}$ –8. Faceted examples are not commonly encountered, and phenakite is typically considered a collector's stone, although it is durable enough for use in jewellery.

In July 2023, gem and mineral dealer Dudley Blauwet (Dudley Blauwet Gems, Louisville, Colorado, USA) faceted some phenakite gemstones from a damaged crystal that he obtained from a Ukrainian miner. The largest stone was fairly clean and weighed 2.45 ct. Blauwet loaned three of the gems for this report (0.47–0.69 ct; Figure 17). All of them were colourless and had an excellent polish with good light return. They had RIs of 1.654–1.670, and a birefringence of 0.016, which are typical for phenakite. Their SG values ranged from 2.98 to 3.08, which are somewhat higher than reported in the literature (e.g. 2.93–3.00; O'Donoghue 2006). The stones were inert to long- and short-wave UV radiation. Each of them displayed distinctive and quite different internal features. The 0.49 ct pear-shape sample was remarkably free of inclusions, with a few thin, randomly oriented needles visible with the microscope. The 0.69 ct rectangular step cut displayed clusters of etch/growth tubes, mostly with parallel orientation (e.g. Figure 18a). The 0.47 ct round-cut stone was more heavily included, with negative crystals and



Figure 17: The three faceted Ukrainian phenakite gemstones examined for this report consist of a 0.49 ct pear with excellent clarity, a 0.47 ct round containing two-phase and negative inclusions, and a 0.69 ct rectangular step cut with distinctive etch tubes. Photo by Breanna McKinney, JTV.

two-phase (liquid and gas) inclusions (Figure 18b), but no needles or etch tubes.

Raman spectroscopy yielded results that closely resembled the reference spectra for phenakite in the RRUFF (<https://rruff.info/Phenakite/R050137>) and Magilabs databases. EDXRF chemical analysis showed weak indications of Fe, Ge and Ca in all three samples. FTIR spectroscopy of the three samples yielded a significant OH signature, consistent with the features recorded for phenakite at http://minerals.gps.caltech.edu/FILES/Infrared_OH/Phenakite/INDEX.html. Although phenakite is a nominally anhydrous mineral, it is not uncommon for it (and other 'anhydrous' minerals) to contain traces of hydroxide ions (Rossman 1996).

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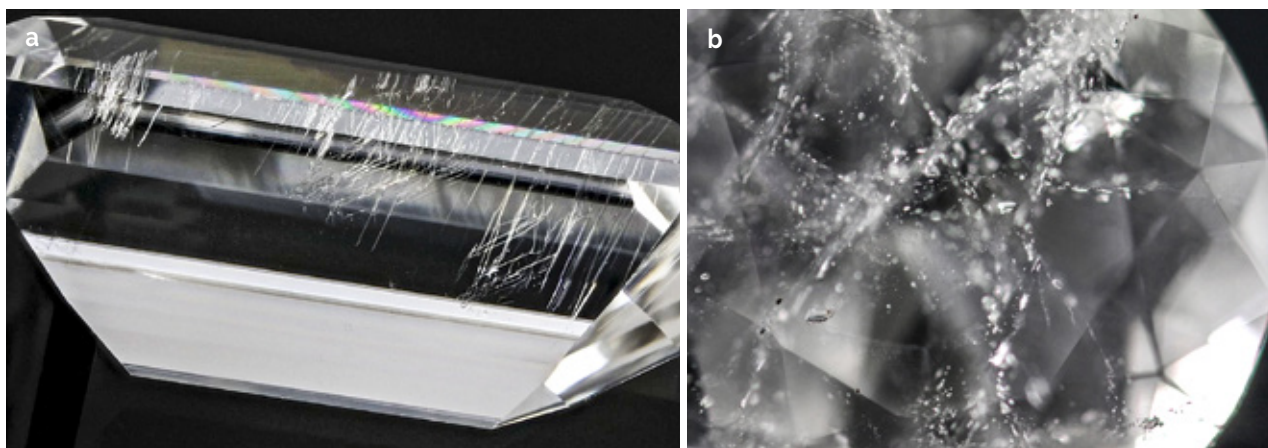


Figure 18: (a) A series of etch tubes create distinctive internal features in the 0.69 ct phenakite. (b) The 0.47 ct phenakite contains networks of two-phase (liquid and gas) inclusions and negative crystals. Photomicrographs by Breanna McKinney, JTV; image widths (a) 6.5 mm and (b) 2.8 mm.

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An Ancient Engraved Pyrite Gem Featuring Aphrodite

There has been a long human association with pyrite, the golden-yellow iron disulphide (FeS₂) mineral commonly called *fool's gold*. Ötzi, the so-called 'Iceman', whose 5,000-year-old body was found in 1991 high in the Ötztal Alps (between Austria and Italy), carried on him a piece of pyrite for striking to make sparks to produce fire. The name *pyrite* comes from the Greek word for *fire*, πυρίτης (pyrites). The stone has borne various names at various times and places—often simply *firestone* or its equivalent in other languages, but there were numerous more localised names. In Cornwall, England, for example, miners knew it as *mundic* (see, e.g., Borlase 1758). In a jewellery context, it has generally been known as *marcasite* in English, until after around 1800 when the term *pyrite* was used for the cubic form of iron sulphide and *marcasite* for its orthorhombic form (Blackburn & Dennen 1997). The term *marcasite* ultimately comes from the Arabic *marqazat* or Persian *marqashota* via the Spanish *marcasite*.¹ In the 1491 *Hortus Sanitatus*, the section of *de lapidibus* lists *pyritides* and says the name used for it by the Arabs was *markasita* (Anonymous 1491).

The use of pyrite as an ornamental stone has been sporadic. It has been employed as a cheap substitute for diamond at least from the eighteenth century in European jewellery. In 1913, the British press noted that it had again become popular in jewellery in France, following the discovery of a large deposit in the Jura Mountains in 1846, and that there was a reawakening of interest in England with 'clever English craftsmen' producing beautiful marcasite jewellery (*The Derby Daily Telegraph*, 30 July 1913, p. 2). We can probably include pyrite with various substances used in ancient recipes for the production of acids, but early decorative use has seldom been reported. Ancient beads described as being of pyrite have been recorded from early Egypt, Iran

and Pakistan (Ogden 1982). A small cubic crystal of pyrite was among a large assemblage of various gem materials found at Mahabodhi Temple (Bodhi Gaya) in South India.² The most extraordinary use known to the present author were pyrite crystals studding the soles of a pair of women's leather boots that were excavated in 1947 in a burial at Pazyryk, Altai, Siberia, dating to around 300 BCE.³

The only ancient gold jewellery set with pyrite known to this author is an Early Byzantine gold ring from about the fifth to sixth century CE set with a partly decomposed, flat, circular pyrite inlay engraved with a monogram (Ogden 1982, p. 105 and figure 5.9) seen some 45 years ago. A few years later, the author was shown a simple little Roman engraved gem, said to be from Egypt (Figure 19). The owner had thought it to be garnet, but examination with a loupe revealed it was pyrite. An opportunity to study it again in more detail arose recently.

The gem has a shiny, wine-red appearance and is approximately circular, averaging about 1 cm in diameter and 2 mm thick. It bears a somewhat cursorily engraved figure of the Greek goddess of love and



Figure 19: A Roman engraved gem in pyrite depicts an image of the goddess Aphrodite, which has been cut through a reddened surface. It has an average diameter of 1 cm (and a thickness of 2.0 mm), and is shown from the front (left) and back (right). Private collection; composite photo by J. M. Ogden.

¹ For example, it was used as an ingredient in enamels in the medieval Arabic recipes of Nishaburi (Rogers & Bayani 2013).

² British Museum reg. no. 1892,1103.64. The excavation was published, but gem finds were not itemised, in Major-General Sir Alexander Cunningham's excavations (Cunningham 1892).

³ Pazyryk, Altai, Siberia, barrow no. 2. H. 36 cm. Hermitage Museum, St Petersburg, Russia. Inv. no. 1681/218 (see Rudenko 1953, pp. 118–121, pl. XXV,2; Anonymous 1973–1974, p. 120, cat. no. 125).

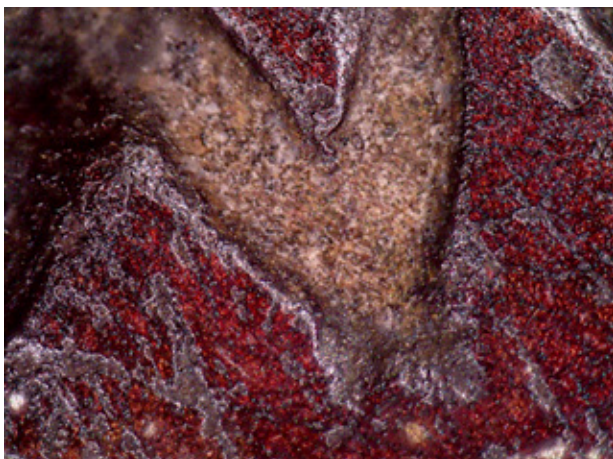


Figure 20: A detail of the gem in Figure 19 shows Aphrodite's 'gold'-coloured engraved left arm and the red surface layer. Photomicrograph by J. M. Ogden.

beauty, Aphrodite, known as Venus in Roman times. She is shown naked, wringing out her long hair—a diminutive version of Aphrodite Anadyomene—representing the goddess's birth, rising from the sea. This form of Aphrodite was particularly popular in Roman jewellery from Egypt (Ogden 1990).

That the material is pyrite is clear, not least from the fracture on the back, which shows the cubic structure. As confirmation, portable X-ray fluorescence spectroscopy analysis revealed peaks for Fe and S. A noteworthy feature, however, is the bright red surface. This is quite different from the rust-like crust on the pyrite in the Early Byzantine ring mentioned above. That this red surface was simply 'tarnish', the result of long burial, is countered by the engraving that cuts through it (Figure 20). The implication is that the red surface colour was deliberately produced, and then the engraving was incised to reveal Aphrodite in 'gold' against a red surround. It is a striking image, despite the small size and relatively inferior quality of the engraving. The engraved depressions show the now-degraded surface of pyrite, while the surface treatment has somehow protected the red-coloured area.

The use of deliberate colour contrast for engraved gems is well known from the Roman world with carnelian. The stone's surface was bleached by painting it with an alkali solution, followed by heating (Ogden 2007). Such Roman (and contemporary Sassanian Persian) engraved gems were produced in two ways: (1) the shaped carnelian could be polished, bleached white all over and then incised through the surface layer to reveal the red beneath, or (2) the stone was engraved first, followed by bleaching, and then the front face (and sometimes other faces) was polished again, leaving the engraved design in white (Ogden 2007).

The present engraved gem featuring a representation of Aphrodite is the only example of an apparently ancient, treated pyrite of which this author is aware. Although there is a possibility that the red surface is due to natural tarnish, this does not appear to be so. If the red background was indeed deliberately produced, this provides another fascinating example in the history of gem use and constant human endeavours to adapt or improve on nature.

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Sapphires from Chimoio, Mozambique

In January 2023, gem dealer Dudley Blauwet informed author BML about some interesting new sapphires that he obtained from Chimoio in central Mozambique, about 100 km east of the border with Zimbabwe. The sapphires are notable for their range of colour and diversity of inclusions, and in some cases they display a noticeable schiller effect when viewed at certain orientations with a pinpoint light source. The largest clean stones that Blauwet obtained consisted of an orangey brown-pink gem weighing 3.75 ct and two red-orange gems weighing just over 3 ct. He also cut several smaller round brilliants measuring 3.0, 3.5 and 4.5 mm in diameter that showed various colours ranging from pink to purplish pink, brownish pink and reddish orange. Two of the 3.0 mm gems were red enough to be classified as ruby.

According to Blauwet's supplier, the mining area is located about 50–70 km from Chimoio. This region is underlain by a series of high-grade gneiss units of the Mozambique Belt adjacent to the north-eastern boundary of the Kalahari craton (Manhica *et al.* 2001). Sapphires have been known from the Chimoio area since at least 2009 (Shigley *et al.* 2010), but the present authors are not aware of any reports on their properties.

In July 2023, Blauwet loaned 12 Chimoio sapphires weighing 0.81–2.29 ct for examination (Figure 21), and five of them displayed some areas of schiller (e.g. Figure 22). Gemmological testing by author NDR yielded the following properties: average RIs—1.763–1.771 with a birefringence of 0.008, hydrostatic SG—3.97–4.00, and UV fluorescence—a



Figure 22: A 2.29 ct Chimoio sapphire shows areas of schiller due to platelets and needles of rutile (and possibly hematite). Photo by Diego Sanchez, © GIA.

weak red reaction to long-wave UV and inert to short-wave UV radiation. Microscopic examination revealed several types of inclusions (identified visually), including platelets and needles of rutile (and possibly hematite), apatite crystal clusters, healing planes composed of irregular crystallites, colourless zircon crystals, and irregular polymineralic inclusions containing unidentified dark red (nearly opaque) and colourless components (Figure 23). The schiller effect displayed by some of the sapphires was caused by the platelets and needles of rutile (possibly with hematite), sometimes in combination with reflective parting planes.

UV-Vis-NIR spectroscopy of a pink sample showed a cutoff below approximately 440 nm, a modest 450 nm Fe-related absorption feature and a broad 560 nm

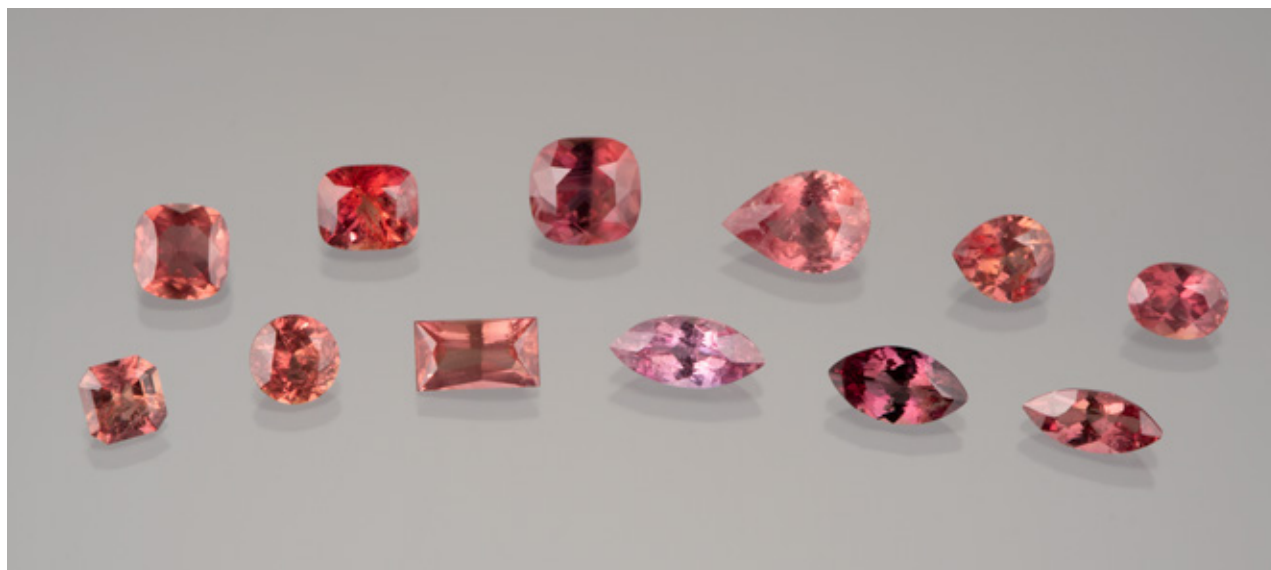


Figure 21: This group of sapphires (0.81–2.29 ct) from Chimoio, Mozambique, was examined for this report. Photo by Diego Sanchez, © GIA.

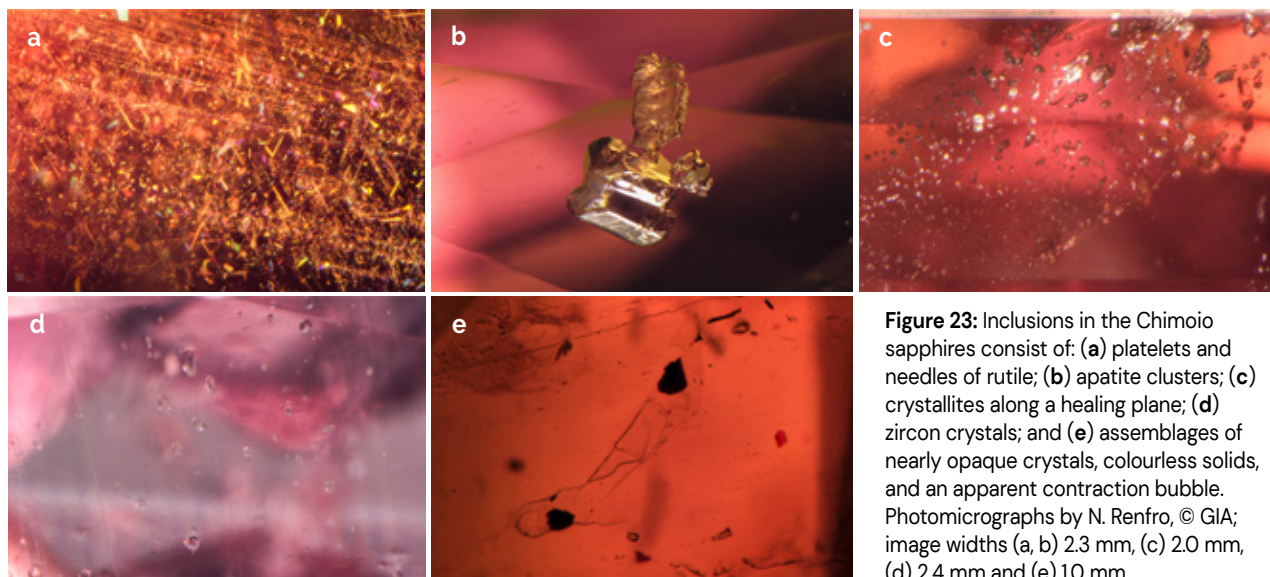


Figure 23: Inclusions in the Chimoio sapphires consist of: (a) platelets and needles of rutile; (b) apatite clusters; (c) crystallites along a healing plane; (d) zircon crystals; and (e) assemblages of nearly opaque crystals, colourless solids, and an apparent contraction bubble. Photomicrographs by N. Renfro, © GIA; image widths (a, b) 2.3 mm, (c) 2.0 mm, (d) 2.4 mm and (e) 1.0 mm.

Cr-related absorption band. A prominent Cr^{3+} emission feature was also recorded at approximately 694 nm. FTIR spectroscopy revealed the presence of boehmite in some samples, as well as a small absorption feature at 3309 cm^{-1} .

LA-ICP-MS trace-element analysis of the sapphires was performed with a Thermo Scientific iCap-Q ICP-MS (plasma RF power of 1,400 W) coupled with a New Wave Research UP-213 laser ablation unit with a frequency-quintupled Nd:YAG laser. The ablation conditions used were a 55 μm diameter ablation spot, a fluence of approximately 10 J/cm^2 and a 15 Hz repetition rate. The analyses showed 3590–8750 ppmw Fe, 385–854 ppmw Cr, 31.3–46.7 ppmw Ga, 22.2–63.4 ppmw Mg and 12.1–17.6 ppmw V.

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Hazy Spinel from Mahenge, Tanzania

Since the 1980s, the Mahenge region of Tanzania has been an important source of attractive pink-to-red spinel. Large transparent gemstones have been cut, but the area is also known for producing ‘pinkish

and often sleepy stones’ (Pardieu & Hughes 2008, p. 17). Recently, gem dealer Bryan Lichtenstein (3090 Gems, San Francisco, California, USA) provided three of these spinels (Figure 24) for examination



Figure 24: Three spinels (1.77–3.00 ct) from Mahenge, Tanzania, were examined to investigate the cause of their hazy appearance. Photo by B. Williams.

so that the cause of their hazy appearance could be investigated.

Gemmological characterisation by authors BW and CW yielded an RI of 1.720 and a hydrostatic SG value of 3.58 for all three stones, which are typical for spinel. They showed strong red luminescence to 405 nm excitation (stronger than from standard long- or short-wave UV lamps). The stones were transparent with a slightly milky quality, and exhibited a girasol-like appearance similar to that seen in some quartz or highly fluorescent diamonds. Viewed with a gemmological microscope and up to 50× magnification, the specimens showed an overall slightly cloudy appearance, and one stone contained some bent-shaped acicular inclusions (Figure 25) that probably consisted of dissolved dislocations.

IR spectroscopy with a Magilabs GemmoFtir unit showed typical features for pink-to-red spinel, with no significant OH content. PL spectroscopy with a Magilabs GemmoRaman-532SG instrument yielded a typical PL pattern for natural pink-to-red spinel, although there were a couple of anomalous peaks in the spinel-fingerprint area of the spectrum that could not be matched with any reference spectra in the RRUFF database. EDXRF chemical

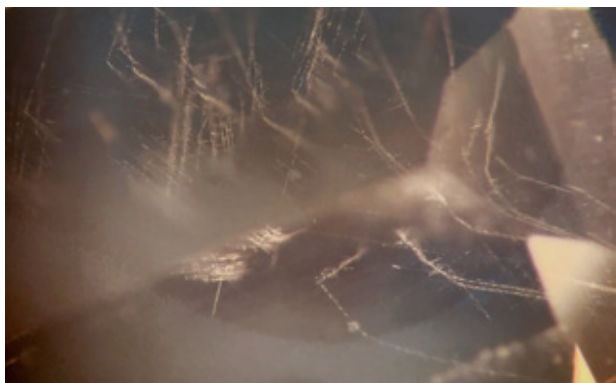


Figure 25: In addition to an overall slightly cloudy appearance, this Mahenge spinel contains some bent-shaped acicular inclusions. Photomicrograph by B. Williams; image width 4.5 mm.

analysis with an Amptek X123-SDD spectrometer showed a typical composition for Tanzanian spinel, but with somewhat elevated Fe and Ti, along with Zn and Cr.

To further investigate the cause of the turbidity, a scanning electron microscope (SEM) study of one of the stones was conducted by authors CM and GRR using a Zeiss LEO 1550VP field-emission SEM equipped with an Oxford X-Max SDD X-ray energy dispersive spectrometer (EDS) for chemical analysis. A series of inclusions ranging from a little over 100 nm to nearly 900 nm long and up to about 30 nm wide were visible just below the gem's table (e.g. Figure 26). EDS analysis showed that the inclusions were highly enriched in Ti compared to the adjacent region of the stone, suggesting that they were TiO₂ (i.e. rutile or anatase).

Using an INAM Expert 3L desktop spectrometer, EDXRF chemical analyses of the three gems showed the following elements (in addition to the expected major amounts of Mg and Al): 0.60–0.85 wt.% Zn; 0.47–0.57 wt.% Fe; 0.03–0.05 wt.% Si; 0.03–0.05 wt.% Cr; 0.02–0.03 wt.% Ti, 0.01–0.02 wt.% V; 0.02–0.03 wt.% Ga; and traces of Sn and Ni. Raman spectra were obtained from several spots in an attempt to obtain a Raman pattern that would indicate whether the inclusions were rutile or anatase. Because the inclusions were both below the surface of the stone and generally smaller than the wavelength of visible light, they could not be seen in the optical microscope of the Raman instrument. After many attempts, no Raman spectral patterns were obtained that showed the presence of an inclusion which exceeded the (low) background noise level of the spinel pattern.

It is likely that the micro-inclusions causing the hazy appearance of this spinel consist of rutile, in view of the frequent occurrence of rutile inclusions

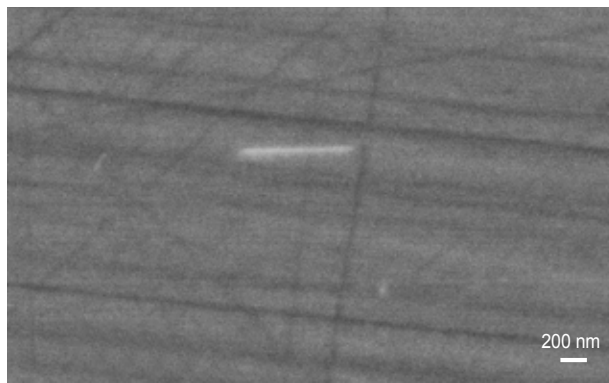


Figure 26: This backscattered electron image shows one of the larger Ti-rich inclusions in the turbid spinel. Also seen are dark polishing lines in the surface of the stone. Image by Chi Ma.

in various gem materials. However, no direct confirmation of this identity could be obtained via the non-destructive analyses of this study.

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DIAMONDS

A Borderline Type IIa-IIaA Diamond

A 10.97 ct oval-shaped diamond ($18.50 \times 12.32 \times 7.51$ mm) with E colour and IF clarity recently attracted our attention (Figure 27). Large, high-purity and high-colour (D–F) diamonds are often type IIa, but the FTIR absorption spectrum of this diamond revealed a trace of A aggregates (peak at 1280 cm^{-1} ; Figure 28). It showed very weak blue luminescence to long-wave UV radiation and was inert to short-wave UV. A weak cross-hatched ‘tatami’ pattern, with first-order interference colours, was visible between crossed polarising filters (Figure 29). This pattern is also reminiscent of type IIa diamond, which is often strongly deformed.

Together with the 1280 cm^{-1} A-aggregate absorption in the FTIR spectrum was a very weak sharp band at 1332 cm^{-1} (again, see Figure 28). A PL spectrum

obtained at liquid-nitrogen temperature with 514 nm laser excitation showed very few features. In addition to the first- and second-order diamond Raman signals, only a weak 741 nm line was present. This feature is due to neutral vacancies, formed presumably through deformation (Breeding & Shigley 2009).

Interestingly, deep-UV luminescence imaging with the DiamondView revealed one area with a distinct yellow-emitting graining pattern (Figure 30) of parallel planes in three different orientations (presumably corresponding to three different octahedral planes). This is often seen in deformed type I



Figure 27: This 10.97 ct diamond with E colour and IF clarity would be expected to be type IIa, but revealed weak type IIaA nitrogen features in its infrared spectrum. Photo by A. Delaunay, © LFG.

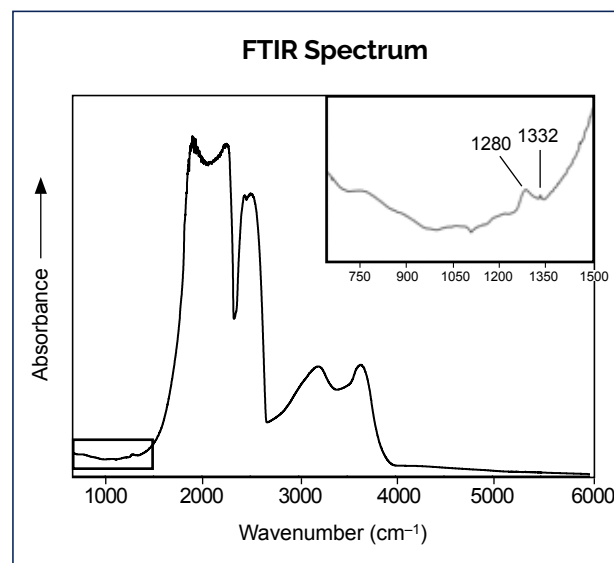


Figure 28: The FTIR spectrum of the stone in Figure 27 shows overall features consistent with type IIa diamonds, but a closer look at the $650\text{--}1500\text{ cm}^{-1}$ region (see inset) reveals a weak band at around 1280 cm^{-1} due to A aggregates, which is present along with a very weak sharp band at around 1332 cm^{-1} .



Figure 29: A distinct tatami pattern, with low-order interference colours, is seen in the diamond when viewed with magnification between crossed polarisers. Photomicrograph by A. Delaunay, © LFG; image width approximately 4.4 mm.

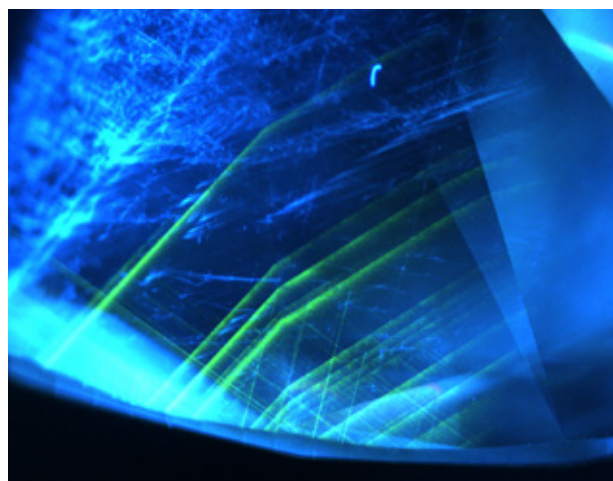


Figure 30: In the DiamondView, the diamond shows a distinct yellow-luminescing graining pattern. A complex pattern of blue-emitting lines due to dislocations is also visible at the top of the view. Photomicrograph by A. Delaunay, © LFG; image width 5.2 mm.

diamonds (Hainschwang *et al.* 2020). However, most of the diamond's volume showed a complex pattern of lines (mostly straight but some curved) emitting strong blue luminescence. We interpret this pattern as being due to dislocations (again related to deformation). In other areas of the stone, these lines formed lozenge-shaped patterns or loops. This appearance is not quite the same as the polygonal network of dislocations observed in typical type IIa diamonds (De Corte *et al.* 2006; Breeding & Shigley 2009). However, it suggests an intermediate state between a 'normal' type Ia diamond with octahedral growth patterns, and a typical type IIa diamond with a pervasive dislocation network.

This large, high-quality gem is thus a rare example of mixed type IIa and type IaA diamond, appearing with FTIR spectroscopy as borderline type IIa-IaA, and showing a unique, complex pattern of dislocations and other deformation-related properties.

TREATMENTS

'Sapphire' Beads Consisting of Stabilised Kyanite

A string of beads (Figure 31a) was recently submitted to the authors' laboratory for confirmation that the stones were sapphire. It consisted of 112 semi-transparent blue rondelles with a diameter of 6.5–6.7 mm. It had a total

length of 40.5 cm and a weight of 168.88 ct (33.77 g). The colour of the rondelles could be described as 'sapphire blue', which is why the client thought they were sapphire. Additionally, the overall colour

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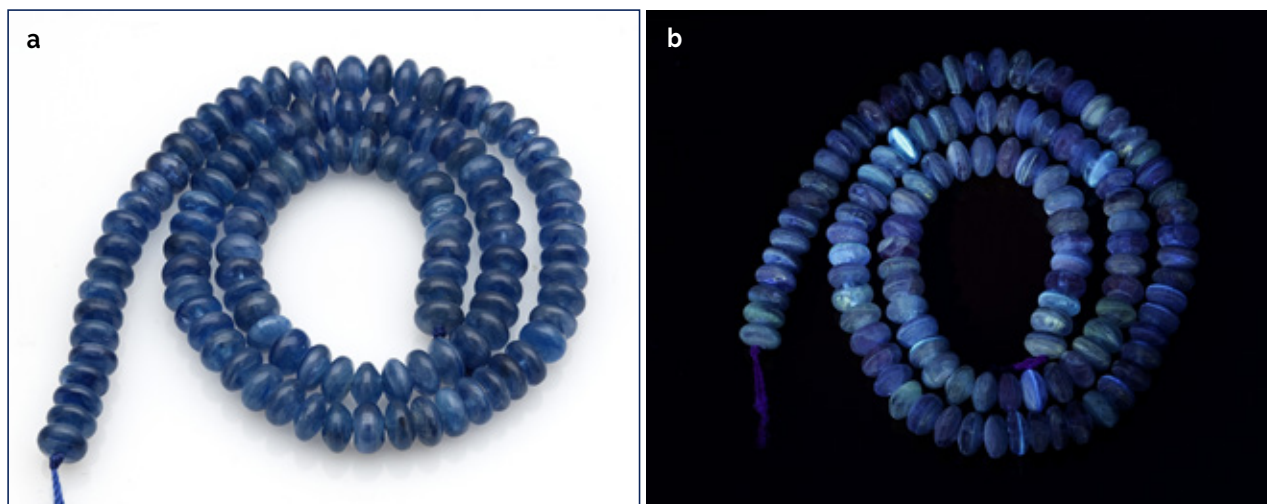


Figure 31: (a) This string of rondelles (6.5–6.7 mm diameter) was represented as sapphire, but was found to consist of kyanite stabilised with a filler consisting of coloured artificial resin. (b) Under long-wave (shown here) and short-wave UV radiation, the resin filling fluoresces chalky white. Photos by Q. Wang.

distribution appeared irregular, and the material was clearly colour zoned, as also seen in some sapphires.

The material was identified as kyanite using Raman spectroscopy (Magilabs GemmoRaman-532SG with a 532 nm laser). Gem-quality blue kyanite is known from various deposits (e.g. Nepal since 1995), and the risk of confusion with sapphire has been highlighted previously (e.g. Henn & Schollenbruch 2012). In addition to different RI and SG values, microscopic features can be used to distinguish kyanite from blue sapphire, including the occurrence of cleavage cracks that may show prominent iridescent effects (cf. Henn & Schollenbruch 2012), as seen in some of the present beads.

We also noticed intense blue layers along some of the cleavage cracks (Figure 32), which appeared more transparent than the surrounding material and showed

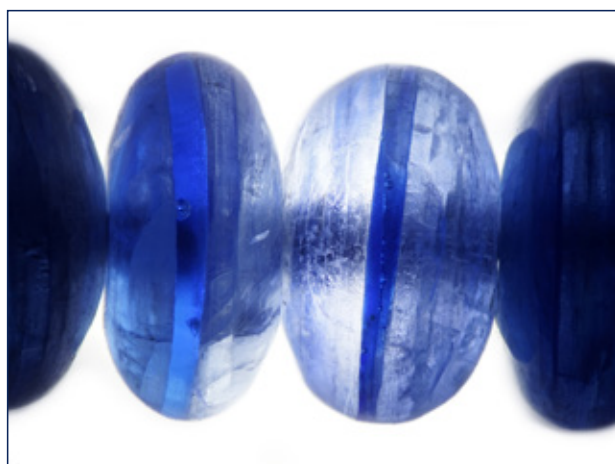


Figure 32: The kyanite rondelles contain cleavage cracks filled with a coloured resin. Gas bubbles are clearly visible in the resin filling. Photomicrograph by Q. Wang; magnified 45 $\times$.

a different shade of blue. With a polarising filter, we observed distinct pleochroism in the beads, but not in these blue layers. Microscopic examination of the layers revealed air bubbles and subtle swirl marks, but no natural-appearing inclusions. In addition, blue colour concentrations were seen along some smaller fissures in the beads.

The beads were mostly inert to UV radiation, except that the intense blue layers mentioned above fluoresced chalky white (Figure 31b) to both long- and short-wave UV, which can be an indicator of artificial resin (Henn *et al.* 2020). Raman spectroscopy of the blue layers confirmed that they were composed of a coloured artificial resin.

Some of the resin-filled areas were extensive enough that the rondelles could have fallen apart if they were not held together along their cleavage fractures. Therefore, we identified the beads as kyanite that was stabilised with the use of coloured resin. According to the wording recommended by LMHC Information Sheet #5 (LMHC 2023), this would be termed ‘kyanite with coloured resin’.

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Coated Synthetic Sapphire as an Imitation of Co-blue Spinel

The colour of most blue spinel is attributed to the presence of Fe, resulting in a slightly greyish blue hue. However, a trace amount of Co (in the absence of elevated Fe) can cause vibrant blue colouration in both natural and synthetic spinel (Schollenbruch *et al.* 2021). Co-blue spinel is among the rarest varieties of this Mg-Al oxide. In recent years, a new coating treatment has emerged on the market, mimicking Co-blue spinel by depositing a Co-rich film on the surface of synthetic sapphire, reportedly using a high-temperature flux method. Cabochons, beads and faceted gems have been treated by this technique, but faceted samples are less commonly encountered on the market since they tend to have lower lustre than the other types. Two samples of coated synthetic sapphire beads (Figure 33), each weighing 18.1 ct, were selected for characterisation in order to distinguish them from natural untreated Co-blue spinel. Permission was granted to slice one piece to facilitate examination.

Standard gemmological testing revealed a spot RI of about 1.77 and a hydrostatic SG of 3.99, identifying the beads as corundum. The samples were inert to long-wave UV radiation but exhibited chalky blue fluorescence to short-wave UV, which is consistent with synthetic sapphire (Hennebois *et al.* 2022). Microscopic examination revealed that both



Figure 33: These two beads (18.1 ct each), imitating Co-blue spinel, were found to consist of coated synthetic sapphire. Photo by S. Li.

samples were relatively devoid of inclusions, but they showed lighter-coloured abraded areas around their drill holes, (Figure 34a). Furthermore, certain areas of the samples exhibited irregular colouration. Magnification of their surfaces displayed unevenness (scratches and pits) and concentrated patches of blue colour (Figure 34b).

Upon slicing one of the synthetic sapphire beads in half, we observed that the blue colour formed a thin layer on the surface, consistent with the presence of a surface coating, while the remainder of the sample was colourless (Figure 35a). Further inspection with a Chelsea Colour Filter showed a vivid red reaction

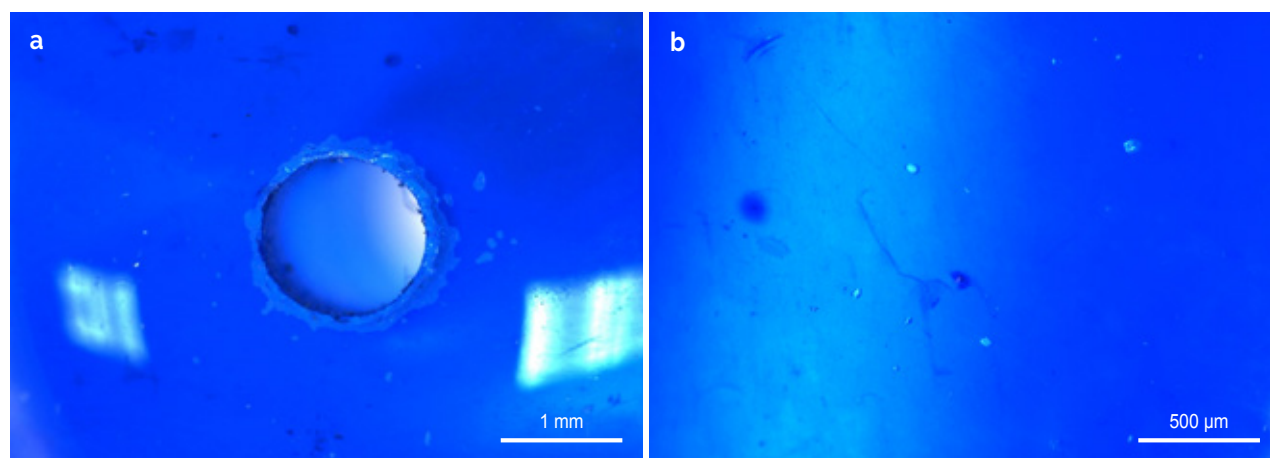


Figure 34: Microscopic examination of the synthetic sapphire beads shows surface characteristics indicative of a coating substance, including (a) lighter-coloured abraded areas adjacent to a drill hole, and (b) concentrated patches of blue colour along with colour anomalies corresponding to scratches and pits in reflected light. Photomicrographs by S. Li.

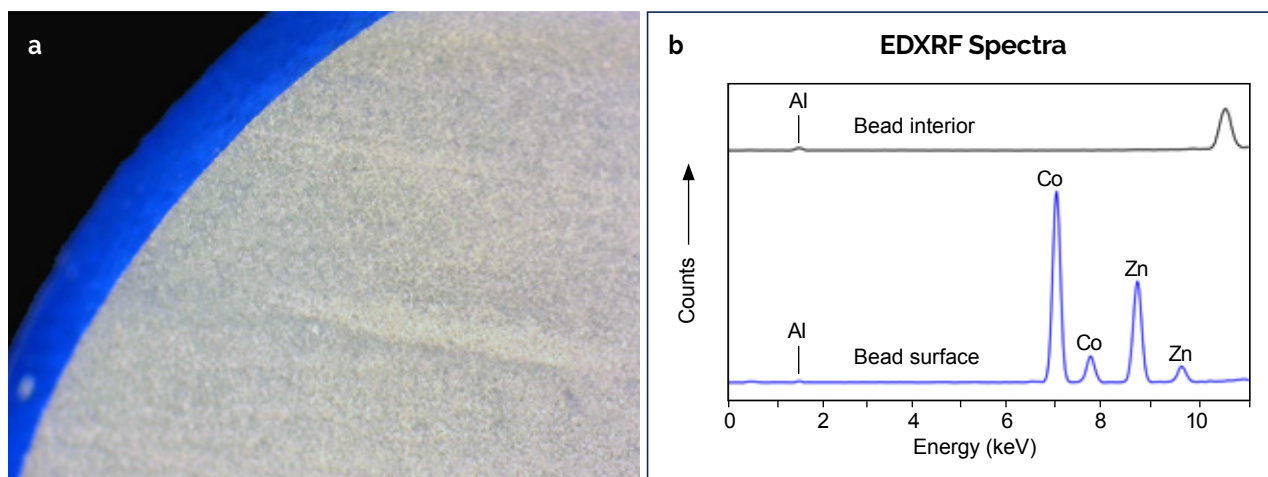


Figure 35: (a) Microscopic examination of the cut surface of this synthetic sapphire bead reveals that the blue colour is limited to a thin surface layer, indicating the presence of a coating. (b) EDXRF spectroscopy of the outer surface of the sliced bead shows distinct Co and Zn peaks, corresponding to the blue coating. However, only Al was detected in the interior portion of the bead, consistent with colourless synthetic sapphire. (The peak at the high-energy side of the spectrum was not found in the authors' EDXRF database.) Photomicrograph by S. Li; image width 8.8 mm.

only for the sample's surface, reinforcing the conclusion that the blue colour was superficially applied.

Reflectance UV-Vis spectroscopy of the coated surface exhibited no notable differences from that of Co-blue spinel (cf. Chauviré *et al.* 2015), with bands at 543, 571 and 630 nm associated with Co^{2+} . EDXRF spectroscopy revealed elevated concentrations of Co and Zn on the surface, but not in the colourless interior (Figure 35b).

Further examination with a scanning electron microscope revealed details of the abrasions near the drill holes that clearly differentiated between the coated and uncoated areas (Figure 36). SEM-EDS analysis confirmed the presence of Co, Zn and Mg in the coating, which was determined to be approximately 8–11 μm thick.

Natural Co-blue spinel can be reliably distinguished from this coated synthetic sapphire by a combination of physical properties (including RI and SG) and surface

features (colour anomalies in scratches and pits, as well as patchy blue colouration). Additional evidence of the coating may be seen along the edges of drill holes (when present). In addition, the presence of elevated amounts of Co and Zn ($\pm$ Mg) on the surface of a sample is distinctive. Of course, it would also be extremely unlikely to encounter Co-blue spinel on the market as such large and transparent beads.

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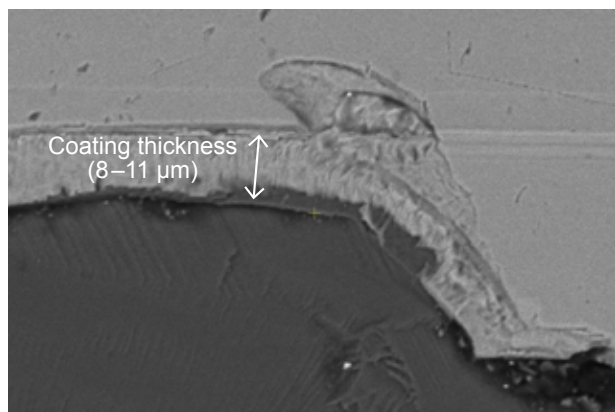


Figure 36: An SEM image near the drill hole of one of the synthetic sapphire beads shows that the coating has a thickness of 8–11 μm . Image by S. Li; magnified 2,500 $\times$.

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Cobalt-Blue Spinel from Baffin Island, Canada: Comparison to Other Mg-Al Spinel and a Chemical Discrimination Approach for the Colouration of Spinel

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ABSTRACT: Cobalt-blue spinel from two localities (Qila and Trailside) on Baffin Island, Nunavut, Canada, are compared with other spinels from 12 occurrences in the same geological terrane and to Co-bearing blue spinel from other localities worldwide. Qila spinel is suitable for cutting cabochons, which commonly incorporate small amounts of associated calcite, dolomite, corundum, fluorapatite, pargasite and other silicates, as well as secondary cobaltpentlandite and fluid inclusions. Trailside spinel can be faceted into small gemstones (generally <0.2 ct), which rarely contain magnesite, fluorapatite, muscovite and CO₂-rich fluid inclusions. The bright blue colour of the spinels from Qila and Trailside is due to Co^{2+} , although they also contain other chromophoric elements such as Fe and traces of Cr, Mn and V. Compared with other Mg-Al spinels from Baffin Island, those from Qila and Trailside are generally enriched in Co, Ni, Mn, Li and Be, and depleted in Ti, V and Cr. In addition, the Qila and Trailside Co-blue spinels are fairly chemically distinct from those of other world localities: they are depleted in V and Ti, fairly poor in Cr and Zn, and considerably enriched in Co and Mn. A new approach for the preliminary chemical discrimination of gem spinels is proposed by plotting the weighted chromophore concentrations in a ternary diagram (i.e. Cr+V vs $40 \times \text{Co}$ vs Fe/8). These weighted percentage values are also plotted against the ppmw concentrations of the chromophoric elements in X-Y plots, which provide further correlations of high Co with vivid Co-blue spinel and elevated Fe with overly dark non-gem spinel. This method can be applied to samples that are difficult or inefficient to characterise using spectroscopy, such as spinel grains in heavy-mineral concentrates obtained during regional exploration programmes.

The Journal of Gemmology, 39(3), 2024, pp. 220–240, <https://doi.org/10.15506/JoG.2024.39.3.220>
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Cobalt-blue spinel has been described from multiple countries, including Vietnam (Chauviré *et al.* 2015; Kuksa *et al.* 2019), Tanzania (Krzemnicki *et al.* 2023), Sri Lanka (Harder 1986; Krzemnicki *et al.* 2023), Pakistan (Schollenbruch *et al.* 2021) and Canada

(Belley & Groat 2019; see Figure 1). With the discovery of new sources of this rare spinel variety in the past few years, there is growing interest in understanding the gemmological and geochemical characteristics of stones from these deposits, which are relevant for origin determination.

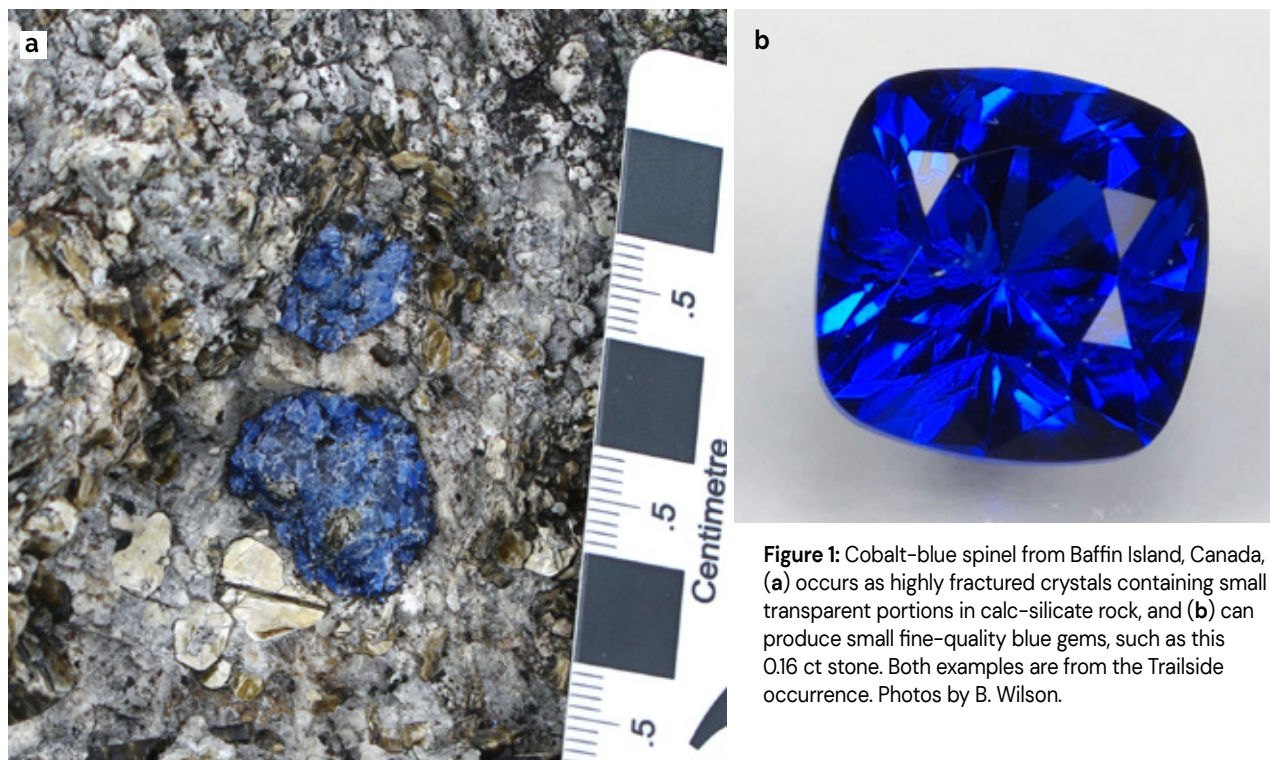


Figure 1: Cobalt-blue spinel from Baffin Island, Canada, (a) occurs as highly fractured crystals containing small transparent portions in calc-silicate rock, and (b) can produce small fine-quality blue gems, such as this 0.16 ct stone. Both examples are from the Trailside occurrence. Photos by B. Wilson.

The colour of Mg-Al spinel is due to Fe^{2+} , Fe^{3+} , Cr^{3+} , Co^{2+} and, to a lesser degree, V^{3+} and Mn^{2+} , in addition to the tetrahedral (T-site) or octahedral (M-site) coordination of Fe in the spinel structure (Schmetzer *et al.* 1989; Hålenius *et al.* 2002; Bosi *et al.* 2012; D'Ippolito *et al.* 2015; Kleišmantas & Daukšytė 2016; Andreozzi *et al.* 2018). Spinel generally becomes darker and less attractive, and eventually black, with high Fe concentrations (e.g. Kruzslicz *et al.* 2020). Studies of the trace-element composition of Mg-Al spinel from metacarbonate rocks have largely focused on high-quality gems, represented by stones rich in $^{\text{M}}\text{Cr}^{3+}$ or $^{\text{T}}\text{Co}^{2+}$ (chromophores causing attractive pink-to-red and blue colouration, respectively; e.g. Malsy & Klemm 2010; Chauviré *et al.* 2015; Kuksa *et al.* 2019). These exceptional gem-quality spinels are seldom compared to their more ordinary counterparts found in the same geological settings. Therefore, there is a relative paucity of trace-element data for the latter; most datasets for non-gem metacarbonate-hosted spinel consist of electron microprobe analyses (e.g. Frost 1991 and references therein), with insufficient precision and levels of detection for comparison with trace-element data collected using mass spectrometry (and often without any measurements of Co and Ni).

The purpose of the present study is to (1) report new data on the gemmological properties, internal features and trace-element concentrations of Co-blue spinel

from two occurrences on Baffin Island, Nunavut, Canada; (2) compare the chemical compositions of these Co-blue spinels to those of other Mg-Al spinels from Baffin Island; and (3) compare Co-spinels from Baffin Island to those from other sources worldwide.

BAFFIN ISLAND SPINEL OCCURRENCES

Spinel occurrences are widespread in the Lake Harbour Group rocks of Baffin Island, Nunavut, Canada (Grice *et al.* 1982; Wilson 2014, 2020; Belley & Groat 2019; see Figure 2), with the earliest written record describing lilac-coloured crystals too highly fractured for use as gem material (Walker 1915).

The Qila and Trailside Co-blue spinel occurrences are located in the vicinity of the Beluga sapphire pit (Belley & Groat 2019), which is situated 2.2 km south-south-west of the hamlet of Kimmirut (formerly Lake Harbour) on southern Baffin Island (again, see Figure 2). In 2005, True North Gems Inc. announced that Co-blue spinel had been discovered on their Beluga sapphire property by company geologist Massoud Robatian (Rohtert & Shortt 2005). The occurrence—originally named ‘Beluga’ by True North Gems, but now called ‘Qila’—is located 900 m south of the sapphire deposit (Wilson 2014; Belley *et al.* 2017). Later, Williams (2009) reported that this Co-bearing spinel contained surprisingly little Fe. A second

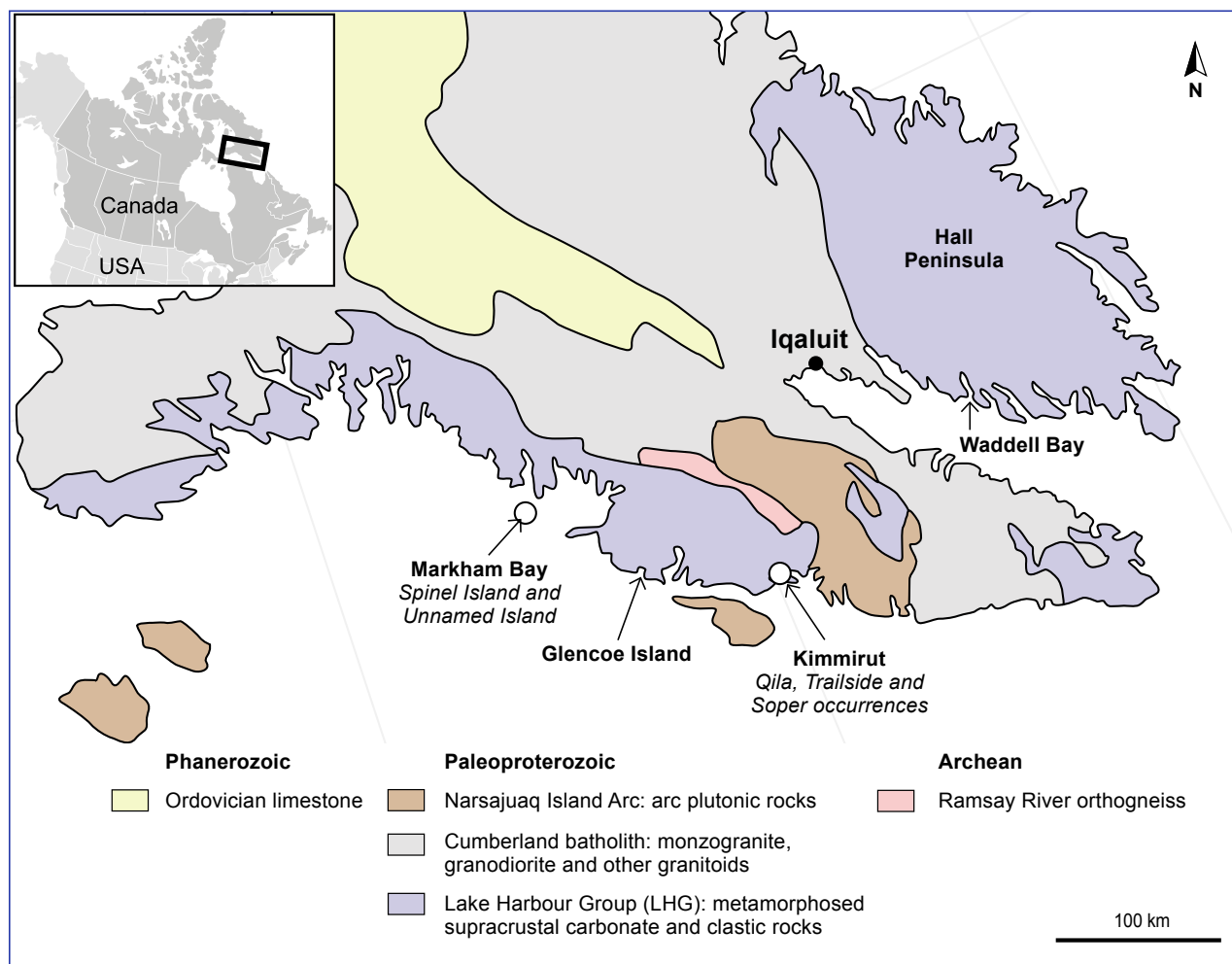


Figure 2: Different areas hosting spinel occurrences in the Lake Harbour Group are indicated on a simplified geological map of southern Baffin Island, Nunavut, Canada. Modified after St-Onge *et al.* (2000), Butler (2007), and Belley and Groat (2019).

occurrence of Co-blue spinel, located approximately 1 km north of the sapphire occurrence, was later identified in the summer of 2005. This locality, shown to two of the authors (LAG and BSW) in the spring of 2006, is now referred to as the ‘Trailside’ occurrence in reference to its proximity to one of the many trails in the area. True North Gems’ claims expired in 2019, and the Trailside spinel and Beluga sapphire occurrences are now part of the later-staked Amaruq claim. The Qila spinel locality is not currently a target for mining or exploration due to its small size.

GEOLOGY

The Lake Harbour Group (LHG), which occurs on the southern coast of Baffin Island (again, see Figure 2), is a supracrustal metasedimentary sequence of marble, calc-silicate rocks, psammite, pelite and quartzite deposited earlier than 1,930 million years ago (Ma) and subjected to regional metamorphism during the Trans-Hudson orogeny (Scott 1997; Scott *et al.* 1997,

2002; St-Onge *et al.* 2009). Prograde granulite-facies metamorphism (810°C, 8.0 kbar) occurred between 1,849 and 1,835 Ma, followed by a high-temperature thermal event around 1,833–1,829 Ma, and subsequent upper-amphibolite-facies metamorphism (720°C, 6.2 kbar) from 1,820 and 1,813 Ma (St-Onge *et al.* 2007). LHG metacarbonates host multiple gem occurrences (Belley & Groat 2020), including spinel (Wilson 2014; Belley & Groat 2019), sapphire (Belley *et al.* 2017) and lapis lazuli (Hogarth 1971).

Spinel occurrences in the LHG are listed in Table I, and their geology is summarised here after Belley and Groat (2019). They mainly consist of metamorphic (*sensu stricto*) deposits formed during the episode of prograde granulite-facies metamorphism. They are hosted by Mg-rich impure marbles and calc-silicate rocks, and there is little-to-no evidence for the involvement of evaporites. Two very dark blue to black spinel occurrences—both at Markham Bay—are metasomatic in origin. By comparison, the spinel from metamorphic (*s.s.*) occurrences varies from light

Table I: Spinel localities on Baffin Island, Nunavut, Canada.*

Region	Locality	Largest Cut Gem(s)	Colour	Host Rock
Markham Bay	Spinel Island (1A)	None	Very dark blue (nearly black)	Metasomatite (pegmatite-marble)
	Unnamed Island (1B)	None	Black	Metasomatic calc-silicate rock
Glencoe Island	Glencoe Main (2A)	F: 0.39 ct	Light to medium violet and dark grey-violet	Calc-silicate pods in marble
	Glencoe Beach (2B)	None	Very dark blue	Impure marble
Kimmirut Area	Soper River (3A)	Fl: 0.57 ct	Violet	Marble
	Soper Falls (3B)	F: 0.37 ct	Light grey-violet	Humitite
	Soper Camp (3C)	None	Violet	Marble
	Soper Mine (3D)	F: 0.23 ct	Very dark greyish purple	Forsterite-rich phlogopite deposit
	Near Soper Mine (3D-M)	None	Dark violet	Forsterite-bearing marble
	Qila (3E)	C: 5.32 ct F: 0.06 ct	Medium vivid blue (Qila-1 and Qila-3) to light vivid blue (Qila-2)	Pargasite-scapolite phlogopite-calcite rock (Qila-1) in marble, pargasite-calcite (Qila-2) and impure marble (Qila-3)
	Near Qila (3E-M)	None	Light violet	Marble
	Trailside (3F)	F: 0.16 ct Fl: ~0.6 ct	Dark to medium-dark vivid blue	Diopside-phlogopite-rich pods in marble (Trailside-1), and calcite-phlogopite marble (Trailside-2)
Hall Peninsula	Waddell Bay (4)	F: 0.23 ct	Blue-violet	Probable skarn
	Hall Peninsula (5)	None	Greyish violet	Marble

* Locality numbers and host rock data are from Belley and Groat (2019). Maximum gem sizes are from Wilson (2014) and the present study. Abbreviations: F = faceted, Fl = faceted and highly included, and C = cabochon.

to medium-dark violet, medium-dark blue-violet, dark purple and dark blue, commonly with greyish overtones.

Of greater interest to the present study are the two occurrences of Co-blue spinel—Qila and Trailside—which are separated by a distance of only 2 km but differ significantly in host-mineral assemblages. At Qila, vivid blue spinel with medium tone occurs in a small (1.2 m wide) calc-silicate rock exposure on marble. Most of this spinel-bearing rock has been eroded away, and no other exposures were found during exploration by True North Gems. Additional investigations of the coarse-grained Qila calc-silicate rock by the present authors revealed that it is mostly composed of pale yellow-green pargasite, grey scapolite (meionite-dominant with marialitic rims), white calcite, light brown phlogopite and bright blue spinel (i.e. Qila-1 in Figure 3a). Spinel crystals in the Qila-1 unit average 2–10 mm (rarely up to 16 mm) and are generally subhedral (rarely euhedral;

Figure 3b). Trace amounts of light grey corundum, dolomite (associated with corundum), diopside and pyrite occur, in addition to fine-grained Mg-chlorite alteration along fractures in scapolite and spinel, and around corundum grains. Light blue spinels were noted from a transitional pargasite-calcite zone (Qila-2 in Figure 3a) and in a marble layer below it (Qila-3 in Figure 3a). Only the main calc-silicate layer (Qila-1) contains spinel of potential gemmological interest, but the stones are heavily fractured and, thus, usually only of cabochon quality.

The Trailside locality hosts two types of spinel occurrences. Trailside-1 consists of several calc-silicate pods (up to 3 × 2 m in size) in marble, which contain medium-dark vivid blue spinel as masses and euhedral crystals, usually smaller than 10 mm and exceptionally up to 27 mm across (Figure 4). The spinel is highly fractured, although some crystals contain small transparent sections that can be faceted into small gems. The rock is composed

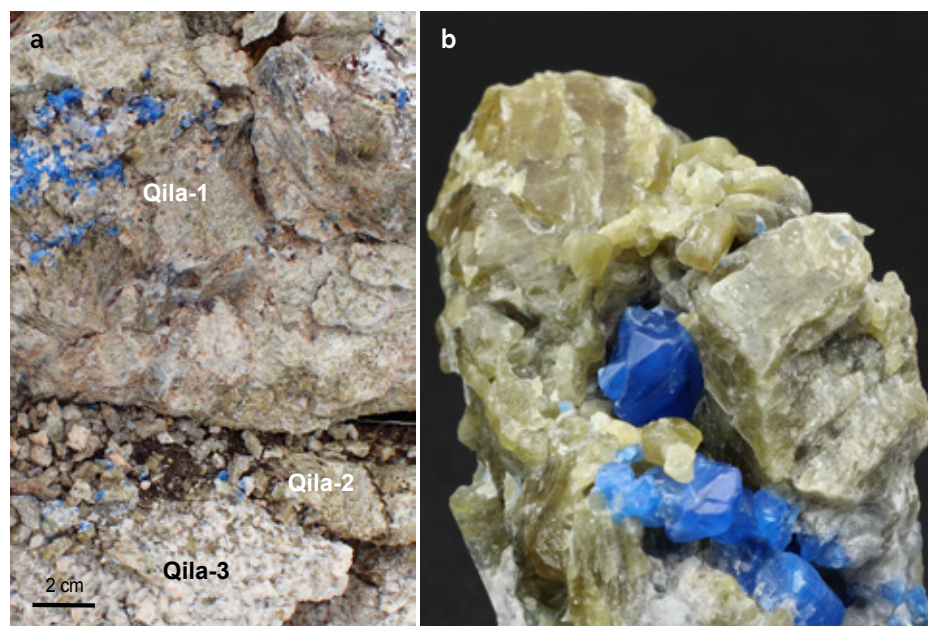


Figure 3: (a) Cobalt-blue spinel in outcrop at the Qila occurrence on Baffin Island illustrates the occurrence of this material. Spinel crystals are largest and most abundant in the calc-silicate rock (Qila-1). Rare light-blue spinel occurs in the transition zone (Qila-2), and common but generally small vivid blue spinel is found in the underlying marble (Qila-3). Some loose spinel crystals near Qila-2 have fallen from the zone above. (b) A rare euhedral spinel crystal (approximately 6 mm across) occurs in pargasite in this sample from Qila-1. (Calcite was removed with hydrochloric acid.) Photos by P. Belley.

of fine-grained muscovite (replacing an unknown mineral), diopside, phlogopite, calcite and spinel (locally altered to chlorite), with traces of pyrite and corundum. Trailside-2 hosts medium-dark vivid-blue spinel in calcite-phlogopite-spinel layers contiguous to the calc-silicate rock, but the spinel crystals are small and not of gem quality.

MATERIALS AND METHODS

Samples

Spinel samples were collected by the authors from multiple occurrences in southern Baffin Island (again, see Table I). The localities, and their mineralogy and petrology, were described in detail by Belley and Groat (2019). The samples analysed in the present study consist of crystals or fragments selected from the same spinel specimens or rock samples studied by Belley and Groat (2019). In addition, several samples were gemmologically characterised from the Qila

and Trailside occurrences. For Qila, these included several dozen fractured rough stones (up to 3.31 g), 80 cabochons (up to 5.32 ct; Figure 5a) and four transparent faceted stones (0.03–0.06 ct). From Trailside, a small number of non-gem-quality crystal fragments and a few faceted stones (0.03–0.50 ct; Figures 1 and 5b) were examined. Also, seven spinel fragments from Qila and three from Trailside were polished for inclusions examination with a scanning electron microscope (SEM) and Raman micro-spectroscopy.

For trace-element analysis, we analysed one representative spinel sample from each distinct lithologic zone at the various Baffin Island occurrences listed in Table I. The hue, saturation and tone of Co-spinel within each zone were very consistent, which is not surprising given the relatively small size of the occurrences.

Trace-element data were also obtained for three Co-bearing medium vivid-blue to dark violet-blue spinel fragments from two areas in Luc Yen District,

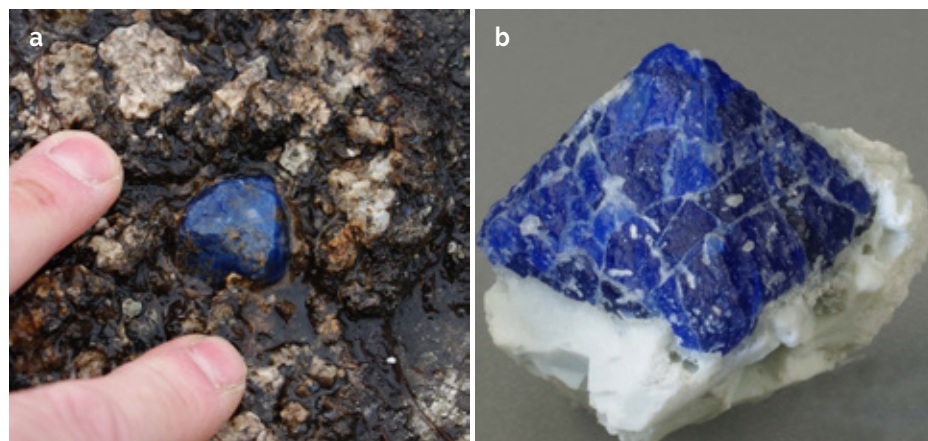
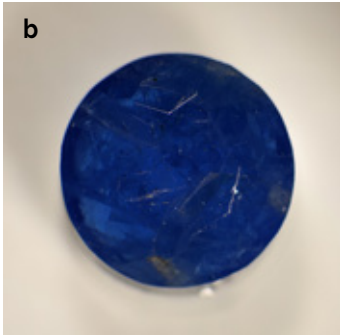


Figure 4: Co-blue spinels from the Trailside occurrence include (a) this euhedral crystal (27 mm) in outcrop and (b) another crystal (16 mm across) on matrix. Photos by B. Wilson.



Figure 5: Among the samples examined for this study are: (a) these spinel cabochons from the Qila occurrence (up to 5.32 ct; the round cabochons range from 2.5 to 4.0 mm in diameter); and (b) this 0.50 ct heavily included faceted spinel from the Trailside occurrence. Photos by P. Belley.



Vietnam (the samples were broken into pieces prior to analysis; Table II). These samples were acquired from Geir Atle Gussiås and Mai Tran (Balder Gems, Yen The, Vietnam), who purchased them from miners at the deposits. One of the specimens, VN-KK, is from the Khao Ka alluvial deposit, which has also produced purple Co- and Cr-bearing gem spinel (Belley & Palke 2021). The other two samples are from a marble-hosted primary deposit in the Minh Tien region (probably the May Trung or Bah Linh Mot deposit of Chauviré *et al.* 2015).

Methods

Refractive indices were measured using a Krüss refractometer with a sodium light source on three flat-polished spinel fragments from each of the Qila-1 and Trailside-1 units. Specific gravity values were determined by hydrostatic weighing of two samples: (1) a 3.31 g fragment from Qila that contained no eye-visible impurities, and (2) a small clean fragment weighing 427 mg from Trailside. Due to the more extensive chlorite alteration of spinel at Trailside, larger clean material was not available. The RI and SG measurements were done at Memorial University of Newfoundland.

Surface-reaching inclusions were identified in the polished fragments by their chemical composition, which was measured using scanning electron microscopy–energy-dispersive spectroscopy (SEM-

EDS) at Memorial University of Newfoundland. Additional inclusion identification of the same samples was carried out at the Gübelin Gem Lab using a Renishaw inVia Raman microscope with a resolution of approximately 1 cm⁻¹. The analyses were done confocally in the 150–1500 cm⁻¹ range using a 514 nm diode-pumped solid-state laser (100 mW power), with a grating of 1,800 lines/mm. To improve the

Table II: Co-bearing spinel samples from Luc Yen, Vietnam, analysed for this study.

Locality	Khao Ka	Minh Tien region	
Coordinates	21°58'54.37" N, 104°50'44.77" E	22°01'30.43" N, 104°48'17.49" E	
Sample no.	VN-KK	VN-MT-1	VN-MT-2
Host rock	Unknown (alluvial)	Pargasite-spinel-bearing marble	Presumably marble
Colour	Medium vivid blue	Dark slightly greyish violet-blue	Medium-dark vivid blue
Largest fragment	3.5 mm	6 mm	4 mm
Images of representative fragments			

signal-to-noise ratio, three scans per measurement were performed on most samples. The inclusions in 12 Qila spinel cabochons were also examined with Raman spectroscopy.

Ultraviolet-visible-near infrared (UV-Vis-NIR) absorption spectra were measured at the Gübelin Gem Lab with a Varian Cary 5000 spectrophotometer in transmission mode. Data were collected in the 350–800 nm range at intervals of 0.5 nm with a 0.2 s collection time, 0.5 nm standard bandwidth and a 1 mm slit. The spectra were collected from a 0.05 ct round brilliant from Trailside and a 0.14 ct cabochon from Qila.

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) was carried out using a 193 nm ArF excimer laser-ablation system (RESOLUTION M-50LR, ASI Australia) connected to a quadrupole ICP-MS (Agilent 7700x) unit at the University of British Columbia's Pacific Centre for Isotopic and Geochemical Research. Data were collected for 40 s with a laser repetition rate of 5 Hz and 20 ns pulse width, using a spot size of 89 μm . On-sample fluence was 3 J/cm². Ablation was carried out in a He atmosphere. Argon served as a carrier gas and was mixed with N₂ for signal enhancement. The mass spectrometer was tuned for sensitivity, with ThO/Th < 0.2% and a mass bias (with a mass fraction of 238/232 $\approx$ 101%). Spots were pre-ablated to remove surface contamination, followed by 40 s of ablation and a 30 s washout time. The following masses were measured: ⁷Li, ⁹Be, ¹¹B, ⁴⁹Ti, ⁵¹V, ⁵³Cr, ⁵⁵Mn, ⁵⁶Fe, ⁵⁹Co, ⁶⁰Ni, ⁶⁷Zn and ⁶⁹Ga. In addition, the following elements were sought but not detected in the spinel samples: Sc, Cu, Sr, Y, Zr, Hf, Ta and REE. Calibration was carried out by standard-sample bracketing using silicate glass NIST SRM 610 as an external standard, Mg as an internal standard and values from electron probe microanalysis (EPMA; see Belley & Groat 2019). The Mg concentrations in the Vietnamese spinel samples were also measured by EPMA using the same parameters as for Baffin Island spinel analysed by Belley and Groat (2019), and are as follows: VN-KK (15.08 wt.%), VN-MT-1 (16.14 wt.%) and VN-MT-2 (16.33 wt.%). The USGS basalt glass reference standard BCR-2G was cross-checked for quality control, and was within a range consistent for values in the GeoReM database (Jochum *et al.* 2005). The coefficient of variation for individual trace-element measurements in BCR-2G was $\leq$ 6%, except for Be ($\sim$ 11%) and B ($\sim$ 38%). Measured B concentrations varied unpredictably despite drift correction, so the data were rejected. Data reduction was performed using Iolite 3.0 software (Paton *et al.* 2011), yielding data in ppmw ($\mu\text{g/g}$).

RESULTS

Gemmological Properties

The RI values obtained for the Qila samples were 1.719, 1.719 and 1.720, and for the Trailside specimens they were 1.722, 1.722 and 1.724. The SG of the Qila spinel was 3.60, while the fragment from Trailside had an SG value of 3.50 (likely an underestimate, since the effect of any air bubbles during hydrostatic weighing was more significant for this small-sized sample). Since Trailside spinel is more Fe-rich (and, thus, Mg-poor) relative to Qila spinel, it would be expected to have a higher SG value.

Inclusions and Microscopic Features

Some of the Qila cabochons contained impurities of surrounding minerals that exceeded 0.5 mm in size. The most common mineral was calcite, but corundum, pargasite and scapolite were also identified. One cabochon contained a localised intergrowth of spinel and calcic plagioclase. Corundum crystals from 70 μm to 1.5 mm in dimension occurred as euhedral to subhedral crystals or clusters (Figure 6) and were associated with chlorite alteration $\pm$ dolomite. Microscopic inclusions in the Qila samples consisted of abundant secondary fluid inclusions in partially healed fractures, and also secondary platelets of Fe-poor, Ni-rich cobaltpentlandite (confirmed with SEM-EDS on grains up to 10 μm exposed at the polished surface) that appeared deep blue due to the metallic reflection of the spinel body colour, but were

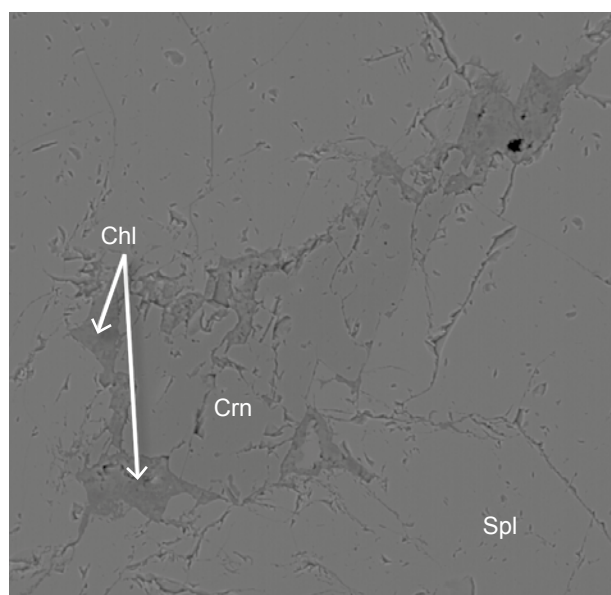


Figure 6: A corundum (Crm) inclusion in spinel (Spl) with chlorite (Chl) alteration at the grain boundary is seen in this backscattered-electron image of a spinel from the Qila occurrence. Image by P. Belley; 600 μm wide.

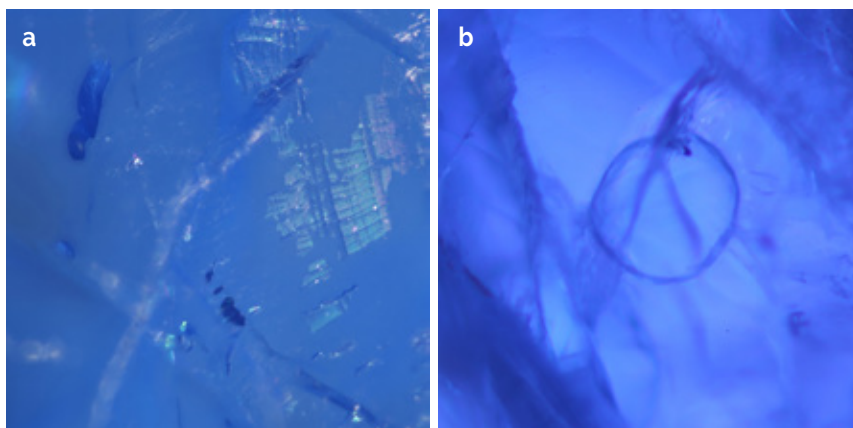


Figure 7: Internal features in Co-spinel from Qila include: (a) secondary fluid inclusions (here appearing slightly iridescent) along partially healed fractures, which also contain dark, opaque, flattened grains of cobaltpentlandite; and (b) a rounded fluorapatite inclusion. Photomicrographs by (a) P. Belley and (b) K. Schollenbruch; image widths (a) 0.65 mm and (b) 0.80 mm.

opaque when backlit (Figure 7a). A single primary inclusion of rounded apatite was identified in a Qila spinel (Figure 7b).

Most of the faceted stones from Trailside weighed less than 0.10 ct and rarely incorporated inclusions. A larger (0.50 ct) heavily included/fractured stone (Figure 5b) contained some dark skeletal inclusions (Figure 8), but they could not be identified since the sample was not available for Raman analysis. However, Raman spectroscopy of the flat-polished crystal fragments identified various inclusions. In one sample, the exterior boundary of a spinel grain was surrounded by calcite and albite, and the latter showed indications of alteration in direct contact with spinel. Microscopic veins of epigenetic mica-group minerals (probably muscovite) cross-cut the spinels. Pyrite grains were found within these veins. In addition to numerous open fractures, the samples contained partially healed fractures, subhedral negative crystals (containing gaseous CO_2) and a few mineral inclusions. The Raman spectra of a colourless hexagonal mineral inclusion in one sample showed a very good match with muscovite, and a nearby anhedral crystal with distinct relief was identified as magnesite (Figure 9a). A small subhedral, hexagonal, colourless grain consisted of fluorapatite (Figure 9b).

UV-Vis-NIR Spectroscopy

UV-Vis-NIR absorption spectra of both Qila and Trailside spinels showed prominent $^{\text{T}}\text{Co}^{2+}$ absorption peaks at approximately 551, 588 and 623 nm (Figure 10; band assignments based on D'Ippolito *et al.* 2015). Small peaks due to $^{\text{T}}\text{Fe}^{2+}$ (371, 387 and 479 nm), a low broad peak attributed to $^{\text{M}}\text{Fe}^{3+}$ (around 458 nm), and a tiny peak caused by $^{\text{T}}\text{Mn}^{2+}$ (427 nm) were also present (band assignments based on Andreozzi *et al.* 2018). No features were observed between 700 and 800 nm.

Trace-Element Composition

The trace-element composition of spinel from Baffin Island is summarised in Tables III–V and plotted in Figure 11. Compared with other Baffin Island spinels, the Co-blue samples from the Qila and Trailside occurrences are chemically distinct in several ways. They are significantly enriched in Co (131–512 ppm, vs <50.4 ppm at other occurrences) and Ni (80–387 ppm, vs <46 ppm at other occurrences; Figure 11a), and extremely poor in Ti (<10 ppm, vs 20–109 ppm at all but one other Baffin Island occurrence; Figure 11c). The Qila and Trailside spinels are relatively enriched in Be and Li (10–36 ppm and 101–281, except for samples Qila-2 and 3, with 3.5–5.6 ppm Be and 16–53 ppm Li) when compared to other Baffin Island spinels (<6.6 ppm Be and <30 ppm Li, except for two outlier samples up to 78 ppm Li; Figure 11b).

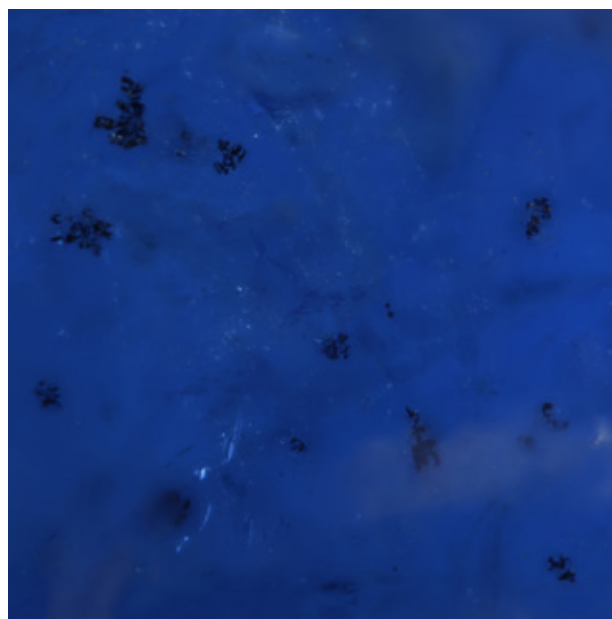


Figure 8: Skeletal opaque inclusions occur in the 0.50 ct spinel (Figure 5b) from Trailside. Focus-stacked photomicrograph by P. Belley; image width 0.8 mm.

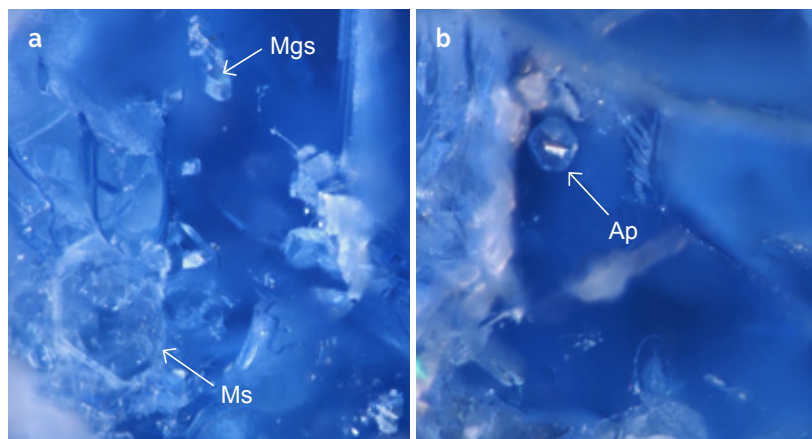


Figure 9: (a) Magnesite (Mgs) and muscovite (Ms) were identified in a fractured spinel from the Trailside occurrence. Raman spectra collected from the other inclusions seen here indicated only the presence of spinel, so they may be fluid inclusions. (b) A fluorapatite (Ap) inclusion is present in another spinel from Trailside. Photomicrographs by P. Belley; image widths (a) 0.62 mm and (b) 0.60 mm.

Qila and Trailside spinels are generally poor in V and Cr (<14 and <100 ppm, respectively, except for Qila-3 with average values of about 35 ppm V and 283 ppm Cr). By comparison, other Baffin Island spinels attain concentrations of just over 250 ppm V and 900 ppm Cr (Figure 11d).

The Qila and Trailside Co-blue spinels have similar Mn, Zn, Ga and Fe concentrations as the other Baffin Island spinels (Figure 11c, e, f). Qila spinel is slightly poorer in Fe than that from Trailside, the latter being at the top of the range of Fe concentrations in medium- to dark-coloured Baffin Island spinels but lower than in very dark blue to black samples (Figure 11f).

Trace-element concentrations in Co-blue spinel from Luc Yen, Vietnam, are presented in Table VI and covered in more detail in the Discussion section. The sample from Khao Ka is relatively rich in Be (average 35.9 ppm), Co (301 ppm), Mn (ca. 1,020 ppm) and Zn (16,610 ppm), but surprisingly poor in Ni (27.9 ppm) compared to Co-blue spinels from Baffin Island

and Minh Tien. The Khao Ka spinel is also relatively poor in V, Cr and Ti. The two samples of Co-blue spinel from Minh Tien show considerable trace-element variability, notably in the concentrations of Li (487 and 10.6 ppm), V (202 and 453 ppm), Cr (640 and 1,550 ppm), Fe (13,250 and 7,260 ppm), Co (195 and 555 ppm) and Ni (1,298 and 706 ppm). Unlike Baffin Island spinel, the two samples from Minh Tien do not show a positive correlation between Co and Ni.

DISCUSSION

Comparison of Co-spinel with Other Spinel on Baffin Island

The trace-element composition of Co-blue spinel from Baffin Island is distinct from that of other Baffin Island spinels in several ways: (1) the former are strongly enriched in Co and Ni, with concentrations of these two elements being positively correlated (Figure 11a); (2) they are enriched in

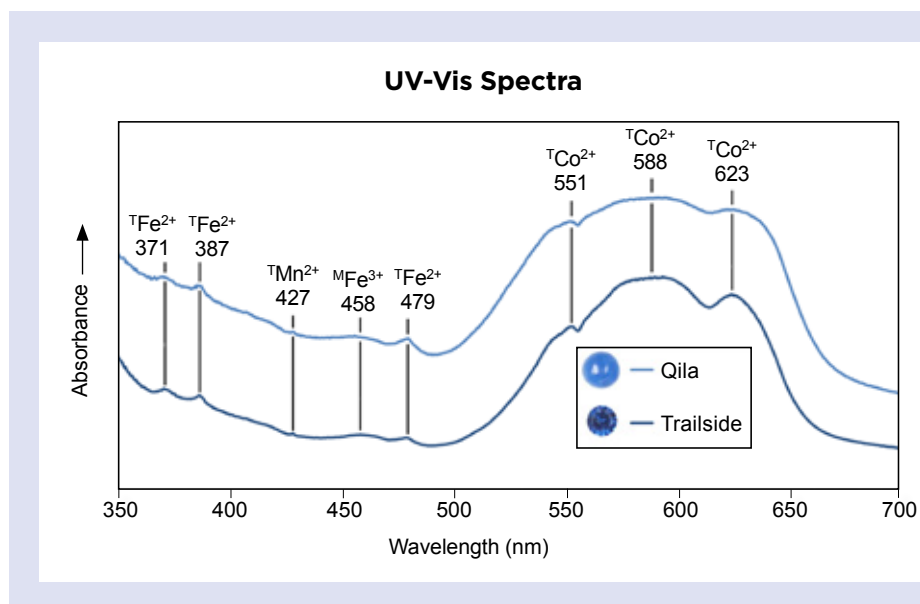


Figure 10: UV-Vis absorption spectra of Co-blue spinel gemstones from the Qila and Trailside occurrences reveal features associated with Co^{2+} , Fe^{2+} and Mn^{2+} (assigned according to D'Ippolito *et al.* 2015 and Andreozzi *et al.* 2018). No features were observed in the 700–800 nm range. The spectrum for the Qila sample is vertically exaggerated to compensate for poor transmission due to the abundance of internal fractures and inclusions.

Table III: Trace-element concentrations in Co-spinel from the Qila and Trailside occurrences, Baffin Island, Canada.^a

Locality	Qila	Qila	Qila	Trailside	Trailside
Colour	Medium vivid blue	Light 'sky' blue	Medium blue	Medium-dark vivid blue	Medium-dark vivid blue
Sample no.	Qila-1 (3E-1) ^b	Qila-2 (3E-2)	Qila-3 (3E-3)	Trailside-1 (3F-1) ^b	Trailside-2 (3F-2)
No. analyses	5	6	7	7	7
Li	116–120 (118)	47.7–53.3 (51.0)	16.2–18.2 (17.2)	101–135 (120)	156–281 (208)
Be	10.3–11.8 (11.0)	3.5–5.6 (4.5)	4.3–5.6 (5.1)	21.3–35.7 (28.2)	11.6–16.7 (13.9)
Ti	<5.0–6.8 (<5.0)	<3.7–6.5 (4.8)	7.1–9.8 (8.3)	<4.6 (<4.6)	<4.4 (<4.4)
V	3.7–4.1 (3.9)	7.9–8.6 (8.3)	32.6–37.1 (34.5)	10.2–13.3 (11.8)	12.6–13.6 (13.1)
Cr	22.2–29.5 (25.6)	52.2–70.1 (60.2)	274–292 (283)	42.3–88.6 (67.7)	42.8–96.7 (71.0)
Mn	455–477 (471)	302–332 (313)	283–293 (288)	619–657 (639)	468–538 (503)
Fe	26890–27750 (27470)	17330–18270 (17700)	18620–19280 (18990)	39640–42500 (40740)	36590–40720 (39120)
Co	483–505 (497)	131–136 (133)	257–271 (264)	412–446 (426)	402–512 (464)
Ni	373–387 (382)	80.4–87.4 (83.9)	184–196 (192)	158–177 (167)	184–199 (191)
Zn	1238–1325 (1298)	476–501 (489)	435–495 (467)	568–652 (610)	1078–1273 (1179)
Ga	233–237 (235)	242–253 (248)	173–182 (178)	172–193 (183)	173–210 (191)

^a Values are in ppmw; the range is shown with the average in parentheses.^b Samples from gem-bearing zones (see Table I for details).

Li and Be (Figure 11b), except for those from Qila-2 and Qila-3; (3) they are somewhat enriched in Mn (Figure 11c), except for those from Qila-2 and Qila-3; (4) they are poor in Cr and V (Figure 11d), except for Qila-3; and (5) they are extremely depleted in Ti (Figure 11c). Outcrop-scale variations in the trace-element content of Qila spinel have been interpreted to be the result of variations in the protolith (see Belley & Groat 2019), and may further be affected by the relative proportions of mineral species in the host rock with differing affinities for various trace elements. Qila and Trailside spinel host rocks are depleted in Ti relative to Al (Belley & Groat 2019), which could suggest low input of Ti in the siliciclastic fraction of the original sedimentary rock (i.e. the protolith). A relatively high abundance of Mg-bearing clays can correlate with elevated Li concentrations in sedimentary rocks and their metamorphic equivalents (Moine *et al.* 1981), and an abundance of such clays could explain the enrichment of Al (i.e. hosted in clays in the protolith) relative to Ti. Belley and Groat (2019)

estimated the protolith composition of metamorphic (s.s.) spinel-bearing calc-silicate rocks to consist of dolomitic marl with a predominance of clay in the siliciclastic fraction of the protolith. While elevated Li can be found in evaporites and their metamorphic equivalents, Belley and Groat (2019) found no compelling evidence to indicate that the Qila and Trailside occurrences are meta-evaporitic in origin, although the elevated Li and Be concentrations in these spinels relative to those from other Baffin Island localities are noteworthy.

Our observation that spinel occurring in marble about 30 m away from the Qila occurrence (sample 3E-M) is poor in Li, Be, Co and Ni, and significantly richer in Ti, reinforces the findings of Belley and Groat (2019) that the Co enrichment, as well as other aspects of the trace-element geochemistry in the Co-spinel occurrences, is highly localised, and thus Co and Ni were likely sourced from within the protolith. This is further supported by the variability in trace-element composition between spinel crystals from different zones in an outcrop. For

Table IV: Trace-element concentrations in spinel from other occurrences near Kimmirut, Baffin Island, Canada.^a

Locality	Marble near Qila	Soper River	Soper Falls	Soper Camp	Soper Mine	Marble near Soper Mine
Colour	Light violet	Violet	Light grey-violet	Violet	Dark greyish purple	Dark violet
Sample no.	3E-M	3A ^a	3B ^a	3C	3D ^a	3D-M
No. analyses	7	7	7	6	8	6
Li	14.5–21.1 (18.7)	24.1–29.4 (26.6)	11.6–14.0 (12.6)	7.2–8.3 (7.9)	15.5–16.6 (16.2)	14.5–15.7 (15.0)
Be	<0.9–2.4 (1.6)	1.7–2.8 (2.3)	<0.9 (<0.9)	<0.9 (<0.9)	3.4–4.4 (3.9)	<0.9–1.5 (1.0)
Ti	38.8–83.0 (65.8)	35.2–87.0 (57.4)	48.3–70.4 (62.4)	99–109 (104)	68.9–85.1 (75.0)	24.1–27.6 (25.8)
V	147–163 (154)	80.4–96.6 (90.2)	197–205 (201)	177–210 (193)	210–221 (216)	143–158 (152)
Cr	22.7–59.4 (40.8)	255–340 (279)	93–139 (120)	317–437 (372)	862–923 (893)	415–458 (437)
Mn	203–219 (208)	224–249 (236)	357–393 (381)	238–249 (242)	467–479 (472)	461–484 (471)
Fe	12760–14140 (13130)	13180–15130 (14200)	15950–17190 (16355)	10690–10950 (10785)	21690–22290 (21950)	25860–27200 (26435)
Co	7.1–8.7 (7.8)	5.2–20.0 (17.3)	10.2–13.0 (11.4)	3.0–3.7 (3.4)	11.7–12.6 (12.2)	11.4–13.0 (12.3)
Ni	11.4–13.4 (12.8)	3.1–4.8 (4.0)	5.1–6.6 (6.0)	<0.8–1.4 (0.8)	10–11.2 (10.6)	6.5–8.5 (7.5)
Zn	606–692 (643)	395–498 (438)	120–148 (137)	298–326 (315)	866–929 (301)	1302–1442 (1371)
Ga	104–108 (106)	136–146 (140)	132–140 (135)	95–101 (98)	265–276 (272)	203–209 (206)

^a Values are in ppmw; the range is shown with the average in parentheses. Localities are described in detail by Belley and Groat (2019).
^b Samples from gem-bearing zones (see Table I for details).

example, Co concentrations in Qila spinels vary between about 130 and 500 ppm across three lithological zones within less than 1 m. The spinel compositions from other localities on Baffin Island indicate that Co enrichment and the formation of Co-blue spinel are both rare and highly localised in the Lake Harbour Group metacarbonate sequence. Known occurrences of Co-blue spinel mineralisation are restricted only to metacarbonates in the Kimmirut area, but Baffin Island is vast, remote and relatively unexplored, so other instances may yet be discovered.

Comparison of Co-spinel from Baffin Island with Other Worldwide Localities

Chemical Composition. We compared the trace-element compositions of Baffin Island Co-blue and other spinels with those of Co-blue spinels from Pakistan (Schollenbruch *et al.* 2021), Tanzania (Krzemnicki *et*

al. 2023) and Vietnam (Chauviré *et al.* 2015¹; Kuksa *et al.* 2019; present study). Data for a saturated purple spinel from the Khao Ka placer in Vietnam (Belley & Palke 2021) was also included since its colour was attributed to approximately equal contributions of Co²⁺ and Cr³⁺, with subordinate Fe. These data are compared in Figure 12.

In Co-blue spinels from Canada and elsewhere, Co and Ni are generally positively correlated, although some outliers from Vietnam show significantly more enrichment in Ni relative to Co (Figure 12a). This positive correlation is most significant in the vivid blue samples from Canada, Pakistan and Vietnam, and in dark vivid blue (‘type II’) spinels from Tanzania

¹ We obtained unpublished trace-element data from Vietnam sample SATBLUchem, which was originally reported in ppma by Chauviré *et al.* (2015) and provided to us in ppmw by the authors.

Table V: Trace-element concentrations in spinel from other regions of Baffin Island, Canada.^a

Locality	Glencoe Main	Glencoe Main	Glencoe Beach	Spinel Island	Unnamed Island	Waddell Bay	Hall Peninsula
Colour	Violet	Dark grey-violet	Dark blue	Very dark blue	Black	Blue-violet	Dark grey-violet
Sample no.	2A(#1) ^b	2A(#2)	2B	1A	1B	4 ^b	5
No. analyses	6	6	6	6	6	8	6
Li	24.5–46.5 (32.3)	5.8–6.4 (6.2)	73.3–78.3 (74.9)	25.6–26.6 (26.2)	16.2–17.6 (16.8)	16.3–17.3 (16.7)	7.4–8.9 (8.0)
Be	5.1–6.6 (5.6)	2.7–4.3 (3.8)	2.0–4.3 (3.0)	1.4–3.1 (1.9)	1.0–2.1 (1.4)	4.8–6.3 (5.5)	<0.9–1.2 (<0.9)
Ti	22.5–25.7 (24.1)	23.3–27.5 (25.3)	28.4–38.7 (33.1)	30.3–39.1 (34.2)	16.1–24.4 (20.8)	<4.5 (<4.5)	62.2–88.0 (70.1)
V	45.8–51.4 (47.2)	233–271 (253)	36.2–37.4 (36.9)	17.7–18.8 (18.2)	33.8–35.7 (34.9)	6.4–7.3 (6.9)	159–175 (167)
Cr	131–169 (151)	2.6–5.5 (3.5)	68.9–81.0 (74.4)	27.8–32.5 (30.6)	304–352 (324)	54.8–69.1 (63.0)	308–388 (345)
Mn	473–487 (483)	320–328 (324)	758–794 (779)	703–722 (713)	612–642 (628)	327–335 (331)	321–343 (330)
Fe	38340–40110 (39540)	32740–33360 (33090)	54580–57900 (56255)	52860–53760 (53400)	67750–69200 (68385)	31590–31880 (31770)	21830–22830 (22220)
Co	17.5–19.2 (18.4)	10.1–10.8 (10.4)	25.1–27.9 (26.4)	21.5–22.5 (22.1)	48.4–50.4 (49.5)	12.8–14.2 (13.4)	13.0–14.6 (13.9)
Ni	38.2–45.5 (42.2)	34.3–38.6 (36.6)	19.4–22.2 (20.8)	13.9–17.7 (15.7)	21.3–26.2 (23.4)	15.3–19.8 (17.5)	16.0–18.5 (17.3)
Zn	19450–21170 (19990)	33900–36470 (35760)	1024–1155 (1107)	2576–2738 (2668)	2584–2740 (2659)	2717–2870 (2772)	515–544 (525)
Ga	165–180 (176)	177–183 (180)	167–171 (169)	164–174 (169)	213–224 (217)	208–213 (210)	111–116 (113)

^a Values are in ppmw; the range is shown with the average in parentheses. Localities are described in detail by Belley and Groat (2019).^b Samples from gem-bearing zones (see Table I for details).

(average 199.5 ppm Co; Krzemnicki *et al.* 2023), while blue ('type I') spinels from Tanzania (generally coloured by TiCo^{2+} and more significant but still subordinate TiFe^{2+}) have much lower Co concentrations (average 31.7 ppm; Krzemnicki *et al.* 2023). The type I spinels from Tanzania are not significantly enriched in Co, but they have an elevated Co-Fe ratio (Figure 12b). Their Co concentrations are comparable to those of dark-coloured Fe-rich spinels from Baffin Island, but are unusual in their enrichment in Co relative to Fe compared to the latter examples. It is not surprising that extremely Fe-rich spinel would contain higher concentrations of period IV transition metals (such as Co), given these elements' siderophile affinity. However, the enrichment of Co relative to Fe, and the enrichment of Co in absolute terms, appear to be unusual features in spinel.

Overall, the more highly saturated blue spinels contain elevated Co (>150 ppm), relatively low Cr (<1,550 ppm, with Pakistan violet-blue samples

containing up to 4,285 ppm; see Figure 12d) and a wide range of Fe concentrations (3,680–40,740 ppm) that are invariably lower than the Fe concentrations in very dark to black spinels (>50,000 ppm). Cobalt-blue spinels do not show correlations between Co and Fe (Figure 12b) or Mn.

Most Co-bearing blue spinels contain elevated Be (typically 8–54 ppm) and Li (mostly 99–550 ppm), with Qila and Trailside samples being in the low-to-moderate range compared to samples from elsewhere (Figure 12c). Some of those from Vietnam, in addition to all the non-Co-enriched Baffin Island spinels, are very poor in Be (<6 ppm) and Li (<75 ppm).

The trace-element composition of Qila and Trailside Co-blue spinel is relatively chemically distinct from that of other localities, particularly when comparing only those Baffin Island samples obtained from the gem-producing zones. Relative to Co-blue spinel from other sources (again, see Figure 12), those from Qila-1 and Trailside-1 are

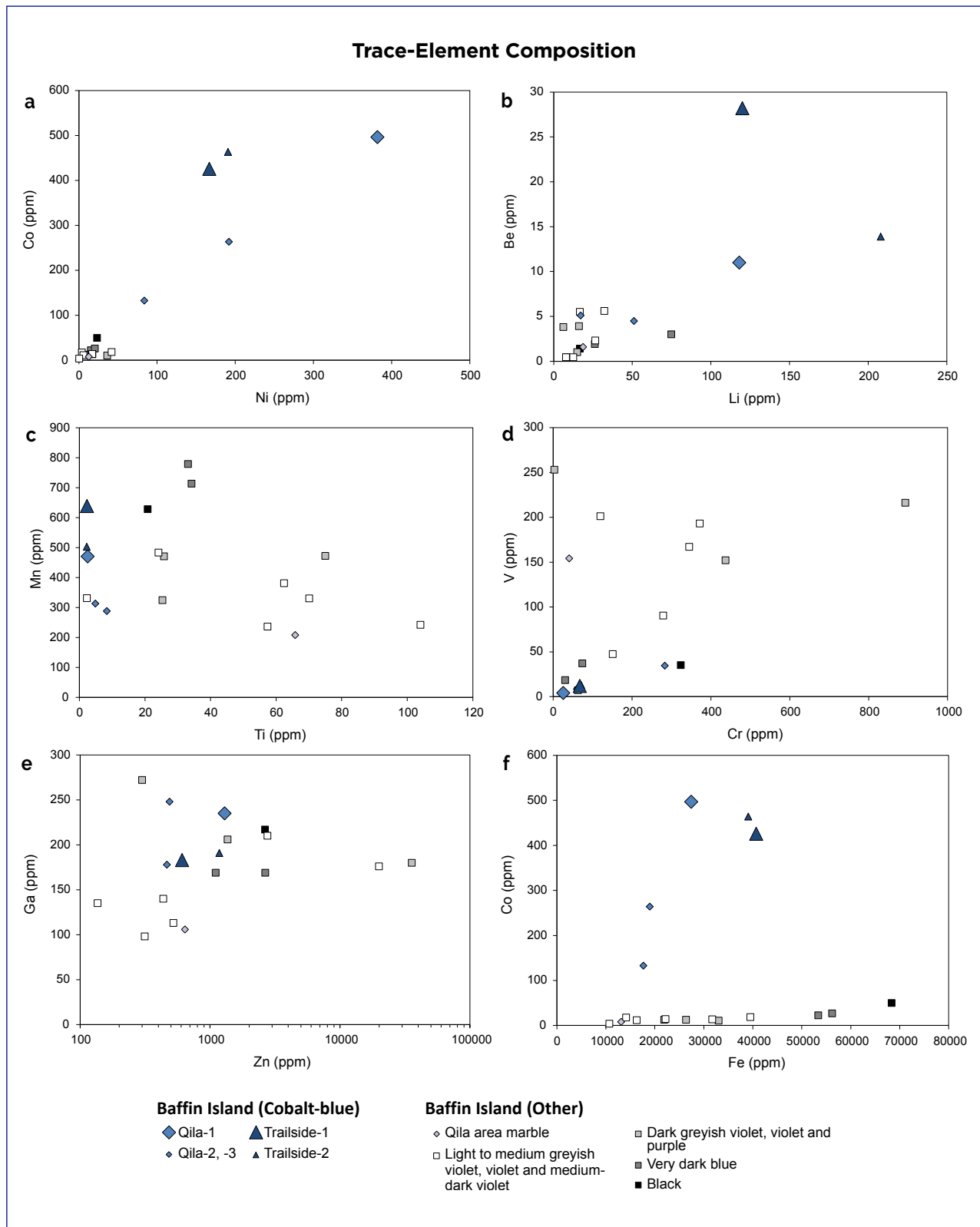


Figure 11: These plots compare the average trace-element concentrations in Qila and Trailside Co-blue spinel to those of other Baffin Island spinels.

very poor in V (<12 ppm vs 28–453 ppm for most other Co-spinels) and Ti (<3 ppm vs about 9–40 ppm for others) and fairly poor in Cr (ca. 25–68 ppm) and Zn (ca. 600–1,300 ppm). In addition, they are

enriched in Co (426–497 ppm, higher than Co-blue spinel from Pakistan and Tanzania) and Mn (471–639 ppm, compared to <150 ppm for most other Co-spinels). Qila and Trailside spinels contain 178–248

Table VI: Trace-element concentrations in spinel from the Luc Yen District, Vietnam.^a

Locality	Khao Ka	Minh Tien	Minh Tien	Luc Yen	Khao Ka
Colour	Medium vivid blue	Dark slightly greyish violet-blue	Medium-dark vivid blue	Medium-dark vivid blue	Purple
Sample no.	VN-KK	VN-MT-1	VN-MT-2	SATBLUchem	VN
No. analyses	6	6	6	4	4
Reference	This study			Chauviré <i>et al.</i> (2015) ^b	Belley & Palke (2021)
Li	151–153 (152)	467–547 (487)	9.7–11.2 (10.6)	103	23
Be	34.3–37.3 (35.9)	2.8–4.3 (3.6)	2.8–4.3 (3.2)	2.93	10
Ti	<6.9	47.2–53.6 (50.9)	43.7–53.3 (48.2)	68.5	31.6
V	26.5–29.2 (28.1)	197–205 (202)	389–502 (453)	131	210
Cr	<2.3	567–734 (640)	1487–1589 (1550)	407	1499
Mn	1004–1024 (1019)	132–142 (138)	169–181 (177)	111	89.9
Fe	17270–17560 (17380)	12940–13380 (13250)	7020–7520 (7260)	5032	6617
Co	295–305 (301)	191–197 (195)	536–576 (555)	514	51.4
Ni	25.6–30.2 (27.9)	1276–1311 (1298)	636–785 (706)	1040	35.6
Zn	15870–17300 (16610)	285–321 (305)	283–358 (326)	262	10510
Ga	270–281 (275)	134–140 (138)	258–282 (269)	115	302

^a Values are in ppmw; the range is shown with the average in parentheses. Average values are shown for the data from Chauviré *et al.* (2015) and Belley and Palke (2021).

^b Also includes unpublished data provided by Chauviré *et al.* (2015).

ppm Ga, higher than vivid blue material from Pakistan (70–136 ppm), but partially overlapping violet-blue spinel from Pakistan and the Co-bearing spinels from Tanzania and Vietnam (Figure 12f).

While Qila-1 and Trailside-1 spinels overlap the composition of Co-bearing blue spinel from Vietnam in some respects, they contain more Fe and less V than all published examples from Vietnam (Figure 12b, d). However, there remain relatively little trace-element data published on Co-blue samples from Vietnam, the world's most prolific producer of vivid blue spinel. The available data show a high degree of variability in the concentration of all measured trace elements. Furthermore, the pair of samples from a primary deposit at Minh Tien analysed for this study demonstrates that spinel trace-element composition can be highly variable within a single deposit (a characteristic shared by the Qila occurrence). Geochemistry-based origin determination

of Co-blue spinel would, therefore, benefit from additional data on the geochemistry of Vietnamese samples.

Inclusions. The inclusions observed in Co-blue spinel from Qila, Trailside and other localities (Vietnam, Pakistan and Tanzania) are summarised in Table VII. Due to the mineralogical similarities of spinel-bearing metacarbonates, caution should always be used in interpreting inclusion data for the purpose of origin determination, since common mineral species such as apatite, carbonates, phlogopite and zircon could occur even if not yet reported in samples studied. For example, zircon has not yet been observed as inclusions in spinel from Qila, but it does occur in the calc-silicate host rock there (Belley & Groat 2019).

Several types of inclusions are, however, unique to one or a few localities. Spinel from Qila contains small platelets of cobaltpentlandite in partially healed

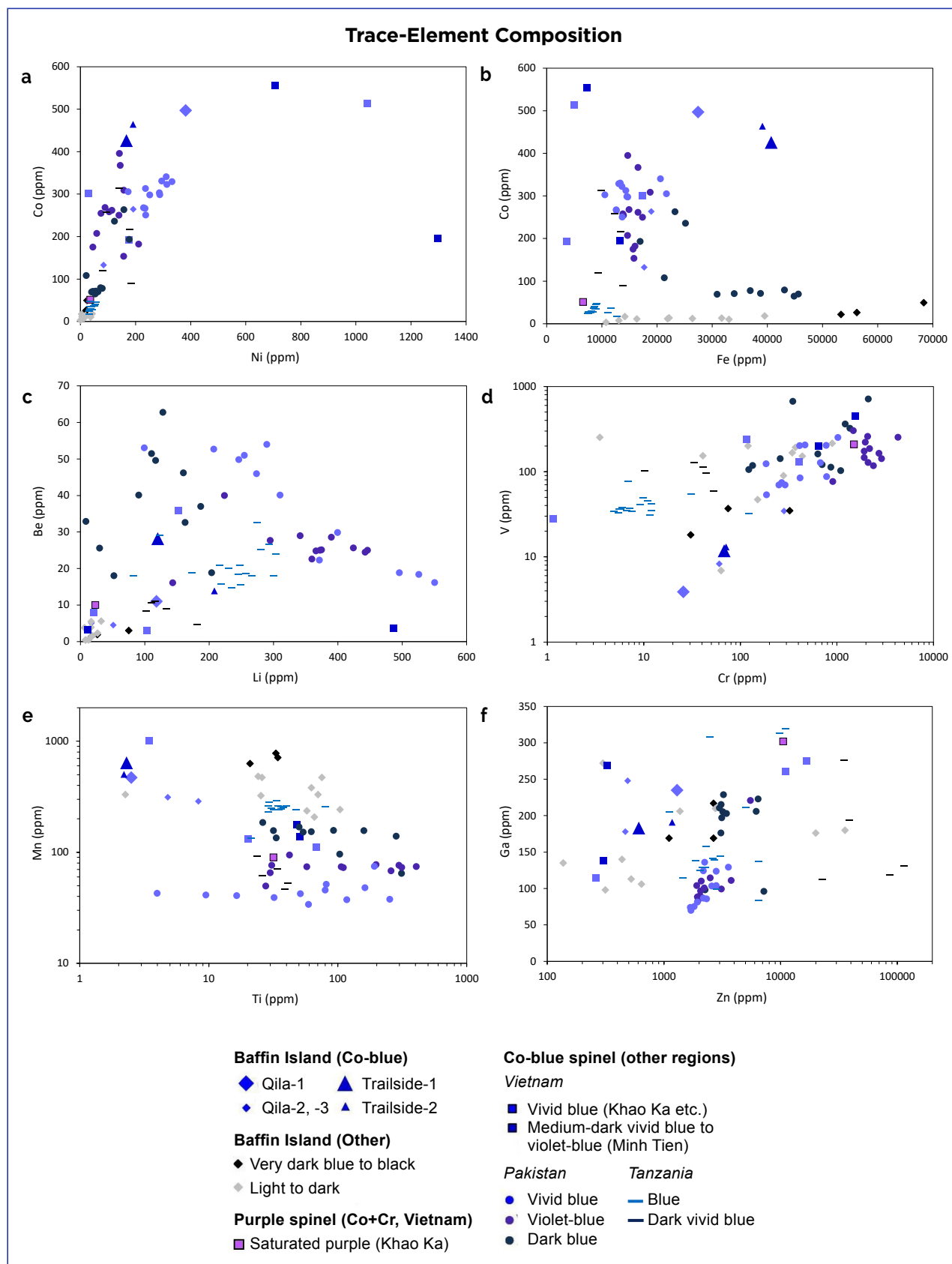


Figure 12: Trace-element concentrations in Baffin Island spinel, including Qila and Trailside Co-bearing samples, are compared to those of Co-blue spinels from Vietnam, Pakistan and Tanzania. Data sources for the samples are as follows: Vietnam (Chauviré *et al.* 2015, including unpublished data; Kuksa *et al.* 2019; Belley & Palke 2021; present study), Pakistan (Schollenbruch *et al.* 2021) and Tanzania (Krzemnicki *et al.* 2023). Complete data sets for the samples from Schollenbruch *et al.* (2021) and Krzemnicki *et al.* (2023) are available in *The Journal's* online data depository.

Table VII: Summary of inclusions found in Co-blue spinel from Canada and other localities.

Locality	Canada		Vietnam	Pakistan	Tanzania
	Qila	Trailside	Luc Yen	Hunza	Lukande
Reference	This study and Belley & Groat (2020)		Chauviré <i>et al.</i> (2015)	Schollenbruch <i>et al.</i> (2021)	Krzemnicki <i>et al.</i> (2023)
Mineral inclusions					
Amphibole (pargasite)	● ^a				
Apatite	●	●			●
Calcite	● ^a			●	
Chlorite (alteration)	●	●			
Cobaltpentlandite (secondary)	●				
Corundum	● ^a				
Dolomite	● ^a				
Högbomite					●
Magnesite		●			
Muscovite		● ^b			
Muscovite (alteration)		●			
Phlogopite	● ^a			●	
Plagioclase	● ^a				
Rutile				●	
Scapolite	● ^a				
Zircon				●	●
Fluid inclusions					
CO ₂ -rich inclusions		●			
Secondary fluid inclusions	●	●	●	●	●
Three-phase inclusions				● (rare)	
Unidentified inclusions					
Black crystals			●		
Black skeletal inclusions		●			
Dispersed micro-particles					●
Geometric iridescent inclusions				●	● (högbomite?)
Needle-like inclusions					●
Tube-like inclusions			●		

^a Associated minerals not fully removed during fashioning of the cabochons (although corundum and dolomite can also occur as true inclusions).

^b Muscovite could have replaced a primary mineral inclusion.

fractures (Figure 7a). Trailside spinel contains black skeletal inclusions (Figure 8), magnesite (Figure 9a) and CO₂-rich fluid inclusions, which have not been previously reported in Co-blue spinel from other localities. Both Qila and Trailside spinels contain apatite inclusions (Figures 7b and 9b), but they differ in their crystal-face development (i.e. anhedral and subhedral, respectively).

Muscovite is also unique to Trailside spinel, but the hexagonal shape of the inclusion in Figure 9a is unusual. Another mica, phlogopite, occurs in the spinel-bearing peak metamorphic stable assemblage, while muscovite was documented only as a retrograde alteration product within this rock (Belley & Groat 2019). The spinel crystal containing this muscovite inclusion is highly fractured, and it is possible that fluids migrated through

these fractures and reached a mineral inclusion, resulting in its alteration to muscovite.

Högbomite inclusions are reportedly unique to Co-bearing blue spinel from Tanzania (Krzemnicki *et al.* 2023), although unidentified iridescent inclusions in spinel from Pakistan are similar in appearance (Schollenbruch *et al.* 2021). Rutile and three-phase inclusions are unique to Co-blue spinel from Pakistan (Schollenbruch *et al.* 2021), although the latter inclusions have been encountered very rarely.

Assessment of Spinel Colour Based on Chromophore Chemistry

‘Cobalt-blue’ spinel and ‘Co-spinel’ are terms often used in the gem trade to refer to blue spinel, generally with high colour saturation, which is primarily coloured by Co^{2+} . Such a determination is most accurately made by observing visible-range absorption spectra, a method superior to approaches based purely on chemical composition, since the latter cannot discern Fe valence and coordination (Krzemnicki *et al.* 2023), which significantly affect the range and intensity of visible light absorption by Fe in spinel (Schmetzer *et al.* 1989; D’Ippolito *et al.* 2015; Andreozzi *et al.* 2018). Although various discrimination approaches have been used that broadly correlate chemistry with colour, these methods are limited in their application to assessing whether a sample should be called ‘Co-spinel’. Sokolov *et al.* (2019) proposed that $\text{Fe}/\text{Co} < 110$ comprises Co-blue spinel, which has been further constrained by $\text{Cr}/\text{Co} < 4$, since greater Cr concentrations result in purplish to violet hues (Schollenbruch *et al.* 2021). Belley and Palke (2021) used a plot of Co/Cr vs Co/Fe to discriminate between dominant chromophores in gem spinel.

Chromophore-based chemical discrimination plots (e.g. Belley & Palke 2021; Schollenbruch *et al.* 2021) are useful to approximate the relative contributions of Co, Cr and Fe to spinel colour, but are limited in three ways: (1) as mentioned above, they do not consider Fe valence and coordination; (2) they do not account for absolute element concentrations, which affect colour saturation and tone; and (3) they are not applicable when a denominator in the fraction (e.g. Co or Cr) is below the detection limit of LA-ICP-MS analysis. While the first problem cannot be easily dealt with, the others can be addressed by a new preliminary approach to spinel chemical discrimination that is described below. In addition to providing insights on the effect of various chromophoric elements on spinel colouration, this approach could be helpful for assessing the colouration of minute grains of spinel recovered during heavy-mineral exploration

programmes. Since evaluating the colouration of small particles is difficult, such chemistry-based colour assessment could be used to rapidly assess whether the sand-sized spinels obtained in such surveys are indicative of Co-blue spinel potential.

Our proposed new procedure multiplies or divides chromophore concentrations by natural numbers (i.e. positive integers) to qualitatively estimate, in a simplified way, the relative percentages of contribution of the major chromophoric elements to the colour of a spinel sample (essentially normalising variations in absorption strength by different trace elements). The scaling factors for these weighted percentages were selected using published examples of spinel with absorption spectra and colours that are considered intermediate between two chromophore types. Since the method is qualitative, the relative proportions between key chromophores in these examples were used as a guide for selecting the appropriate scaling factors. The examples from the literature that we used are: (1) a saturated purple spinel coloured by a combination of Co^{2+} and Cr^{3+} (and V^{3+} ; Belley & Palke 2021), (2) a purple spinel coloured by a combination of Fe and Cr^{3+} (and V^{3+} ; Zhao *et al.* 2023) and (3) a dataset for Tanzanian blue spinels ranging from those primarily coloured by Co^{2+} to those mainly coloured by Fe^{2+} with subordinate Co^{2+} (Krzemnicki *et al.* 2023). A plot showing the estimated relative contribution to spinel colouration by various trace elements is presented in Figure 13. Cr and V are combined, as Cr contributes to the red colour of spinel, and V to orange (e.g. Zhao *et al.* 2023). Relative to Cr and V, the absorptivity is significantly higher for Co and lower for Fe (see, e.g., the purple spinel described by Belley & Palke 2021), so to scale for these differences, we used $40 \times \text{Co}$ and $\text{Fe}/8$, respectively.

In Figure 13, all Co-enriched blue spinel samples with saturated colour plot in the region with $40 \times \text{Co} > 70\%$ and $\text{Cr} + \text{V} < 10\%$. However, the ternary plot alone cannot differentiate among Co-bearing blue spinels by colour, since a pale stone with low absolute concentrations of Co and very low concentrations of Fe could plot similarly to a deep blue spinel with higher concentrations of both Co and Fe despite having similar relative concentrations.

Therefore, plotting both the estimated relative contribution to colour (in %) and the absolute concentrations of major chromophores can better characterise spinels (Figure 14). Most blue samples with very highly saturated colour have $40 \times \text{Co} > 70\%$ (as mentioned above) and $\text{Co} > 150$ ppm (Figure 14). A further problem is posed by the absolute concentrations of Fe, as Fe-rich spinels are very dark to black in colour. An

exceptionally Fe-rich spinel could be too dark to have value as a gemstone even if it contains relatively high Co, and thus the calculated $40 \times \text{Co}$ percentage value would be meaningless in estimating its colour since it would be black at very high Fe concentrations. It is therefore important to consider the absolute concentration of Fe when assessing whether a sample should be termed Co-spinel (Figure 14).

CONCLUSIONS

Qila and Trailside Co-blue spinels from Baffin Island, Canada, are geochemically distinct from other Baffin Island spinels in that they are strongly enriched in

Co and Ni. Except for samples from Qila-2 and Qila-3 (zones of less significant spinel mineralisation contiguous to Qila-1), these Co-blue spinels are also enriched in Li and Be (and somewhat in Mn), are poor in Cr and V, and are depleted in Ti. The high variability of Li, Be, Ti, Mn, Co, Ni, Cr and V in spinel at outcrop scale at Qila is consistent with an interpretation that trace-element geochemistry favouring Co-spinel formation is highly localised and dependent on protolith composition.

Qila and Trailside Co-blue spinels are relatively chemically distinct from those of other world localities, being very poor in V and Ti, fairly poor in Cr and Zn, and somewhat more enriched in Co and Mn.

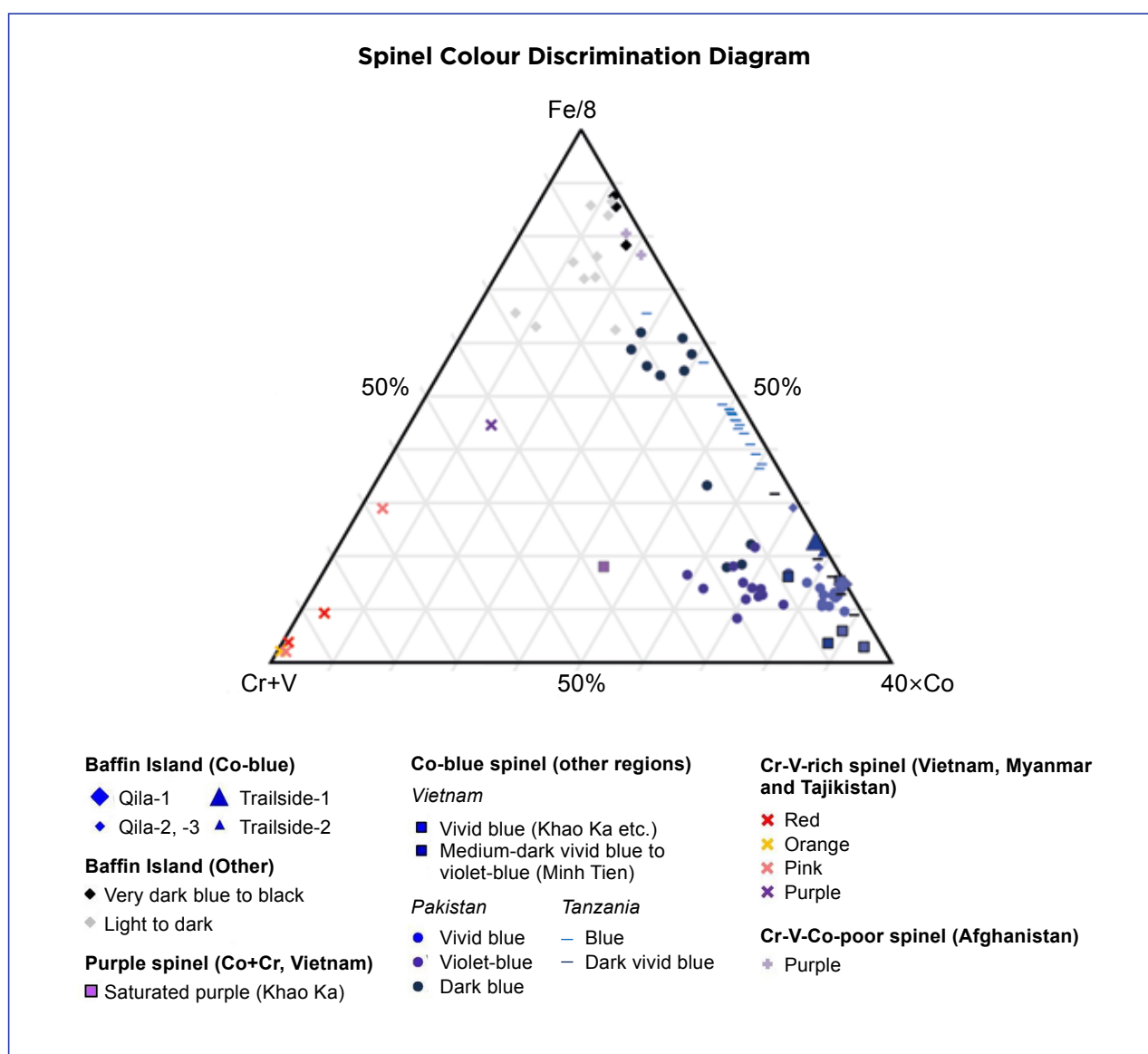


Figure 13: A ternary colour-discrimination diagram for MgAl_2O_4 spinel compares approximate percentage contributions from the chromophores Co, Fe and Cr+V (with appropriate scaling factors for Co and Fe) to colouration for Co-spinel from this study and various colours of spinels from other localities. Data sources for the samples are as follows: Vietnam purple spinel (Belley & Palke 2021); Vietnam blue spinel (Kuksa *et al.* 2019; present study); Pakistan blue spinel (Schollenbruch *et al.* 2021); Tanzania blue spinel (Krzemnicki *et al.* 2023); Cr-V-rich spinel (Malsy & Klemm 2010; Kuksa *et al.* 2019; Zhao *et al.* 2023); Afghanistan purple spinel (Belley & Palke 2021; Hänsel *et al.* 2021).

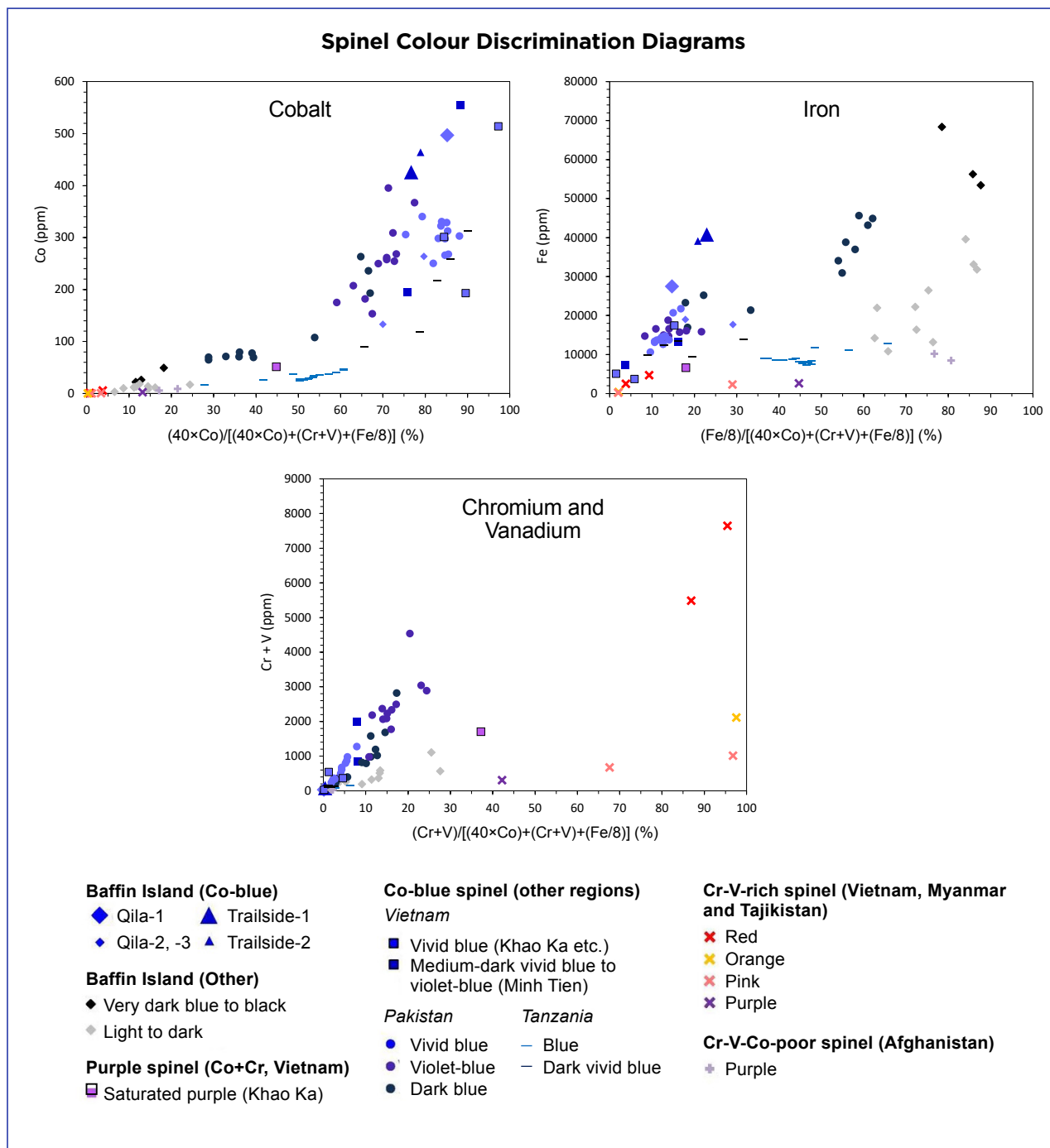


Figure 14: Colour-discrimination diagrams for MgAl_2O_4 spinel are based on approximate percentage contribution to colour from the chromophores Co, Fe and Cr+V vs the absolute concentrations of these elements (in ppmw). Data are shown for the same samples as in Figure 13.

Some inclusions in Baffin Island Co-blue spinel have not been described from other localities: secondary cobaltpentlandite in partially healed fractures (Qila), magnesite (Trailside), muscovite (Trailside; possibly an altered primary inclusion), CO_2 -rich fluid inclusions (Trailside) and unidentified black skeletal inclusions (Trailside). Cabochons of Qila spinel commonly incorporate small amounts of associated minerals, including calcite, pargasite, phlogopite,

scapolite, plagioclase, corundum and dolomite, although the last two minerals also occur as isolated inclusions.

When it comes to assessing whether a gem should be considered a ‘Co-blue’ spinel (or a ‘Co-spinel’), there is no substitute for an accurate assessment of hue, saturation and tone, plus analysis of visible-range absorption spectra to identify the presence and relative contribution of Co^{2+} to a spinel’s colour. A

preliminary new approach described here for classifying spinel samples by colour plots the weighted percentage of the major chromophores against the concentrations of Co, Fe and Cr+V. While not a substitute for spectrophotometry, this approach can

be used to perform an initial estimate of the relative contributions of the chromophores to colour. It could be applied in special-use cases, such as for the colour assessment of small spinel grains collected in heavy-mineral exploration surveys.

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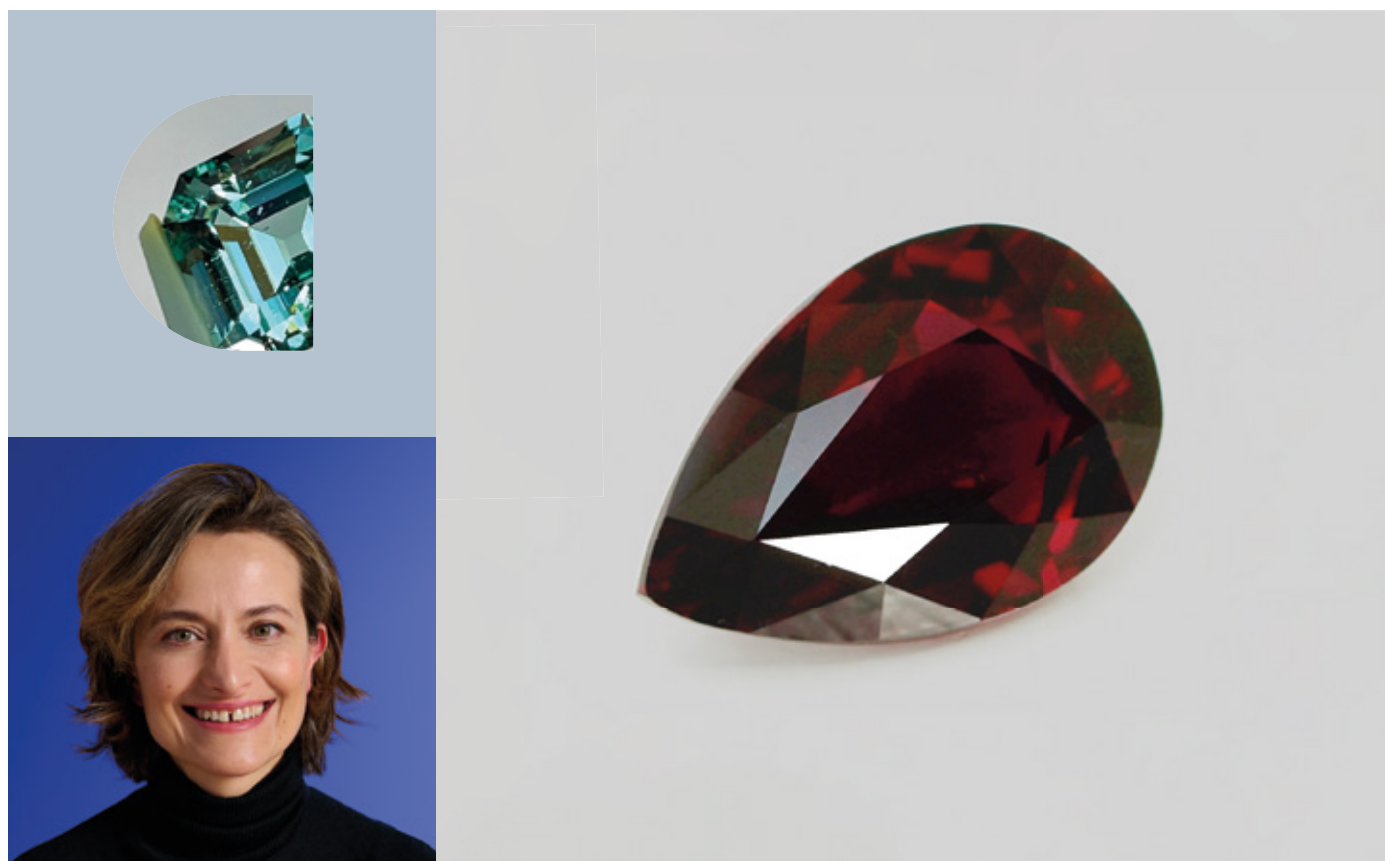
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Acknowledgements

Helpful comments from three anonymous reviewers improved the quality of the manuscript. We thank Dr Marg Amini (University of British Columbia) for assistance with LA-ICP-MS. We thank True North Gems Inc. and the Qikiqtani Inuit Association, who permitted research sampling to authors PMB and LAG. Financial support for this research was provided by the Dr. Eduard Gübelin Research Scholarship to PMB and NSERC Discovery Grants to LAG (funding reference #06434) and PMB (funding reference #05910).

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A Review of Bohemian Garnet (Cr-bearing Pyrope) from the Czech Republic

Radek Hanus, Pavel Hladký and Aleš Hladký

ABSTRACT: Bohemian garnet is Cr-bearing pyrope from what is today the Czech Republic that possesses a distinctive ‘blood-red’ colour. The origins of garnet mining in this part of Europe date back to the fifth century CE. The deposits are known in three non-contiguous areas in the Czech Republic (or Czechia): the Central Bohemian Highlands, the Podkrkonoší area and the Kolín region. During the past two decades, one garnet mine (at Vestřev) closed and one new mine (at Dolní Olešnice) opened, both in the Podkrkonoší region. An open-pit mine at Podsedice in the Central Bohemian Highlands is still productive. Considered the Czech national gemstone since the nineteenth century, Bohemian garnet has been used in a wide range of historical and modern jewellery, although it is rare in sizes above 5 mm (even as rough material). The stones show a characteristic inclusion assemblage, and the presence of Cr in this garnet can be detected by photoluminescence or absorption spectroscopy.

The Journal of Gemmology, 39(3), 2024, pp. 242–258, <https://doi.org/10.15506/JoG.2024.39.3.242>
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Bohemian garnet is the traditional name for Cr-bearing pyrope of ‘blood-red’ colour found in the Czech Republic (e.g. Figure 1). Although this term does not comply with accepted mineralogical nomenclature, it is well known in the gem and jewellery industry, and was first mentioned in *Gemmarum et Lapidum Historia* (de Boodt 1609). Since the nineteenth century, Bohemian garnet has been considered the Czech national gemstone.

The pyrope end member of the garnet group is characterised by the formula $\text{Mg}_3\text{Al}_2(\text{SiO}_4)_3$. In pyrope, Mg^{2+} is partially replaced by Fe^{2+} , and Al^{3+} is partially replaced by Cr^{3+} . A. G. Werner first described pyrope from the type locality of Měrunice in the Central Bohemian Highlands in north-west Bohemia (Ludwig 1803). The name *pyrope* is derived from the Greek word *pyropos*, meaning ‘fiery eyed’. It describes the characteristically intense red colour of the stone, which is more prominent after cutting. Red colour in pyrope is due to Cr^{3+} and/or Fe^{2+} (e.g. Rost *et al.* 1975). Interestingly, the characteristic colour of Bohemian garnet is seen only when Cr is present in

the optimum amount of approximately 1.5–4.0 wt.% Cr_2O_3 , as shown by data from the literature (e.g. Hanus *et al.* 2013).

The aim of this article is to review the development of Bohemian garnet over the past 20 years in terms of its mining and gemmological characterisation, as well as to provide some historical background.

HISTORICAL OVERVIEW

The first written mention of Bohemian garnets is found in the work of the Jáchymov naturalist and physician Georgius Agricola (1494–1555) in his 1546 treatise *De Natura Fossilium*, in which he referred to them as ‘garnets [*carbunculus*] in the fields of Bohemia’ (Agricola 1546, p. 113). He further mentioned their source area as the Central Bohemian Highlands (‘five miles from Litomerice in the fields along the road to Trebenice [Třebenice], also near Schelkowitz [Želkovice] about three miles from this locality’; p. 135). Anselmus Boetius de Boodt (1550–1632), the personal physician of Emperor Rudolf II, was the first to describe Bohemian garnet



Figure 1: These gem-quality Bohemian garnets from the Central Bohemian Highlands show the typical appearance of the rough material. They range from 2.5 to 5.5 mm in diameter. Photo by Aleš Hladký.

as *granatus Bohemicus* (rather than *carbunculus*) in his *Gemmarum et Lapidum Historia*, published in 1609. It was during the reign of Rudolf II that the first systematic exploration for Bohemian garnet deposits took place (Urban 1976; Hladký 2021). Prospectors searched for various precious stones demanded by the imperial chamber, including Bohemian garnet. This activity was initially somewhat disorganised, but it became more systematic under the leadership of Mathes Krätsch, who worked at the imperial court from 1 January 1589 until his death in 1605 (Urban 1976; Hladký 2021).

GEOLOGY AND MINING

Deposits of Bohemian garnets occur in three non-contiguous areas within the present-day Czech Republic: the Central Bohemian Highlands (particularly around Podsedice), Podkrkonoší (including the Bohemian Paradise area) and near the town of Kolín (Figure 2; Table I).

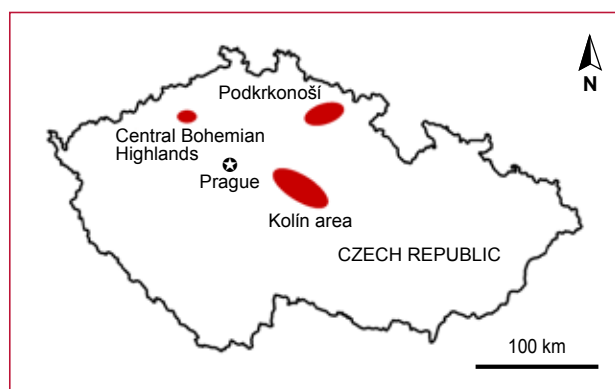


Figure 2: The three main locations for Bohemian garnets in the Czech Republic consist of the Central Bohemian Highlands, the Podkrkonoší area and the Kolín region. Map adapted from Hanus (2019).

Geology

The following geological descriptions of the various deposit areas are summarised from Hanus (2019).

During the Tertiary period (i.e. from the Oligocene to the early Miocene), the Central Bohemian Highlands experienced volcanism from numerous diatremes, which were sources of pyroclastic rocks and volcanic breccia containing ultramafic mantle xenoliths of garnet peridotite. These pyrope-bearing rocks originally crystallised in the earth's mantle—at temperatures of 850–1020°C and pressures of 30–40 kbar—before being transported to the earth's surface by the volcanic eruptions. Weathering of the volcanic deposits (mainly during the Quaternary period) resulted in accumulations of garnet-bearing sediments of mostly deluviofluvial character that were affected by cyclic freezing and thawing (solifluction) and aeolian processes.

In the Podkrkonoší area, the source rock of the pyrope is hypothesised to be serpentinised garnet peridotite. The weathering products were incorporated into Permian-Carboniferous sediments of the Krkonoše piedmont basin in the southern part of the Giant Mountains (i.e. Čistá sandstones of the upper part of Vrchlabí Formation).

In the Kolín area, the garnet deposits are associated with material weathered directly from the source rocks (consisting of more-or-less serpentinised garnet peridotite) within the so-called Bečvary-Dobešovice zone of ultramafic bodies hosted by schists of the Kutná Hora crystalline complex (see also Strnad 1972).

Historic Mining Activities

The oldest actively mined Bohemian garnet locality is the Central Bohemian Highlands. The

Table I: Host sediments and formation conditions of Bohemian garnet from various localities in the Czech Republic (Gilg & Hyršl 2014).

Deposit area	Host sediments	Crystallisation temperature (°C)	Pressure (kbar)	Age
Central Bohemian Highlands (Podsedice)	Pleistocene gravel derived from garnet peridotite	890–1020	33	Visean (Carboniferous)
Podkrkonoší (Vestřev)	Holocene gravel probably derived from garnet peridotite	850–1000?	>30?	Carboniferous?
Kolín	Holocene gravel derived from garnet peridotite	850–900	40	Carboniferous?

first haphazard activities, consisting of collecting the garnets from fields and streams or from shallow shafts and furrows, took place as early as 480 CE (Hanus *et al.* 2023b). Gradually, more efficient methods of extraction were developed. Although there is no direct evidence of Bohemian garnet exploitation during the Middle Ages and part of the modern era, some jewels from these periods have been preserved, so it is possible to conclude that some mining occurred. From around the eighteenth century onwards, excavations took place in larger open pits in the higher-grade areas of the pyrope-bearing gravels at depths of up to 7 m (e.g. Figure 3; Hanus & Hladký 2019a). Subsequently, rather than continuing to remove the surface soil and overlying sediments (sometimes up to 7 m thick), the miners dug narrow shafts just wide enough for a wicker basket to pass through and, later, a shackle (a large, often metal-plated jib). The depth of these workings reached 15–40 m (Pařík 1901; Sýkora 1952). The shafts were either circular or, more often, rectangular in cross-section. Each shaft was connected to a hand-operated winch on the surface, usually powered by two people. When the shafts reached the garnet-bearing layer, tunnels were dug in all

directions. The extent of these galleries was limited by the stability of the layers above the ceiling and the courage of the workers to brave cave-ins (Hanus *et al.* 2013). While most of the garnet production from the Central Bohemian Highlands was derived from alluvial deposits as described above, mining from primary rock (Figure 4) was also experimented with during the eighteenth and nineteenth centuries (i.e. near Měřunice and at Linhorka, near the village of Staré in the Central Bohemian Highlands; Čermáková 1972).

In the Podkrkonoší region, garnets have been known since as early as the seventeenth century, when they were collected from river gravels or in fields after rain. Such activity was reported by Bartholomew Berffort in 1623 in a report to Governor Karl I, Prince of Liechtenstein. Berffort drew attention to a particular type of Bohemian garnet found near the villages of Olešnice (‘langen Els’) and Čistá (‘langen Zist’), which the locals sold abroad without paying customs duties (Urban 1976).

Garnet mining in the Kolín region took place mainly during the eighteenth and nineteenth centuries, and according to official records, all activities ceased before 1812.



Figure 3: Mining of Bohemian garnets in Třebenice (Bohemian Central Highlands) around the end of the nineteenth and beginning of the twentieth century was done via both open-pit and underground methods. Image from the collection of R. Hanus.



Figure 4: A drill core from Linhorka, Central Bohemian Highlands, Czech Republic, shows the presence of Bohemian garnets in serpentinised garnet peridotite. The sample measures 12 cm across and is from research drill hole T7, obtained from a depth exceeding 209 m. Photo by Aleš Hladký.

Modern Mining Activities

Podsedice. During the second half of the twentieth century, the communist government abolished private ownership and garnet exploitation switched to quarrying, initially by the Granát cooperative in Turnov, which worked in the Podsedice area from 1953 until 1960. The operation was then taken over by the state mining company Rudné doly, which exploited the deposit by underground methods and sent the gem gravels to their processing factory at Cínovec. Mining subsequently took place in open pits, which is the method used to the present day. The first area to be quarried was the site where Rudné doly subsequently built its complex, a ‘temporary’ gravel-treatment plant that was in use until the mid-1980s. A new, modern treatment plant was then built, which is still

in operation today with a few modifications (Tvrzník & Boudný 2019). After its construction, mining activities moved across the I/15 road (Figure 5a), where systematic extraction of garnet-bearing gravels took place. The mined material was processed on-site to a concentration of approximately 10–20%, and then was transported to the treatment plant in Cínovec, where it was washed to a concentration of approximately 90–95%. This was followed by manual sorting to extract the garnet (Hanus *et al.* 2013). Rudné doly operated this pit until 1996.

In 1996, the mining operation was purchased by the Granát Turnov cooperative, which in the following year acquired the buildings, technology, permits and rights to the deposit area. Mining continued in the same way (Figure 5b), with the final sorting being moved to Turnov. At present, other areas are gradually being prepared for future exploitation, and the mining operation will soon be moved to another site in the Chrástany area.

Podkrkonoší. Geological exploration of this area started in 1986 and continued until 1988, culminating with the discovery of a new deposit of Bohemian garnet (Žežulka 1989). The first modern small-scale mine in the area opened in 1994, called Vestřev (Figure 6). TRL Ltd operated the mine, and its production was purchased by the Granát Turnov cooperative, which took over the company at the beginning of the twenty-first century. The Granát Turnov cooperative then became the world’s only miner of Bohemian garnet. The Vestřev pit was mined over an area of approximately 12 hectares. First the overburden was removed (approximately 1.8 m thick, including topsoil) and then the garnet-bearing gravel layer was extracted to a final depth of 2 m. Mining proceeded from north-west to south-east, and the pit was simultaneously



Figure 5: (a) An aerial view (from www.mapy.cz) of the Podsedice mining area in the Central Bohemian Highlands shows the locations of (1) the present mining area and (2) the treatment plant. (b) At Podsedice, overburden is removed and garnet-bearing gravel is extracted from open pits using an excavator. Photo by Aleš Hladký.



Figure 6: An aerial view (from www.mapy.cz) of the Vestřev mining area in 2007 shows a series of ponds that were formerly open pits at this now inactive mine, which opened in 1994.

reclaimed by filling it with tailings (Ševiola 1994). The Vestřev mine ceased production in 2007.

A second mine, at Dolní Olešnice, was opened in 2019 and is currently in operation (Figure 7). At the start of mining, geological surveys predicted extraction of 700 kg of garnets annually, but production during the first half of the year was 20% more than the anticipated annual output (Prouza 2019). However, after such an excellent start, the year 2020 brought COVID-19, significantly reducing mining activities at Dolní Olešnice (as well as at Podsedice). The resulting restrictions are still impacting mining operations today.

The Dolní Olešnice quarry lies along the Kalenský stream, upstream from the reclaimed Vestřev mine. The mine covers an area of 2 hectares, divided into four blocks for sequential exploitation. Open-pit mining takes place to a depth of approximately 3.5–4 m. The mine's location within Dolní Olešnice village requires that noise levels be minimised.

Both the Dolní Olešnice and Podsedice quarries operate only from spring to autumn because the water used to wash the garnet-bearing gravels freezes in the winter.



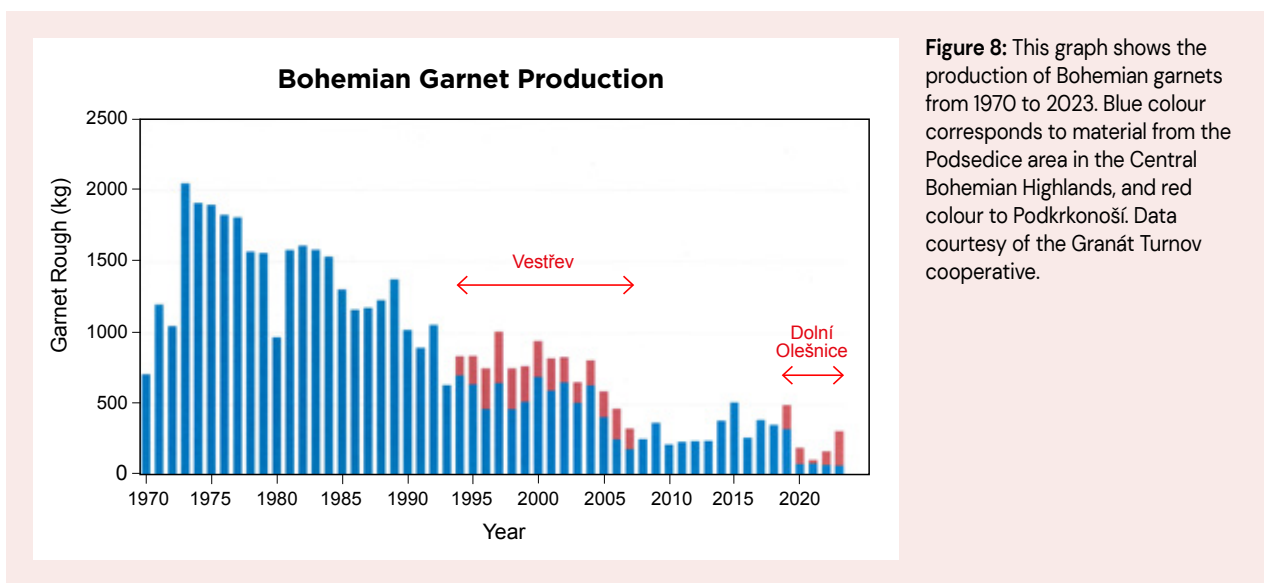
Figure 7: (a) An aerial view (from www.mapy.cz) of the small mine at Dolní Olešnice in the Podkrkonoší area shows its location in the village. (b) Some of the mining equipment used at Dolní Olešnice is seen here. Photo by R. Hanus.

Kolín Area. Exploration work by the Granát Turnov cooperative in 2014–2018 identified the presence of additional Bohemian garnets in this area, but they were mostly of low quality, with 95–98% unsuitable for jewellery use (Tvrzník & Boudný 2019). Poor clarity, together with other problems (disagreement with local residents over mining), led to the decision that the Kolín region was not promising for the extraction of gem-quality Bohemian garnets and to the termination of further activities in the area (J. Boudný, pers. comm. 2024).

MODERN PRODUCTION

The evolution of rough garnet production from 1970 to 2023 is illustrated in Figure 8. Before 1992, production fell below 1,000 kg per year only three times since 1970, with a record output of more than 2,000 kg in 1973. Twenty years later, in 1993, there was a big drop in extraction, after which production never reached former levels. This was probably related to the shift of mining to locations with lower garnet yield and grades. Currently, the garnet grade is typically 10–20 g/tonne of gravel, whereas in the past it was as high as 80 g/tonne (Granát Turnov cooperative, pers. comm. 2024). Production also decreased when previously mined areas were encountered, which has occurred frequently in recent years (e.g. 2012–2014; J. Boudný, pers. comm. 2019).

In the Podkrkonoší area, the Vestřev quarry was active for 14 years (1994–2007) before its reserves were exhausted. While in operation, it supplied only a minor part of the total annual Bohemian garnet output. Production from Dolní Olešnice has also been relatively minor (mainly due to the impact of COVID-19). Nevertheless, according to public statements by the representatives of the Granát Turnov cooperative, the operation has had a very good yield so far (150 g/tonne), but this needs to be evaluated in the



context of the small area mined. By comparison, the Podsedice area has a long history of productivity, where mining took place over tens of hectares, and hundreds of thousands of tonnes of garnet-bearing gravels were processed. Even in ‘off’ years, high yield (e.g. 188 g/tonne) has been reported for Podsedice (Kouřimský & Hyršl 2008). Therefore, the vast majority of modern Bohemian garnet production has come from the Podsedice area.

Since the closure of the Vestřev mine, the average annual production of rough gem-quality Bohemian garnet has been around 300 kg. The vast majority of the stones measure 2–5 mm (again, see Figure 1). Those larger than 5 mm form less than 1% of the total current production. The Granát Turnov cooperative reported obtaining 100–250 g of garnets in the 6–8 mm range annually (Tvrzník & Boudný 2019); this represents just 0.025–0.080% of the total garnet production. In the past, this figure may have varied depending on the method and location of mining, but ‘large’ Bohemian garnets have always been

exceedingly rare.

All garnets recovered from both Podsedice and Dolní Olešnice are processed in Granát Turnov’s facility, where those of a quality and size suitable for gem use (e.g. Figure 9) are cut and fashioned into jewellery. The remainder are used to produce decorative objects, especially in combination with glass.

DEVELOPMENT OF USE AND CUTTING

The earliest use of Bohemian garnets in the Czech Republic is known from two jewellery finds dated to the second half of the fifth century CE (i.e. the Migration Period). The first is from the grave of an unknown nobleman found in Cezava near Blučina (Moravia, eastern Czech Republic), and the second consists of gem-encrusted gold items found in 2020 near Rakovník in central Bohemia (e.g. Figure 10; see



Figure 9: Bohemian garnets are occasionally faceted as brilliants, although their typically small size makes this a rarity. These stones weigh approximately 0.5–1 ct and the diameter of the largest stone is 5.7 mm. Photo by Aleš Hladký.



Figure 10: A gold belt ornament from the second half of the fifth century CE (i.e. the Migration Period), in the Museum of T.G.M. Rakovník, is richly decorated with cabochons of Bohemian garnet, polished plates of Indian almandine and three pieces of green glass. The piece measures 3.7 × 5.7 × 0.9 cm and weighs 71.61 g. Photo by Martin Frouz.

Hanus *et al.* 2023a). In all these jewels, the Bohemian garnets consisted of tall round cabochons and were accompanied by flat polished plates of almandine with curved edges. Many other Bohemian garnets have been found in jewellery from archaeological finds dating back to the late seventh century CE (e.g. Arrhenius 1985).

There was then a long interval during which there is no material evidence for the use of Bohemian garnet. The next documented find is from an archaeological site in Prague, which yielded a flower-shaped jewel containing Bohemian garnets that were accompanied by small freshwater pearls, which the authors dated to the thirteenth century using the radiocarbon method (Hanus & Hladký in prep.).

The reign of Rudolf II (1576–1612 as Holy Roman Emperor and 1575–1611 as King of Bohemia) is significant for the history of the processing of Bohemian garnets. The first gem-cutting plant was established at the end of the sixteenth century (Urban 1976; Hladký 2021) in Prague, following those in the Breisgau region of present-day Germany, where Bohemian garnet was already being processed in the first half of the sixteenth century. The first written evidence of garnets being fashioned in the Breisgau region is found in the 1544 rules (*‘Bruderschaftsordnung’*) pertaining to gem cutters in Freiburg im Breisgau and Waldkirch (Schragmüller 1914). Although there were gem-cutting facilities in Bohemia until around 1750, most Bohemian garnets were still processed in Nuremberg or the Breisgau region. Only the larger Bohemian garnets were cut in the Kingdom of Bohemia (Urban 1976; Hladký 2021). Initially, the garnets were used mainly to decorate religious objects (canticles, monstrances, etc.), as well as in objects used for presentation at the courts of the rulers and elites of the time (e.g. from the Miseroni family workshop; see Urban 1976; Hladký 2021).

From the middle of the eighteenth century came the Golden Fleece, which contains the largest known Bohemian garnets (see the Important Jewels section below). After 1750, a significant development in garnet cutting began in Bohemia, associated with a ban on the export of rough material issued by Empress Maria Theresa (Cogan 1997) and subsequently confirmed by her son

Joseph II. The export ban was linked to the War of the Austrian Succession (1740–1748), when French troops threatened Baden in southern Germany. As a result, not only did cutting activities expand in the existing centre in Turnov and its surroundings, but a new guild of cutters was established in Kolín, near a then-source of garnet rough (Hanus 2019). According to archival documents, new cutting plants were also established by the owners of estates where Bohemian garnets were being mined, or by traders in Bohemian garnets. These include facilities in Podsedice (run by Count Hatzfeld) and its surroundings, and in Jistebnice¹, near Tábor in southern Bohemia. Another cutting plant was built in Světlá nad Sázavou by Count Krakowski of Kolowrat. These facilities gradually dominated garnet processing in Bohemia. The processing of Bohemian garnets in the Breisgau region ended at the close of the nineteenth century.

The growth of garnet cutting in Bohemia in the second half of the eighteenth century also brought with it the production of jewellery and decorative objects containing Bohemian garnets. This was followed in the nineteenth century by a boom in bourgeois and folk jewellery, reinforcing the revival that made Bohemian garnet the Czech national gemstone (Figure 11). Jewellery with Bohemian garnet was produced in Prague, in Turnov and its surroundings, and in Vienna.

At the turn of the twentieth century, garnet cutting became concentrated in only two centres: the Turnov region and Světlá nad Sázavou. The Turnov area and Prague have remained the centre for jewellery makers using Bohemian garnets. Events of the mid-twentieth century had a significant influence on the development of this industry. During the Second World War, the trades of Jewish goldsmiths were liquidated. After 1948, the Communist government nationalised the rest of the private jewellery workshops and closed the cutting operations in Světlá nad Sázavou (Kratochvíl family, pers. comm. 2012). Production was then limited to Turnov, associated with the Granát cooperative. After 1989, small workshops began to re-emerge, which renewed the cutting and production of Bohemian garnet jewellery. However, the Granát Turnov cooperative remains the dominant jewellery producer (e.g. Figure 12; Hanus *et al.* 2013; Hanus & Hladký 2019a). Currently, the

¹ Jistebnice is not situated in the garnet mining area, but the cutting facility was established there by the sixth Fürst Lobkowitz because it had a better source of water used to power the grinding wheels. The garnets were imported from the estate in Třebívlice (Čermáková 1972).



Figure 11: Examples of antique jewellery set with Bohemian garnets include (a) a nineteenth-century brooch (5.5 × 2.5 cm, foil-backed), (b) another brooch that dates to 1850–1875 (5 cm across) and (c) a necklace of faceted beads ranging from 4.0 to 6.4 mm with a total length of 43 cm. Photos by Aleš Hladký.

various entities involved with the garnet industry (from mining to finished jewellery) employ around 200–220 people.

IMPORTANT JEWELS

Among the largest known Bohemian garnets are two set in the Golden Fleece, now in the Green Vault in Dresden, Germany (Figure 13). The Golden Fleece was created in Prague by goldsmith Franz Christoph Georg Diesbach in 1749 (Hráský 1987; see also <https://skd-online-collection.skd.museum/Details/Index/185946>), and the gems were identified in 1998 and 1999 by Czech gemmologist Dr Jaroslav Hyršl (Hyršl 2000, 2001). The centre (largest) stone in the jewel was initially referred to as Bohemian garnet, and although it may have a Bohemian origin,



Figure 12: This ring from the Granát Turnov cooperative contains Bohemian garnet and light-green moldavite (8 × 4 mm marquise-cut gem), and provides an example of modern garnet jewellery produced in the Czech Republic. Photo by P. Hladký.



Figure 13: The Golden Fleece jewel, commissioned by Augustus III and created by Franz Christoph Georg Diespach of Prague in 1749, represents the insignia of the Habsburg Knights. The largest cabochon is pyrope-almandine and the other two prominent gems consist of Bohemian garnet. Measuring $21.5 \times 19.8 \times 5.2$ mm (bottom) and 19.2×16 mm (top), these stones are the largest-known Bohemian garnet gems. The backs of all three large garnets are concave cut to lighten their dark red colour. The jewel resides in the Green Vault, Staatliche Kunstsammlungen Dresden (inv. no. VIII/6). Photo by Jürgen Karpinski.

it was identified by Hyršl (2000) as pyrope-almandine. Since the term Bohemian garnet refers only to pyrope, we thus point to the red gem below it as the largest-known Bohemian garnet gemstone: an oval cabochon measuring 21.5×19.8 mm and approximately 5.2 mm deep. The second-largest Bohemian garnet is the top stone, an oval measuring 19.2×16 mm, with a faceted girdle and cabochon top. All three large stones in the Golden Fleece have a concave back to lighten their otherwise over-dark appearance.

Created in the early nineteenth century, Theodore Ulrike Sophie von Levetzow's jewellery (currently in the Regional Museum and Gallery in Most, Czech Republic) is the most extensive collection known of large Bohemian garnets (Figure 14). The suite consists of two matching bracelets, a necklace, a ring, a pair of earrings and a brooch. It contains 469 Bohemian garnets ranging from 5 to 9 mm in largest dimension. Of these, 458 are faceted beads and 11 are oval brilliants. In 2018, detailed research was carried out to fully characterise the stones, as well as determine the composition of the metals in the settings (Hanus *et al.* 2022).

In 2023, the Granát Turnov cooperative created a luxurious anniversary set (named '70') to celebrate 70 years since their foundation. Comprised of a necklace, bracelet, ring and two pairs of earrings (Figure 15), the set is made with a total of 81 g of 14 ct yellow gold and contains 65.22 carats of Bohemian garnets. These include 70 faceted stones, each with the exceptional size 6.8×4.8 mm, which are accented by 1,492



Figure 14: The nineteenth-century jewellery suite of Theodore Ulrike Sophie von Levetzow, now in the Regional Museum and Gallery in Most, is the most extensive collection known of large Bohemian garnets. It contains 469 garnets ranging from 5 to 9 mm, including 458 faceted beads and 11 oval brilliants. Photo by Pavel Škácha; from Hanus and Hladký (2019b).



Figure 15: The luxurious jewellery suite '70' was created by three goldsmiths (H. Stehlíková, M. Cymbálová and M. Duffek) and one lapidary (author AH) to celebrate the seventieth anniversary of the Granát Turnov cooperative. The suite contains 65.22 carats of Bohemian garnets: 70 matched stones (6.8 × 4.8 mm each) and 1,492 melee gems (1.1–1.5 mm each). Photo courtesy of the Granát Turnov cooperative.

melee garnets (1.1–1.5 mm). The set was created by three goldsmiths (H. Stehlíková, M. Cymbálová and M. Duffek) and one lapidary (author AH). The larger Bohemian garnets came from a collection of stones created at the beginning of the twentieth century. They were re-cut to all be the same size using techniques developed during the nineteenth and twentieth centuries that are no longer in general use.

GEMMOLOGICAL PROPERTIES

As reported by Hanus *et al.* (2019), Bohemian garnet has a homogeneous 'blood-red' colour, with an RI value ranging from 1.748 to 1.755 and an SG of 3.70–3.79. The stones are inert to long- and short-wave UV radiation, and appear deep red with

the Chelsea Colour Filter and dark red with the Hanneman ruby filter.

Stones from all three localities in the Czech Republic are identical in colour, so their origins cannot be distinguished by their appearance. The material is not subjected to any treatments, although the gems are sometimes backed with shiny foil (especially in historical jewellery) to brighten their appearance.

Inclusions

So far, only solid inclusions have been found in Bohemian garnets. There have been no documented fluid or gas-liquid inclusions, which is consistent with the genesis of the pyrope in the earth's mantle (Hanus 2019). The presence of various inclusions

Table II: Inclusions in Bohemian garnet from various localities in the Czech Republic (Hanus 2019).

Inclusion type	Podsedice	Podkrkonoší (Vestřev)	Kolín
Apatite	+	+	+
Chlorite	—	+	+
Crichtonite-group minerals	—	—	+
Diamond	+	—	—
Diopside	+ (Cr)	—	+
Enstatite	—	—	+
Fe hydroxyl-oxides	—	+	—
Fe-Ni sulphide	+	+	—
Ilmenite	+	—	+
Kyanite	—	+	—
Magnesite	—	+	+
Nontronite	+	—	—
Olivine	—	+	+
Pargasite	+	—	+
Phlogopite	—	—	+
Rutile	—	+	+
Spinel	+ (Al-Cr)	+	+
Sulphides	—	—	+
Trichitic ducts	—	+	—
Zircon	+	+	+

may be indicative of a particular geographic origin of Bohemian garnet (Table II). The inclusions discussed below were all identified by Hanus (2019) with wavelength-dispersive spectroscopy using an electron probe micro-analyser.

Garnets from the Central Bohemian Highlands (e.g. Podsedice) are characterised by high clarity, and it is rare to find any inclusions in them. When present, they consist of small polymineralic inclusions with tension cracks (sometimes resembling fluttering flies; Figure 16a, b). Polymineralic assemblages of ilmenite and other minerals are also present (Figure 16c, d). Rarely, short-to-long prismatic crystals are encountered (Figure 16e, f), such as apatite, olivine and zircon. A diamond inclusion was reported by Jakubová (2022) in one Bohemian garnet obtained from research drill hole T38 near the village of Staré (in the Linhorka area).

Garnets from Podkrkonoší (Vestřev) typically contain trichitic ducts and cavities (Figure 17a). Crystals of apatite are rarely found (Figure 17b, c), but are more commonly present near the surfaces of rough garnets from this area (and from Dolní

Olešnice). Ilmenite (Figure 17b) and olivine (Figure 17d) are also encountered.

Typical inclusions in garnets from the Kolín region include oriented rutile needles, enstatite and ilmenite (Figure 18). However, garnets from this area are rarely found in jewellery and historical objects.

Chemical Composition

The composition of Bohemian garnet is quite consistent (see Table III), according to data from numerous sources (e.g. Schlüter & Weitschat 1991; Řídkošil *et al.* 1997; Seifert & Vrána 2005; Vrána 2008; Hanus *et al.* 2013). Oxide compositions from Hanus *et al.* (2013) were converted to garnet end members according to the procedure of Locock (2008), but only three major end members are considered here (pyrope, almandine and grossular), as they account for 95–100 mol.% of the components in Bohemian garnets. According to these calculations, the pyrope content varies between 77 and 81 mol.%.

Data for the major chemical components of pyrope (Mg, Al and Si) are similar for all the sources compared in Table III, except for some samples reported by Lind (2015), which have a lower minimum Mg content (14.88 wt.% MgO) than the others. As for the other components, Fe does not exceed 10 wt.% FeO except for somewhat higher maximum values reported by Lind (2015) and for samples from Kolín, with a maximum value of 11.34 wt.% FeO. Ca is mostly in the range of 4–6 wt.% CaO. The exceptions are the minimum CaO value of 3.44 wt.% for stones from Kutná Hora (Kolín area; Hanus *et al.* 2013) and the maximum of 7.16 wt.% CaO reported by Lind (2015).

Pure pyrope is colourless, and Cr is an important component of Bohemian garnet because it contributes to its beautiful red colour (e.g. Rost *et al.* 1975). The minimum Cr₂O₃ value for Podsedice pyrope is typically about 1.5 wt.%, although Lind (2015) reported half that amount. The highest Cr content (4.21 wt.% Cr₂O₃) was reported for a garnet from Podsedice (Hanus *et al.* 2013).

Photoluminescence (PL) Spectroscopy

To distinguish Cr-bearing pyrope from other garnets, it is useful to detect the presence of Cr using PL or absorption spectroscopy. Cr-bearing pyrope from Bohemia and elsewhere (e.g. Arizona, USA; Umba, Tanzania, etc.) is characterised by the presence of five distinct PL peaks between 4100 and 4500 cm⁻¹ (Figure 19). Those at 4181, 4241, 4302 and 4374

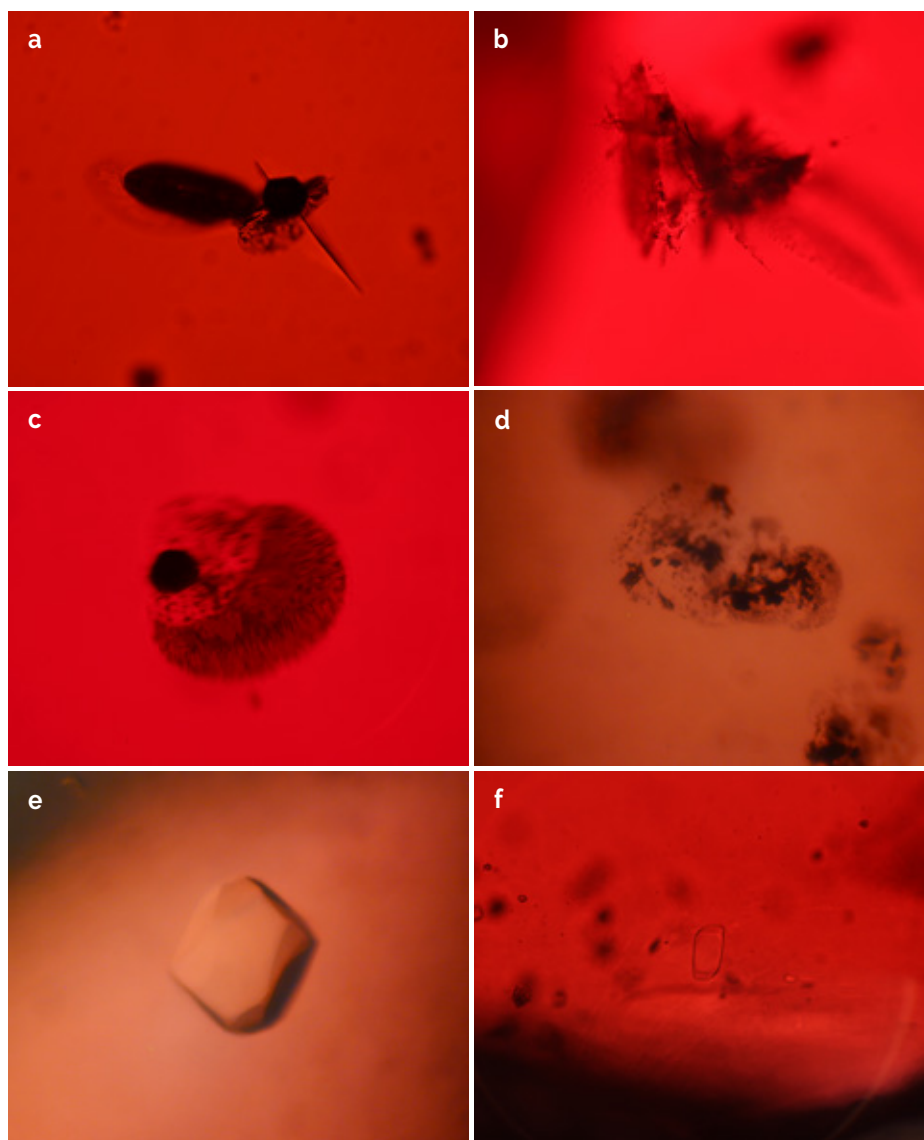


Figure 16: Internal features in Bohemian garnets from Podsedice include (a, b) polymineralic 'fly'-type inclusions, (c) ilmenite with a polymineralic veil, (d) a polymineralic isotropic inclusion, (e) apatite showing an abundance of crystal faces and (f) a flattened anisotropic elongated inclusion. The samples are from Třebívlice (a, c, e, f) and Měrunice (b, d). Photomicrographs from Hanus (2019); image widths (a, b) 2.0 mm, (c) 2.1 mm, (d) 1.0 mm, (e) 0.5 mm and (f) 1.1 mm.

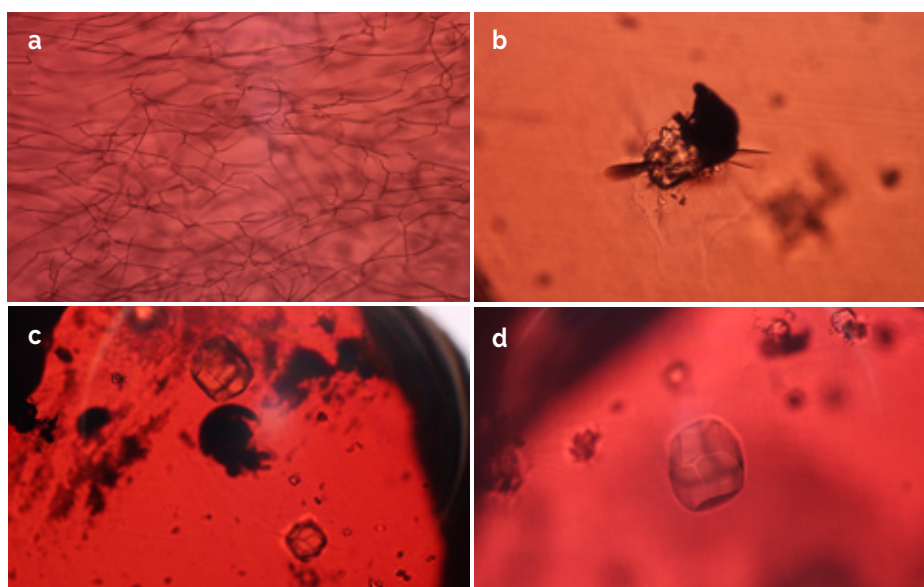


Figure 17: Internal features in Bohemian garnets from Podkrkonoší (Vestřev) include (a) trichitic ducts, (b) apatite and ilmenite, (c) euhedral apatite crystals accompanied by opaque inclusions and (d) euhedral olivine. Photomicrographs from Hanus (2019); image widths (a) 0.4 mm, (b) 0.5 mm, (c) 2.0 mm and (d) 0.6 mm.

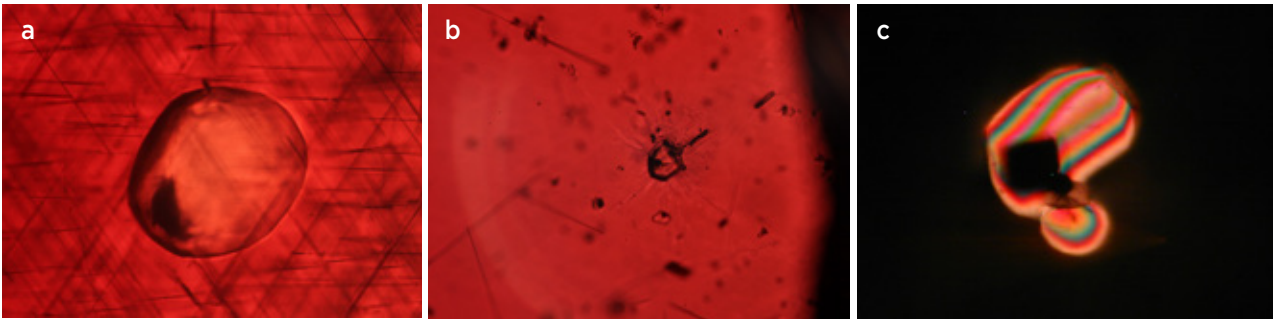


Figure 18: Internal features in Bohemian garnets from Kolín include: (a) an oriented network of rutile needles, shown here with a rounded apatite crystal; (b) colourless enstatite (here with long rutile needles); and (c) an unidentified anisotropic inclusion with ilmenite (seen in cross-polarised light). The samples are from (a) Hranice-Granátnice and (b, c) the Hranice-Chotoukovský stream. Photomicrographs from Hanus (2019); image widths (a) 0.2 mm, (b) 0.5 mm and (c) 1.0 mm.

cm^{-1} correspond to Cr, and the peak at 4445 cm^{-1} is probably due to V (Jasinevicius 2009).

Vis-NIR Spectroscopy

The absorption spectra for Cr-bearing pyrope from major world localities (i.e. Arizona, USA; Yakutia, Russia; and Tanzania) are characterised by two distinct maxima at 445 and 575 nm and a small Cr^{3+} peak at 690 nm. By comparison, the spectrum of Bohemian garnet (i.e. from the Central Bohemian Highlands and the Podkrkonoší area) is characterised by a very weak maximum at 445 nm and a significant absorption at 575 nm, as well as the small Cr^{3+} peak at 690 nm (Figure 20). No significant differences have been noted between the spectra of Bohemian garnet from the various important mining sites (Hanus 2019).

Therefore, it is possible to distinguish Bohemian garnets from Cr-bearing pyrope from elsewhere. The only exception is material from Kolín area, which has a weak (rather than very weak) peak around 445 nm along with the significant absorption at 575 nm and the small Cr^{3+} peak at 690 nm. This makes Bohemian garnets from Kolín partially similar to Cr-bearing pyrope from Arizona, USA (i.e. so-called Anthill garnet). However, Bohemian garnets from Kolín are quite small and have not been used in jewellery for more 200 years.

CONCLUSION

Bohemian garnet (Figure 21) is ‘blood-red’ Cr-bearing pyrope from the Czech Republic, and

Table III: Chemical composition of Bohemian garnet from various localities in the Czech Republic.*

Locality	Podsedice	Podkrkonoší (Vestřev)	Kolín			Unspecified, probably Podsedice (Lind 2015)	Podsedice (Schlüter & Weitschat 1991)	Podsedice (Řídkošil <i>et al.</i> 1997)	Podsedice (Seifert & Vrána 2005)
			Kutná Hora area	Kolín area	Železné Hory area				
Oxides (wt.%)									
SiO ₂	41.23–42.58	41.19–42.69	41.87–42.91	41.41–42.54	41.41–42.71	39.48–43.02	41.02–41.46	39.72–40.63	42.57–43.10
TiO ₂	0.17–0.63	0.39–0.60	0.30–0.46	0.18–0.61	0.18–0.56	0.01–0.59	0.55–0.70	0.32–0.70	0.48–0.66
Al ₂ O ₃	19.33–22.12	20.39–21.67	21.05–22.46	20.69–22.58	20.69–22.56	20.88–22.32	21.39–21.51	21.38–21.48	21.15–21.94
Cr ₂ O ₃	1.48–4.21	0.09–2.66	0.19–1.64	0.66–2.46	0.66–2.84	0.73–3.80	1.62–1.76	1.63–2.20	1.60–2.52
FeO	7.36–9.27	7.48–8.77	8.63–10.15	7.06–11.34	7.06–8.96	7.15–14.13	9.10–9.21	7.56–8.14	8.48–9.09
MnO	0.04–0.41	bdl–2.33	0.16–0.39	0.13–0.42	0.13–3.17	0.28–0.58	0.31–0.34	0.28–0.78	0.32–0.37
MgO	19.29–21.77	19.48–21.56	20.24–21.24	18.45–21.53	18.45–20.88	14.88–21.38	20.82–21.29	20.48–21.95	20.65–21.13
CaO	4.17–5.53	4.26–4.70	3.44–4.59	4.13–5.15	4.13–5.15	4.37–7.16	4.45–4.48	5.49–5.88	4.31–4.52
End members (mol.%)									
Pyrope	81 ± 2.0	77 ± 1.6	79 ± 2.9	79 ± 4.7	78 ± 2.2	nd	nd	nd	nd
Almandine	17 ± 1.6	16 ± 1.3	18 ± 0.9	16 ± 3.3	15 ± 1.6	nd	nd	nd	nd
Grossular	2 ± 1.7	2 ± 1.9	2 ± 2.4	5 ± 2.2	3 ± 2.3	nd	nd	nd	nd

* Data are from Hanus et al. 2013, except as noted otherwise. End members were calculated according to Locock (2008), but only the three major end members are shown, and therefore totals do not always add up to 100%. Abbreviations: bdl = below detection limit; nd = not determined.

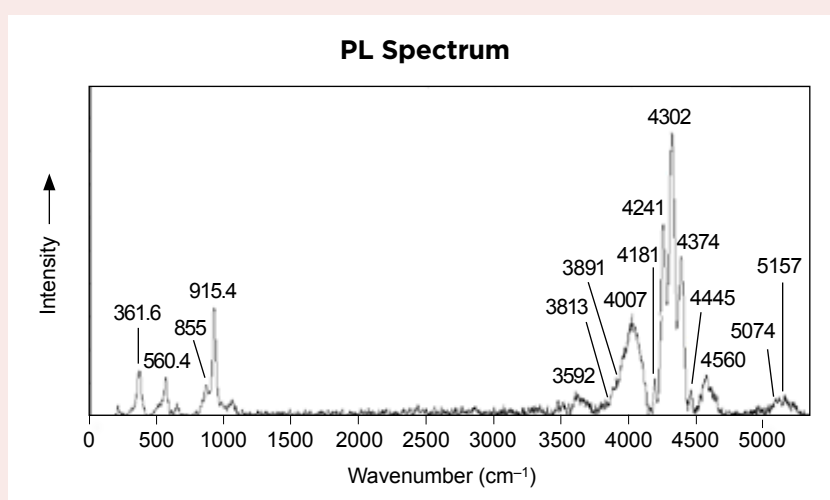


Figure 19: The PL spectrum in the 100–5400 cm^{-1} range of a Bohemian garnet from Třebívlice (Central Bohemian Highlands) shows typical Cr peaks in the 4100–4500 cm^{-1} region. The peak at 4445 cm^{-1} is probably due to V. Modified from Hanus (2019).

is the Czech national gemstone. Mining currently takes place at Podsedice in the Central Bohemian Highlands and at Dolní Olešnice in the Podkrkonoší area. The former deposit has been worked for a longer period and will continue to be active for a long time in the future. The Dolní Olešnice mine is located directly in the village of the same name, and is a smaller operation.

Bohemian garnet has a homogeneous red colour and an RI value ranging from 1.748 to 1.755. The occurrence of inclusions in garnets from the Central Bohemian Highlands is rare. When present, they form polymineralic inclusions accompanied by tension cracks (which may resemble the wings of a fly), as well as prisms of apatite, olivine and zircon. Hollow trichitic channels are typical in stones from the Podkrkonoší area, and apatite may be present mainly

near the surface of the garnet rough, so it may not be retained in cut stones.

The chemical composition of Bohemian garnet is quite homogeneous. The pyrope component is 77–81 mol.%, with the remainder attributed mostly to almandine and grossular. Chromium (the red chromophore) ranges mostly from 1.5 to 4.0 wt.% Cr_2O_3 , but may occasionally be slightly higher. The Vis-NIR absorption spectrum of Bohemian garnet is dominated by a single strong absorption around 575 nm with a weaker feature at 445 nm and a small Cr^{3+} peak at 690 nm. This potentially can distinguish it from Cr-bearing pyrope from other worldwide localities (Arizona, Tanzania and Yakutia), which show two strong maxima at 445 and 575 nm.

Significant reserves of Bohemian garnet exist in both currently productive areas, providing a good

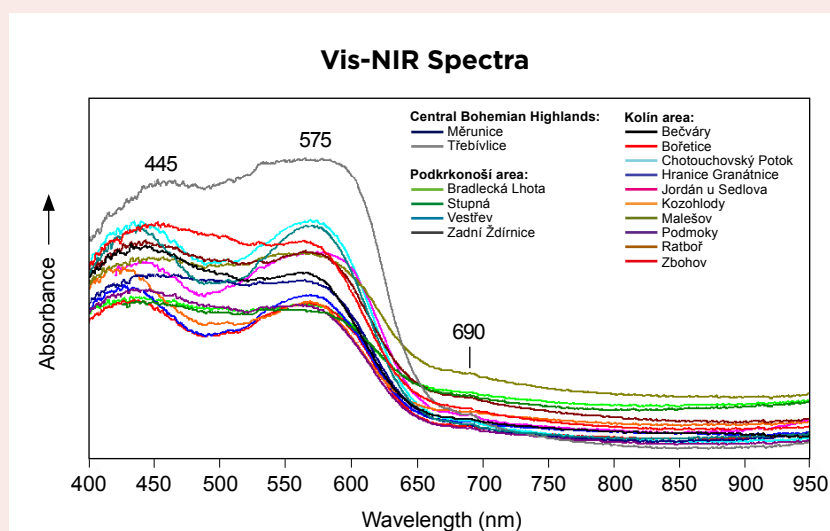


Figure 20: Vis-NIR absorption spectra of Bohemian garnets from various localities in the Czech Republic show maxima at about 440–450 nm and 575 nm, as well as a weak peak around 690 nm, features typical of Cr^{3+} in garnet. The approximate path length of the beam through the samples was 0.7 mm. Modified from Hanus and Hyršl (2019).



Figure 21: These jewellery items feature Bohemian garnet (with the exception of the large cabochon in the brooch, which is almandine). The pieces are from various manufacturers in the Czech Republic and were produced between 1850 and 1910. The garnets exhibit different types of cuts, and some of the stones are foil-backed to brighten their appearance. The square brooch measures 4.5 cm across. Photo by Martin Frouz.

outlook for future production. In the Central Bohemian Highlands, large amounts of garnet are economically mineable, while at Podkrkonoší the reserves are smaller and the situation is more complicated because the garnet-bearing sediments are located in a relatively

confined area near buildings within the village.

With its centuries-old tradition of jewellery use and status as the Czech national gemstone, Bohemian garnet is admired not only as a stone for collectors, but also in jewellery for everyday wear.

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Acknowledgements

The authors thank Michal Soukup and the Regional Museum and Gallery in Most, Czech Republic, as well as Dirk Weber and Staatliche Kunstsammlungen Dresden, Germany, for photographs. We also thank Drs H. Albert Gilg and Karl Schmetzer for their consultations. We are grateful to the Kratochvíl family, Jiří Boudný and the Granát Turnov cooperative for valuable information and photographs. Special thanks to the three anonymous reviewers for their valuable suggestions and advice.



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Gemmological Characteristics and Origin of Brown Olivine from Southeast Vietnam

Le Ngoc Nang, Pham Minh Tien, Pham Minh, Ho Nguyen Tri Man and Pham Trung Hieu

ABSTRACT: Olivine from Southeast Vietnam is notable for its dark brown colour, rather than the yellowish green appearance exhibited by typical gem-quality peridot. Discovered in 2020, this material occurs as xenocrysts weathered from the Xuan Loc alkali basalt. It is transparent to opaque, with a vitreous lustre. It has relatively high RIs ($n_a = 1.680\text{--}1.685$ and $n_v = 1.702\text{--}1.715$) and relatively low birefringence ($0.022\text{--}0.035$), as well as elevated SG values ($3.39\text{--}3.55$). Inclusions consist of distinctive curly fibres of serpentine, and a hazy appearance of some stones is caused by amphibole particles. Raman and FTIR spectroscopy show features characteristic of olivine, and both powder X-ray diffraction and EDXRF chemical analysis indicate the olivine is forsterite. Based on geothermometer calculations from trace-element contents, the olivine crystallised from garnet peridotite in the temperature range of approximately $1400\text{--}1460^\circ\text{C}$ and a pressure of 50 kbar. Although this brown olivine has limited usefulness as a gem material, its unusual properties and inclusions may draw the attention of gem collectors.

The Journal of Gemmology, 39(3), 2024, pp. 260–269, <https://doi.org/10.15506/JoG.2024.39.3.260>
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The olivine group consists of several minerals having the general formula $M_2\text{SiO}_4$, where $M = \text{Ca, Fe, Mn, Ni or Mg}$. The word *olivine* is commonly used to refer to a member of the forsterite–fayalite series ($\text{Mg}_2\text{SiO}_4\text{--Fe}_2^{2+}\text{SiO}_4$). All gem-quality olivine (peridot) is forsterite, and it is typically yellowish green. Some important sources of peridot include Tanzania (Stockton & Manson 1983), China and North Korea (Koivula & Fryer 1986; Zhang *et al.* 2019), Italy (Adamo *et al.* 2009), Pakistan (Kane 2004) and Myanmar (Seneewong-Na-Ayutthaya *et al.* 2022). In Vietnam, attractive yellowish green peridot is mined from the Gia Lai area of the Central Highlands region (Thuyet *et al.* 2016).

In recent years, gem-quality brown olivine (Figure 1) has been collected in Southeast Vietnam. This region experienced up to 30 volcanic eruptions during the Cenozoic era, producing a series of extrusive rocks

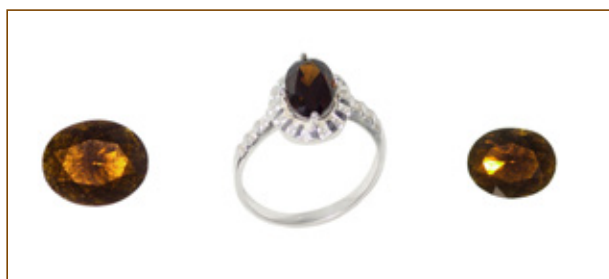


Figure 1: Faceted dark brown olivine from Southeast Vietnam is shown here as two loose gems in transmitted light (2.50 and 1.93 ct) and a 2.04 ct stone mounted in a ring. Composite photo by Le Ngoc Nang.

that include alkali basalt, tholeiitic basalt and andesite (Hoang & Flower 1998). In previous studies related to basaltic gem minerals in Southeast Vietnam, the authors found that gem-quality olivine and other gem materials (e.g. sapphire, zircon, garnet, augite and anorthoclase) are often associated with xenocrysts and xenoliths in the

alkali basalt (Nang *et al.* 2023b).

This study was initiated during the authors' search for new gem sources in Southeast Vietnam. Although the brown olivine is not currently being mined, the authors believe that this material is widespread, given the extensive distribution of its host rock in the study area. The aim of this article is to describe the distinct gemmological properties and geological origin of brown olivine from Southeast Vietnam, and to compare it with yellowish green peridot from Vietnam's Central Highlands and elsewhere.

GEOLOGICAL SETTING

Cenozoic basalt in Vietnam covers an area of about 28,000 km², with a calculated volume of about 250,000 km³ (Figure 2a; Barr & Macdonald 1981). The basalt flows had two main eruptive styles: massive eruptions from large fissures and subsequent explosive eruptions. They are mainly distributed in the southern part of the country (Figure 2a), in areas such as Buon Me Thuot, Pleiku, Bao Loc, Phuoc Long, Binh Phuoc and Dong Nai (Xuân *et al.* 2004; Tri & Khuc 2011). Most of the Cenozoic basaltic rocks in southern Vietnam are found in

the Xuan Loc District of Dong Nai Province. According to drill cores, the basalt layers have an average thickness of 50–125 m (Thang *et al.* 1998). The Cenozoic basalts in Dong Nai include the Cay Gao, Soc Lu and Xuan Loc flows (Figure 2b), as well as others (Tri & Khuc 2011).

In Xuan Loc District, basalt is distributed over an area of 8,000 km² in the higher elevations of the mountainous Tuc Trung area north-east of Gia Kiem. The flows exhibit gentle topography, with evenly high terrain in their centre, and gradually spread out from a height of over 180 m to 100 m. The main petrographic composition in the study area is alkaline olivine basalt. Phenocrysts account for about 10–20% by volume, in a scattered distribution, and include mainly plagioclase (50–55%), olivine (20–30%) and pyroxene (20–30%). Groundmass forms about 80–90% of the basalt, consisting mainly of plagioclase (60–70%) in the form of short prisms or rods in a criss-cross arrangement. Interspersed between the plagioclase prisms are pyroxene grains (20–25%), metallic minerals (5%) and a little glass (<5%; Tri & Khuc 2011).

The area surveyed by the authors is in Thong Nhat District, which lies just east of Xuan Loc District and is located about 70 km north-east of Ho Chi Minh City.

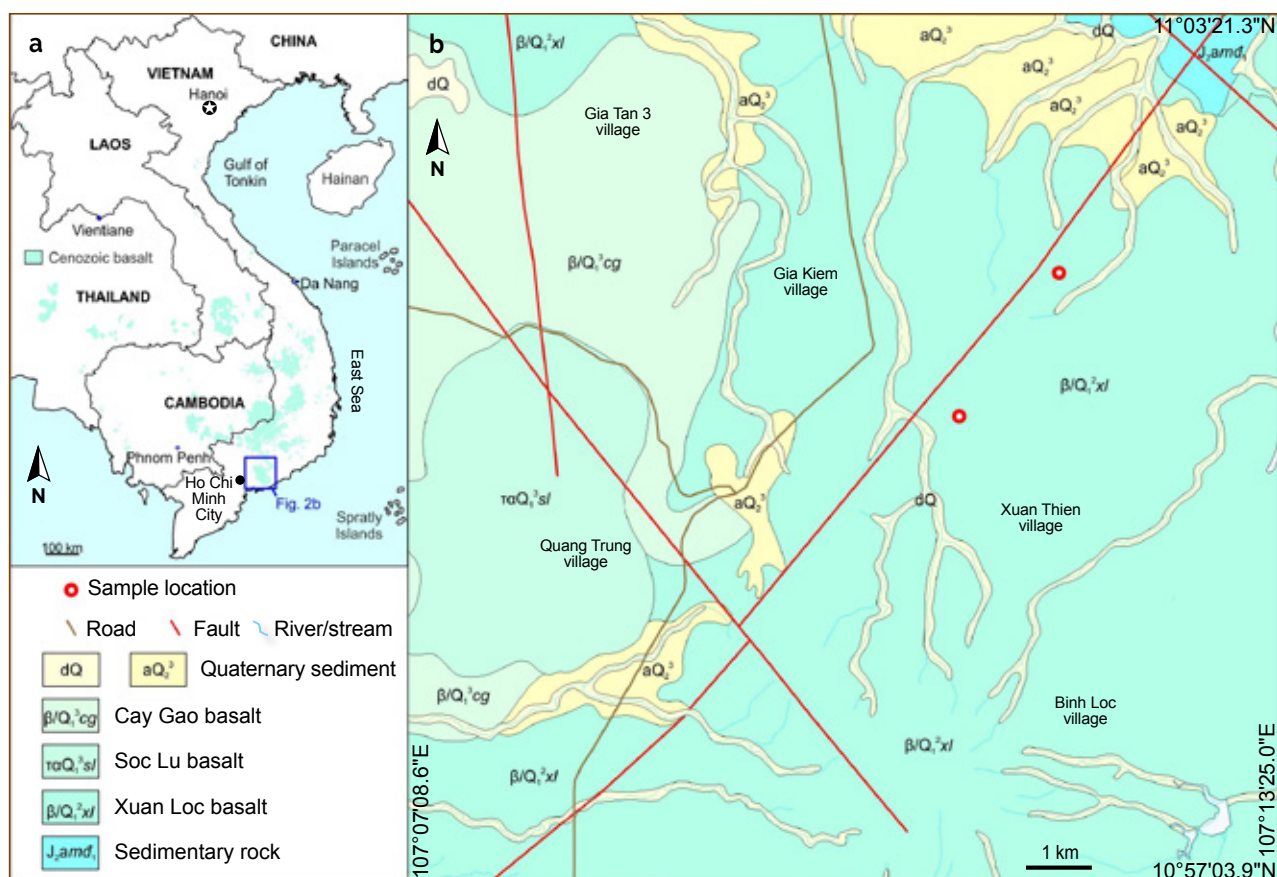


Figure 2: (a) A regional map shows the distribution of Cenozoic basalts in Vietnam, Laos, Cambodia and Thailand. (b) A geological map of the study area shows the regional Cenozoic basalt units, as well as two locations (red dots) from which samples used in this study were collected. Adapted from Thang (1998).



Figure 3: (a) Brown olivine from Southeast Vietnam is found in areas containing alkali basalt that weathers into a layered or blocky structure. (b) Colluvial material includes a reflecting fragment of xenocrystic olivine (see arrow). Photos by Le Ngoc Nang.

The olivine-bearing volcanic rock belongs to the Xuan Loc basalt unit, which commonly hosts mantle xenoliths. The Xuan Loc basalt erupted in mid-Pleistocene time (making it the youngest basalt in Vietnam) and consists of three main layers that together are 100–150 m thick (Nguyen & Kil 2000). In the study area, the olivine-bearing basalt has a dense layered or blocky structure (Figure 3a) and is grey on unweathered surfaces. Concentrations of olivine and pyroxene are often found in the basalt as xenoliths. These aggregates ranged from 1 to 20 cm in diameter (as seen by the authors), and the unweathered olivine appeared light yellowish green (Figure 4). None of the yellowish green olivine was gem quality due to the small grain size of the aggregate nodules. By contrast, brown olivine was found mostly as loose pieces in soil (Figure 3b) and consisted of xenocrysts or xenoliths ranging from a few centimetres up to 10 cm (averaging around 7 cm). The aggregates of brown olivine contained pieces of suitable clarity and size for polishing into gemstones.

MATERIALS AND METHODS

From 2020 to 2022, with the help of local people, the authors obtained more than 50 samples of the brown olivine, 19 of which were selected for detailed study. Of these, nine were collected by the authors and ten by the locals. Nine of these specimens were cut into the following stones: four faceted gems (sample numbers P1–P4), four cabochons (with polished flat bottoms; P5–P8) and a carving (P9); the remaining specimens (P10–P19) were retained as rough material (Figure 5).

All samples were examined with fibre-optic lighting (both reflected and transmitted) using a 60 W GLS LED daylight bulb with a colour temperature of approximately 5000–6000 K. RI values were obtained

from the faceted stones and cabochons using a refractometer with a sodium light source and a contact liquid consisting of a mixture of methylene iodide and tetraiodoethylene ($n = 1.81$). All samples were measured by hydrostatic weighing to obtain SG values, and they were also tested for UV fluorescence using 4 W long-wave (365 nm) and short-wave (254 nm) bulbs. Absorption spectra of the polished specimens were observed with a Kruss 1504 handheld spectroscope. Optical properties and pleochroism of the faceted stones were determined with a polariscope and dichroscope, respectively.



Figure 4: Yellowish green olivine was also encountered as xenoliths (aggregate nodules) enclosed in basalt. Such material is unsuitable for gem use due to the small grain size of the aggregates. Photo by Le Ngoc Nang.

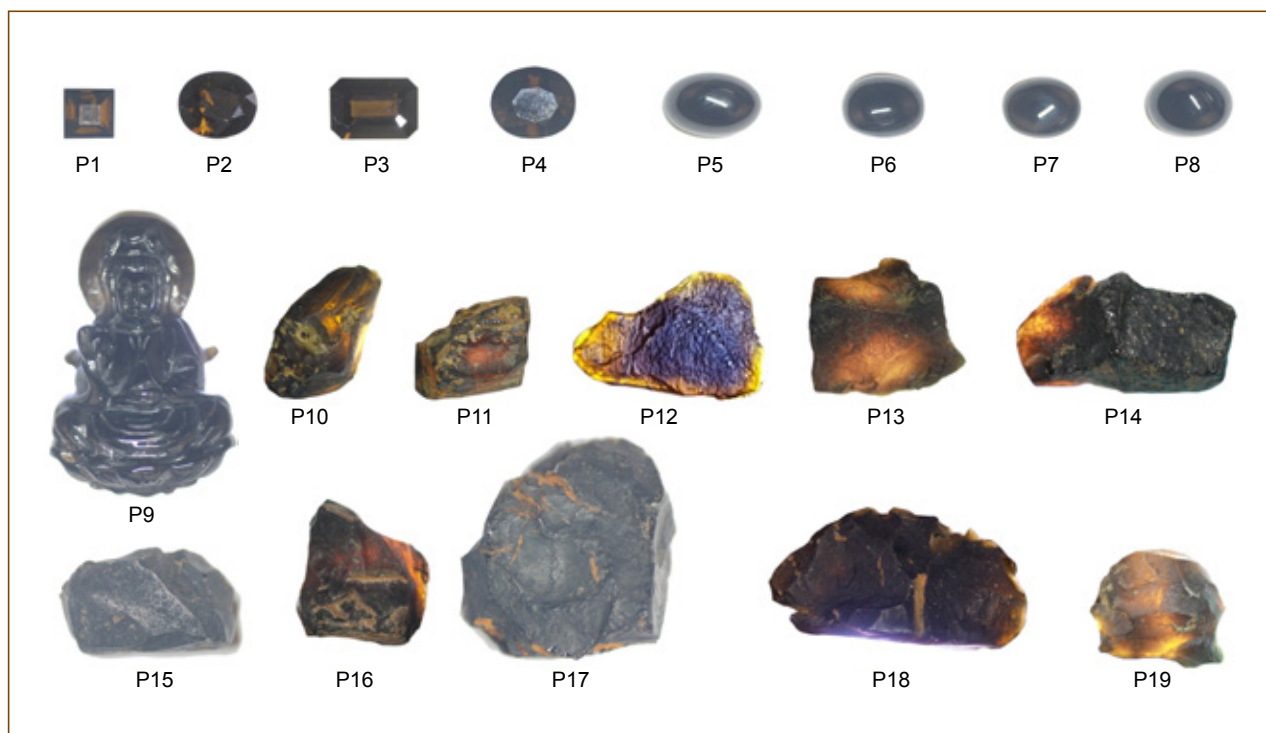


Figure 5: The brown olivine samples used for this study include four faceted stones (1.23–2.50 ct), four cabochons (2.44–6.60 ct), one carving (27.19 ct) and ten rough pieces (2.69–25.30 g). Samples P1–P4, P10–P14, P16 and P18–P19 were photographed using transmitted light, and the others are shown in reflected light. Composite photo by Le Ngoc Nang.

Internal features in samples P2, P3 and P6 were viewed using a Carton gemmological microscope with $7\times$ – $50\times$ magnification.

A Horiba XploRA One Raman confocal microscope equipped with a 532 nm laser was used to obtain Raman spectra of sample P1 in the range of 0 – 3750 cm^{-1} with an acquisition time of 15 s, two accumulations, a grating with 900 grooves/mm, a $50\times$ objective and a 50% filter.

Fourier-transform infrared (FTIR) spectroscopy was conducted in transmission mode using a Bruker Tensor 27 spectrometer in the range of 400 – 4000 cm^{-1} , with a broadband KBr beam splitter, resolution of 4 cm^{-1} and scan speed of 3 s. The spectra were acquired from a portion of sample P12, which was ground into powder using agate mortar and pestle.

Powder X-ray diffraction (XRD) patterns of sample P12 were collected by a Bruker D2 Phaser diffractometer, using $\text{CuK}\alpha$ ($1.5406\text{ \AA}$) radiation in the range of 5 – $75^\circ 2\theta$ with a scan speed of $0.02^\circ/\text{s}$, at 40 kV and 30 mA. The sample was ground to a particle size of approximately $5\text{ }\mu\text{m}$. X'Pert HighScore Plus software was used to analyse the results and compare them with the Inorganic Crystal Structure Database (Levin 2018).

Quantitative chemical analysis was performed on five samples (P1–P5) by energy-dispersive X-ray fluorescence (EDXRF) spectroscopy using a Shimadzu EDX-8100 instrument operated with a voltage of 30 kV and a current of 10 mA, along with a 3 mm collimator.

Gemmological testing was performed at Liu Gemmological Research and Application Center (LIULAB). Raman and FTIR spectroscopy, as well as XRD and EDXRF analyses, were performed at the Center of Analytical Services and Experimentation in Ho Chi Minh City, Vietnam.

RESULTS

Appearance

The rough specimens consisted of fragments without any crystal faces. All samples displayed a vitreous lustre and were transparent to opaque (Table I). They looked black in reflected daylight, but appeared brown or greenish brown in transmitted light (Figure 5).

Gemmological Properties

The gemmological properties of the brown olivine are listed in Table I. The RIs of the polished samples were $n_\alpha = 1.680$ – 1.685 and $n_\gamma = 1.702$ – 1.715 for the faceted stones, and $n = 1.69$ – 1.71 for the cabochons (spot readings). The birefringence of the faceted samples ranged from 0.022 to 0.035. The SGs of all 19 specimens were 3.39–3.55, and they were inert to long- and short-wave UV radiation. The absorption spectra of the polished samples displayed three bands at 453, 477 and 497 nm associated with their high Fe content (see chemical analysis section below). The faceted

Table 1: Gemmological properties of brown olivine from Dong Nai, Southeast Vietnam.

No.	Sample type	Weight	Colour in transmitted light	Diaphaneity	SG	RI (birefringence)	Pleochroism
P1	Faceted	1.23 ct	Dark greenish brown	Transparent	3.53	1.685–1.712 (0.027)	Brown and greenish brown
P2	Faceted	1.93 ct	Dark greenish brown	Transparent	3.50	1.683–1.712 (0.029)	Brown and greenish brown
P3	Faceted	3.56 ct	Dark brown	Transparent	3.50	1.680–1.715 (0.035)	Brown and greenish brown
P4	Faceted	2.50 ct	Dark greenish brown	Translucent	3.48	1.680–1.702 (0.022)	nd ^a
P5	Cabochon	5.35 ct	Dark greenish brown	Transparent	3.39	1.70 ^b	Brown and greenish brown
P6	Cabochon	6.60 ct	Dark greenish brown	Transparent	3.55	1.71 ^b	Brown and greenish brown
P7	Cabochon	3.22 ct	Dark greenish brown	Transparent	3.49	1.69 ^b	Brown and greenish brown
P8	Cabochon	2.44 ct	Dark greenish brown	Translucent	3.51	1.70 ^b	nd
P9	Carving	27.19 ct	Dark greenish brown	Translucent	3.49	1.70 ^b	nd
P10	Rough	5.03 g	Dark greenish brown	Translucent	3.48	nd	nd
P11	Rough	4.42 g	Dark greenish brown	Translucent	3.41	nd	nd
P12	Rough	2.69 g	Dark greenish brown	Translucent	3.47	nd	nd
P13	Rough	4.66 g	Dark greenish brown	Translucent	3.47	nd	nd
P14	Rough	8.81 g	Dark greenish brown	Translucent	3.55	nd	nd
P15	Rough	6.91 g	Very dark brown	Opaque	3.46	nd	nd
P16	Rough	4.42 g	Dark greenish brown	Translucent	3.46	nd	nd
P17	Rough	25.30 g	Very dark brown	Opaque	3.45	nd	nd
P18	Rough	9.28 g	Dark greenish brown	Translucent	3.47	nd	nd
P19	Rough	3.65 g	Dark greenish brown	Transparent	3.42	nd	nd

^a Abbreviation: nd = not determined.

^b Spot RI value.

stones showed biaxial patterns with the polariscope, and moderate dichroism in brown and greenish brown.

Internal Characteristics

None of the samples contained any of the ‘lily pad’ inclusions that are typical of peridot. Instead, most of them showed curly thread-like inclusions that consisted of serpentine (Figure 6a), as determined by Raman spectroscopy and documented previously (Nang 2023). Also present were tiny particles—identified as amphibole by Raman spectroscopy—which caused some samples to appear whitish and cloudy (Figure 6b).

As is typical for peridot, the brown olivine in this study displayed a strong doubling effect (Figure 6c), consistent with its birefringence.

Raman and FTIR Spectra

Raman spectra of the brown olivine in the 100–1200 cm⁻¹ range displayed peaks at 212, 299, 415, 585, 817, 850, 914 and 951 cm⁻¹ (Figure 7a). Peaks in

the 700–1100 cm⁻¹ region are related to the internal bonding of SiO₄ ions, while those in the 400–700 cm⁻¹ range represent a curved bonding group of SiO₄ ions (Karampelas *et al.* 2012). The Raman spectral features in the 100–400 cm⁻¹ region indicate Mg- and Fe-substituted bonds in the octahedral structure of SiO₄ (Karampelas *et al.* 2012).

FTIR spectra in the 400–1200 cm⁻¹ range displayed bands at 416, 499, 518, 602, 839, 887 and 976 cm⁻¹, all of which have been assigned to the Si-O bonds of olivine (Figure 7b; Adamo *et al.* 2009). The exact positions of these spectral peaks are known to depend somewhat on the composition of the olivine (Adamo *et al.* 2009).

XRD Analysis

The XRD pattern (Figure 8) was consistent with that of forsterite reference sample 00-046-1212. PD3. Accordingly, we identified our brown olivine samples from Southeast Vietnam as forsterite.

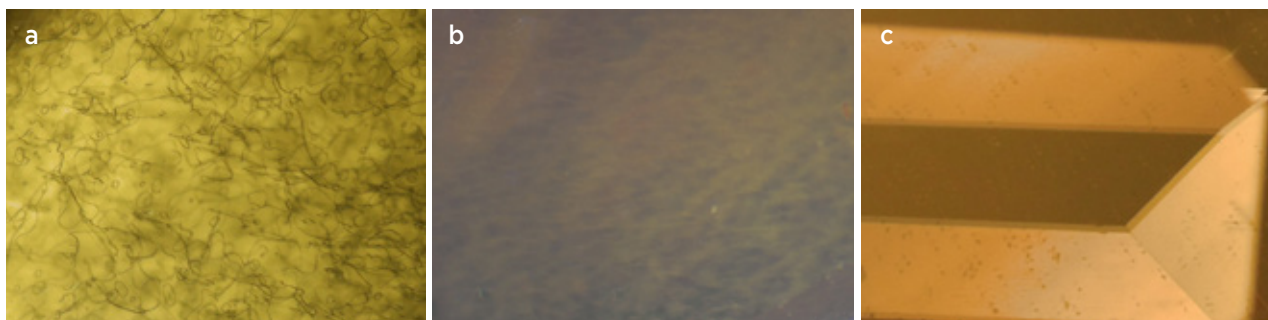


Figure 6: Internal features of brown olivine from Southeast Vietnam consist of (a) curly thread-like inclusions of serpentine (shown here in sample P2), (b) amphibole particles that cause an overall hazy appearance (sample P6) and (c) a doubling effect caused by strong birefringence (sample P3). Photomicrographs by Le Ngoc Nang; magnified 30× (a, b) and 40× (c).

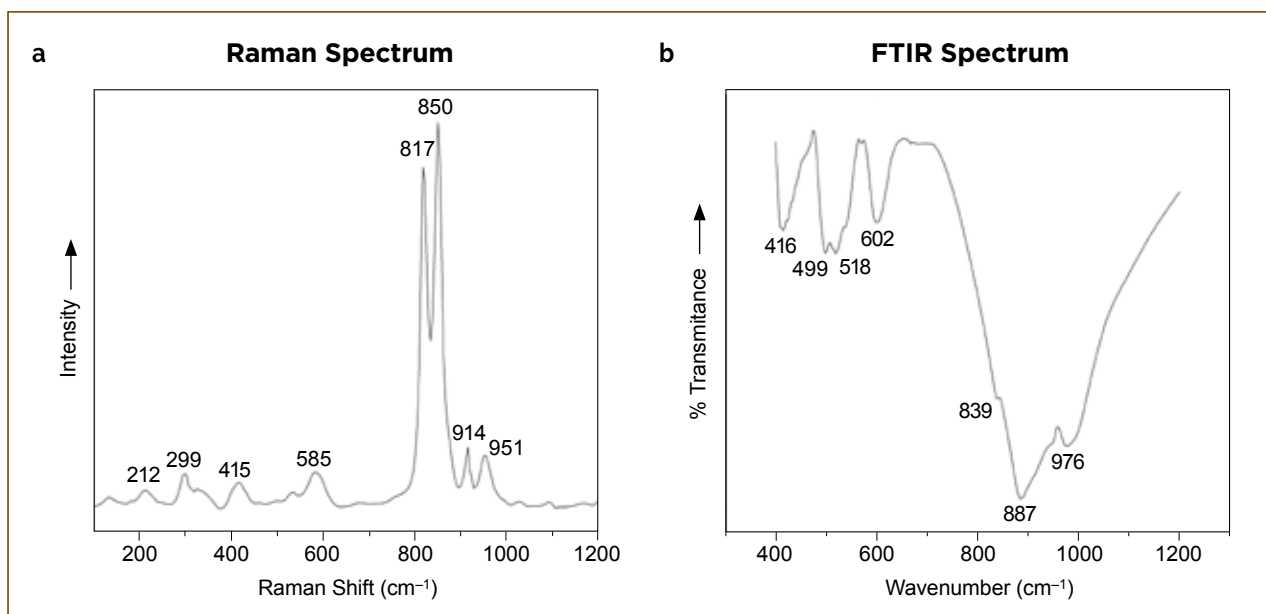


Figure 7: (a) A typical Raman spectrum of the brown olivine (sample P1) shows two main peaks at 817 and 850 cm^{-1} . (b) The FTIR spectrum of sample P12 displays bands at 416, 499, 518, 602, 839, 887 and 976 cm^{-1} , which are indicative of olivine (Adamo *et al.* 2009; Karampelas *et al.* 2012).

Chemical Composition

EDXRF analysis documented the three major elements expected for forsterite: 52.36–53.99 wt.% MgO, 34.43–36.75 wt.% SiO_2 and 9.23–11.93 wt.% FeO (Table II). It also revealed traces of Al, Mn, Ni and Ca. Other elements were below the detection limit.

The chemical composition of the brown olivine classified it as forsterite (i.e. composed of 88.71–91.17% forsterite and 8.74–11.14% fayalite).

DISCUSSION

Both yellowish green and dark brown olivine have been found in Southeast Vietnam, but only the latter occur in individual pieces that are large and transparent enough for polishing into gemstones. Gem-quality brown olivine is also known from various other occurrences, such as Nye County, Nevada, USA (Führbach

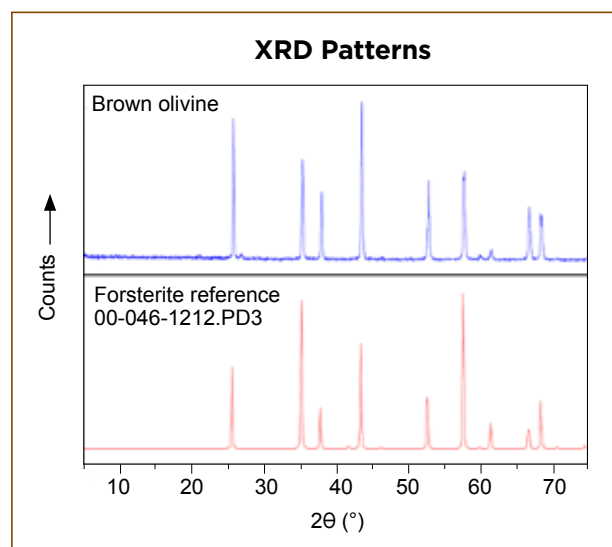


Figure 8: The XRD pattern of powdered sample P12 shows an excellent match to a reference sample of forsterite.

Table II: : Chemical composition of gem-quality olivine from Southeast Vietnam and selected localities.*.

Locality	Southeast Vietnam (this study)					Central Highlands, Vietnam (Thuyet <i>et al.</i> 2016)	Nevada, USA (Führbach 1998)	Pyauung-Gaung, Myanmar (Seneewong-Na-Ayut-thaya <i>et al.</i> 2022)
	P1	P2	P3	P4	P5			
Colour	Dark greenish brown	Dark greenish brown	Dark brown	Dark greenish brown	Dark greenish brown	Yellowish green to brownish green	Yellowish green to 'olive' green, brownish green and dark brown	'Olive' green and yellowish green
Oxides (wt.%)								
SiO ₂	35.29	34.43	36.75	36.58	36.04	39.82–41.22	37.90–40.55	41.90–43.20
MgO	52.36	53.29	53.22	53.99	52.62	47.19–51.04	47.34–47.62	49.23–50.77
FeO	10.89	11.93	9.29	9.23	10.77	8.24–9.99	10.27–13.81	7.25–7.88
Al ₂ O ₃	0.30	0.29	0.35	0.28	0.32	0.05–0.07	0.08–1.62	nr
CaO	0.07	0.07	0.05	0.01	0.08	0.03–0.1	bdl–0.22	0.01–0.03
MnO	0.10	0.07	0.07	0.09	0.10	0.03–0.24	0.16–0.20	0.09–0.16
NiO	0.04	0.12	0.05	0.10	0.06	0.19–0.54	bdl–0.28	0.02–0.34
Cr ₂ O ₃	0.07	0.10	0.11	0.10	0.10	bdl	bdl–0.034	bdl
Cations per 4 oxygens								
Si	0.861	0.830	0.886	0.876	0.871	nr	0.941–0.998	1.021–1.024
Mg	1.903	1.916	1.912	1.927	1.896	nr	1.740–1.763	1.789–1.793
Fe	0.269	0.329	0.216	0.238	0.247	nr	0.211–0.234	0.148–0.156
Al	0.009	0.008	0.010	0.008	0.009	nr	0.000–0.047	nr
Ca	0.002	0.002	0.001	<0.001	0.002	nr	0.000–0.006	0.000–0.003
Mn	0.002	0.001	0.001	0.002	0.002	nr	0.003–0.004	0.002–0.003
End members (mol.%)								
Forsterite	89.39	88.71	90.96	91.17	89.53	90.6–91.3	85.67–89.02	92.00–92.37
Fayalite	10.43	11.14	8.90	8.74	10.28	nr	10.81–13.94	7.63–8.00

* Abbreviations: bdl = below detection limit; nr = not reported..

1998); Kilbourne Hole, Texas, USA (Führbach 1992); and the Molong meteorite found in New South Wales, Australia (Sinkankas *et al.* 1992).

Gemmological Characteristics

Significant differences were found between the brown olivine from Southeast Vietnam and typical peridot (as reported in the literature). The SG values obtained for the brown olivine (3.39–3.55) are much higher than those of their yellowish green forsterite counterpart (e.g. 3.35; Kammerling & Koivula 1995), but are close to the SG values of meteoritic peridot from Esquel, Argentina, and Eagle Station, Kentucky, USA (Sinkankas *et al.* 1992), and similar to that of peridot from Kilbourne Hole (Führbach 1992).

In addition, the RI values of the brown olivine from Southeast Vietnam were higher than those of typical peridot (e.g. from the Central Highlands of Vietnam and other localities). However, the opposite is true for the brown olivine’s birefringence (0.022–0.035),

which tended to be lower or nearly equal to that of typical peridot. Furthermore, the inert UV reaction and presence of Fe absorption lines noted for the brown olivine from Southeast Vietnam are consistent with those of peridot.

Raman and FTIR Spectra

The Raman spectral features of the brown olivine were identical to those of their yellowish green counterpart, and were sufficient to confirm the identification as olivine. In particular, the two peaks at 817 and 850 cm⁻¹ are key indicators for the olivine group (Hibbert & Price 2014; Saito & Miura 2020). Some weaker peaks (e.g. those at 212, 299, 415, 585, 914 and 951 cm⁻¹) are indicative of forsterite. By contrast, fayalite does not show the Raman peaks 914 and 951 cm⁻¹ but does have one at 175 cm⁻¹ (Takashi & Masaki 2008), which is not present in the brown olivine from Southeast Vietnam. Other members of the olivine group have quite similar Raman features to forsterite

but with slight differences in the 150–200 cm^{-1} range (Takashi & Masaki 2008).

The FTIR spectral features of the brown olivine were similar to those of yellowish green peridot from Sardinia, Italy (Adamo *et al.* 2009).

Chemical Composition

The Si content of the brown olivine was lower than in peridot from the Central Highlands of Vietnam (Thuyet *et al.* 2016), Nevada, USA (Führbach 1998), and Pyaung-Gaung, Myanmar (Seneewong-Na-Ayutthaya *et al.* 2022), while the amount of Mg was higher (Table II). Notably, the Fe content of the brown olivine was generally higher than in peridot from the Central Highlands and Pyaung-Gaung, but generally lower than in material from Nevada. The relatively high Fe content resulted in the dark brown colour of this olivine. Furthermore, the Al and Cr contents of the brown material were slightly greater than those of typical peridot. The variations in chemical composition between brown and green olivine suggest different geological origins and conditions of formation, thus leading to different physical properties and inclusions.

Geological Origin

Alkali basalt from Southeast Vietnam contains gem materials such as xenolithic garnet and olivine, and xenocrysts of zircon, feldspar, augite and olivine. However, none of these actually crystallised from the basaltic magma (Nang *et al.* 2023a).

The properties of the brown olivine are in part similar to those of both terrestrial and meteoritic olivine. To evaluate its origin, we plotted data for our study specimens (and for three peridot specimens from the Central Highlands of Vietnam; Thuyet *et al.* 2016) on the NiO vs MnO diagram of Deer *et al.* (1982; Figure 9). The result confirmed that the brown olivine (as well as peridot from the Central Highlands) is of terrestrial origin.

Next, we plotted data from the same specimens on the CaO vs mol.% forsterite diagram from Gao *et al.* (2008) to determine the formation environment—magmatic or xenocrystic (Figure 10). The result showed that the brown olivine (and the peridot) did not crystallise directly from the alkali basaltic magma, but are xenocrystic and therefore were derived from a different source (Gao *et al.* 2008). Thus, the basalt was only responsible for transporting the xenocrystic olivine to the earth's surface and is not related to its formation.

De Hoog *et al.* (2010) classified various mantle-source lithologies of lherzolite (clinopyroxene-bearing peridotite) using Al and Mn in olivine (Figure 11).

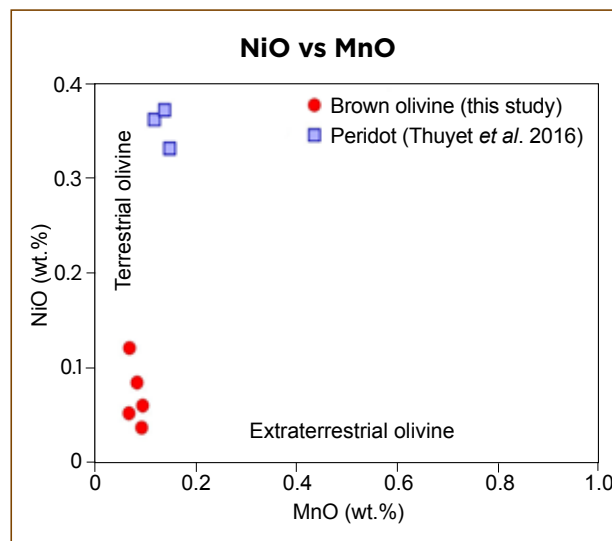


Figure 9: Data obtained for the brown olivine from Southeast Vietnam (samples P1–P5) are plotted along with data for peridot from Vietnam's Central Highlands (from Thuyet *et al.* 2016) in the NiO vs MnO diagram of Deer *et al.* (1982), which indicates that both are of terrestrial origin.

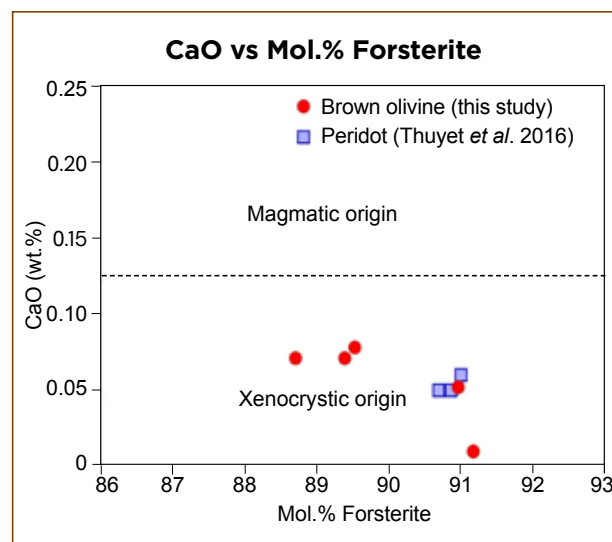


Figure 10: The CaO vs mol.% forsterite diagram of Gao *et al.* (2008) indicates a xenocrystic origin for the brown olivine from Southeast Vietnam, as well as the peridot from Vietnam's Central Highlands (data from Thuyet *et al.* 2016).

The contents of these elements in the brown olivine plot within the field of garnet lherzolite, whereas data for peridot from the Central Highlands of Vietnam shows that it is derived from spinel lherzolite (as also indicated by Thuyet *et al.* 2016).

Pressure-Temperature Conditions

As described by De Hoog *et al.* (2010), trace elements in olivine can be used to determine the geothermometry of the peridotites, such as lherzolite, harzburgite and spinel peridotite. Another method to estimate the equilibrium temperature and pressure

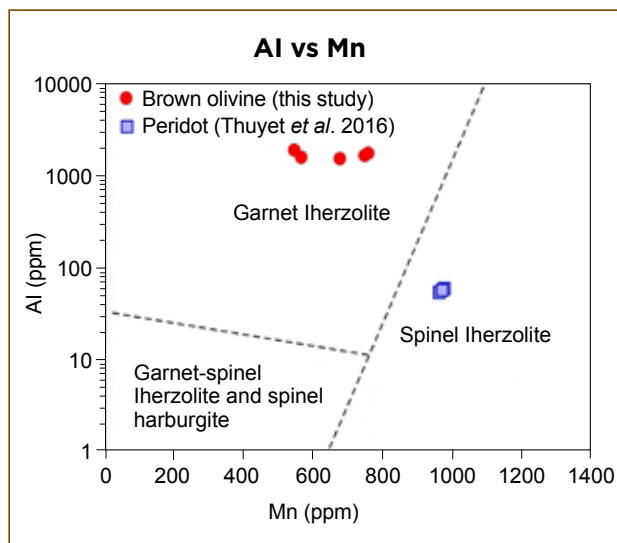


Figure 11: The graph of Al vs Mn identifies various mantle lithologies, and places brown olivine from Southeast Vietnam in the garnet lherzolite field. By contrast, peridot from Vietnam's Central Highlands (data from Thuyet *et al.* 2016) plots in the spinel lherzolite field. The dotted reference lines are after De Hoog *et al.* (2010).

of crystallisation is geothermobarometry using Al in orthopyroxene and in two pyroxenes (for lherzolite), and Ca in orthopyroxene (for harzburgite), but there is no suitable barometer for spinel peridotite (Brey & Köhler 1990).

We used the Al geothermometer to calculate the formation temperature of the brown olivine from Southeast Vietnam, using the formula from de Hoog *et al.* (2010), where $[Al]^{ol}$ is the Al content of the olivine (in ppm) and $Cr\#^{ol}$ is $Cr/(Cr + Al)$:

$$T_{Al}(^{\circ}C) = \frac{9423 + 51.4P + 1860Cr\#^{ol}}{(13.409 - \ln[Al]^{ol})} - 273$$

We assumed that the brown olivine from Southeast Vietnam was derived from garnet lherzolite (as per Figure 11), in which the corresponding equilibrium pressure P was 50 kbar (cf. De Hoog *et al.* 2010). According to this formula, the brown olivine crystallised at approximately 1400–1460°C. Garnet lherzolite formed under an equilibrium pressure of 50 kbar might have originated from a depth of approximately 150 km, according to geostatic pressure.

By comparison, for the peridot from the Central Highlands of Vietnam reported by Thuyet *et al.* (2016), we obtained a formation temperature of approximately 940–985°C, which is much lower than that of the brown olivine described here. Although these two olivines originated from different magmatic sources, their geographical areas are nearly contiguous in this part of Southeast Asia.

CONCLUSION

Brown olivine from Southeast Vietnam is a curiosity for gem collectors—especially those with an interest in peridot—owing to its unusual brown colour and anomalous gemmological properties. It can be fashioned into faceted gems, cabochons and carvings. It is distinct from typical peridot found worldwide, which may create identification challenges. Raman/FTIR spectroscopy and/or chemical analysis is necessary to confirm the identity of the material as forsterite.

The brown olivine from Southeast Vietnam originated from garnet lherzolite (crystallised at 1400–1460°C and 50 kbar), and was brought to the earth's surface from a depth of approximately 150 km as xenocrysts and xenoliths in alkali basalt.

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Acknowledgements

This research was funded by Vietnam National University (Ho Chi Minh City) under grant number B2023-18-11. We would like to express our deep gratitude to Tran Ngoc Vien, who guided us to the study location during our field research.

Large and Unusually Coloured Type IIb Diamonds, Possibly Cut from the Same Rough

Aurélien Delaunay, Stefanos Karampelas, Annabelle Herreweghe and Emmanuel Fritsch

ABSTRACT: Two pear-shaped old-cut diamonds (7.79 and 5.90 ct) of dark greenish brownish grey and dark greenish grey colour, respectively, were submitted to LFG for grading. Both were found to be type IIb diamonds containing about 0.1 ppm uncompensated boron (as calculated from FTIR spectra). The two diamonds presented similar spectroscopic and structural features, and they were most likely cut from the same rough. We offer two hypotheses for the relative positions of the stones and the potential shape of the rough.

The Journal of Gemmology, 39(3), 2024, pp. 270–275, <https://doi.org/10.15506/JoG.2024.39.3.270>
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The Laboratoire Français de Gemmologie (LFG) often encounters beautiful jewellery pieces, but few are of scientific interest. However, in early May 2024, an interesting brooch was submitted to LFG for identification of its two large gems, which had a colour that was difficult to describe—a mixture of grey, green and brown (Figure 1). The current owners knew nothing about the history of this jewel. Preliminary testing with Fourier-transform infrared (FTIR) spectroscopy revealed the stones were type IIb diamonds. Such diamonds are commonly blue to greyish blue to grey (Breeding & Shigley 2009; Gaillou *et al.* 2012), but a green component has seldom been reported (Scarratt 1989; Breeding *et al.* 2018). Because the present stones showed an unusual colouration for type IIb diamond, we asked the client to unmount them for further examination (Figure 2).

Type IIb diamonds are some of the rarest natural diamonds (Breeding & Shigley 2009), are semi-conductive and are thought to be among the deepest-formed diamonds, also called sublithospheric or super-deep diamonds (Smith *et al.* 2018). Such diamonds may originate from the earth's transition

zone (670 km depth) between the upper and lower mantle, or the top of the lower mantle.

The purpose of this article is to present the gemmological and structural characteristics of these rare diamonds, and to assess whether they may have been cut from the same rough.

MATERIALS AND METHODS

All observations and measurements were performed at LFG. Because of time constraints, only limited testing was possible. Colour was graded in a MacBeth Judge 2 standard viewing environment with D65 lighting. Internal features were examined with a Zeiss Stemi 508 binocular microscope and between crossed polarisers. Luminescence reactions were observed in a dark room with a 6 W UV lamp equipped with long-wave (365 nm) and short-wave (254 nm) bulbs, with a distance of 7 cm between the sample and the lamp.

FTIR spectra were obtained in the 650–10000 cm⁻¹ range using a Nicolet iS50 spectrometer with 4 cm⁻¹ resolution and 200 scans. Ultraviolet-visible-near infrared (UV-Vis-NIR) spectra were acquired over 365–1000 nm with a Magilabs GemmoSphere using



Figure 1: The two coloured diamonds (top, 7.79 ct; bottom, 5.90 ct) in this brooch were submitted to LFG for identification. Photo by Artcurial, © Studio Sebert.

a 0.1 second acquisition time, 50 accumulations and spectral resolution of about 1.5 nm.

Photoluminescence (PL) spectra were acquired in the 520–900 nm range at liquid nitrogen temperature (approximately -196°C), using a Renishaw inVia spectrometer coupled with an optical microscope, with 514 nm laser excitation from a diode-pumped solid-state laser. Laser power on the sample was about 10 mW, and the spectral resolution was about 0.1 nm, using a 10 s exposure time and one accumulation. Deep-UV luminescence images were obtained using a DiamondView instrument.

RESULTS AND DISCUSSION

Table I provides a summary of the main characteristics of the two diamonds. Both have a pear shape with an extra-large culet, reminiscent of an ‘old cut’. Sample A weighed 7.79 ct and measured $16.07 \times 10.81 \times 6.58$ mm, and sample B was smaller, weighing 5.90 ct and measuring $14.18 \times 10.43 \times 5.89$ mm (again, see Figure 2). The colour of the stones was Fancy Dark grey with, for sample A, green and brown modifiers and, for sample B, a green modifier (King 2006). Such



Figure 2: The two pear-shaped old-cut diamonds were unmounted from the brooch in Figure 1 for further examination. Sample A measures $16.07 \times 10.81 \times 6.58$ mm and has a dark greenish brownish grey colour; sample B is $14.18 \times 10.43 \times 5.89$ mm and is dark greenish grey. They are both type IIb diamonds. Composite photo by A. Delaunay, © LFG.

Table I: Summary of the main characteristics of the two diamonds.

Sample	A	B
Weight (ct)	7.79	5.90
Size (mm)	16.07 × 10.81 × 6.58	14.18 × 10.43 × 5.89
Colour	Dark greenish brownish grey	Dark greenish grey
Clarity	VS ₁	SI ₁
UV fluorescence	None	None
FTIR spectral characteristics	Type IIb	Type IIb
Calculated uncompensated boron (ppmw)	0.09 ± 0.01	0.11 ± 0.01

colours are sometimes called ‘olive’, but this poorly defined term is not colourimetrically correct. The clarity grades of the diamonds were VS₁ for sample A and SI₁ for sample B (due to feathers and bruises). Brown graining was observed in both stones, similar to that seen in many natural-colour brown diamonds. Both were inert to long- and short-wave UV radiation, with no phosphorescence.

Between crossed polarisers, strong graining with second-order interference colours (Gaillou *et al.* 2012) was observed in both gems (Figure 3). Dark brown graining was seen without crossed polarisers in a few orientations, which indicates significant deformation.

The FTIR spectra of the two samples were almost identical, and were characteristic of type IIb diamonds (Figure 4), including bands linked to boron at 1290, 2456, 2802, 2930, 4090, 5000 and 5365 cm⁻¹ (Gaillou *et al.* 2010, 2012, 2014). The concentration of uncompensated boron can be calculated using either the area of the peak at 2802 cm⁻¹ (Collins & Williams 1971;

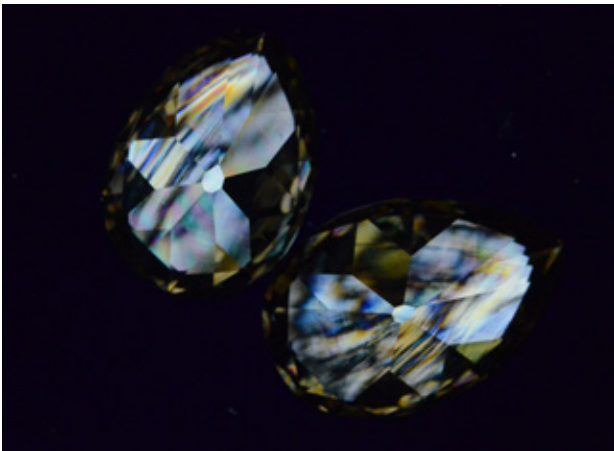


Figure 3: Observed between crossed polarisers, the two diamonds (left, sample B; right, sample A) show significant deformation, with stronger graining and associated second-order interference colours on one side. Photo by A. Delaunay, © LFG.

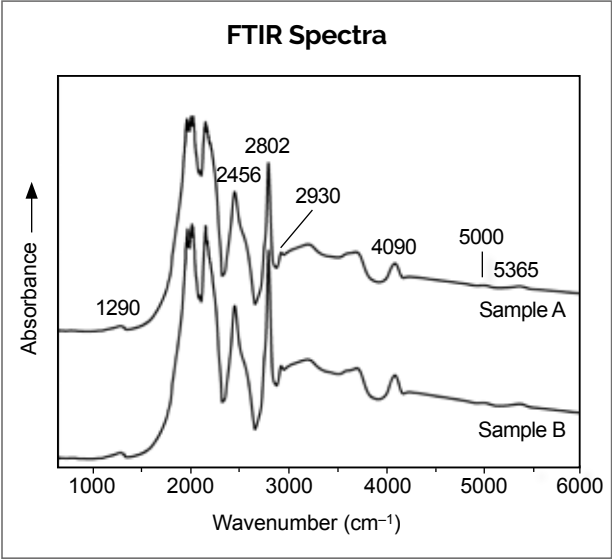


Figure 4: Infrared spectra of the two type IIb diamonds in the 650–6000 cm⁻¹ range are nearly identical. The spectra are offset vertically for clarity.

Fisher *et al.* 2009) or the heights of the peaks at 2802, 2456, or 1290 cm⁻¹ (Collins 2010). Both methods gave similar results for both samples: an uncompensated boron concentration of 0.09 ± 0.01 ppm for sample A and 0.11 ± 0.01 ppm for sample B. These concentrations are comparable to those reported for type IIb diamonds in other publications, and lower than those of other important (blue) type IIb diamonds such as the Hope, the Wittelsbach or the Blue Moon, which have 0.19–0.36 ppm uncompensated boron (Gaillou *et al.* 2010, 2012, 2014). Diamonds often show a heterogeneous impurity distribution, and it is not uncommon to see varying concentrations of boron in a single stone (Gaillou *et al.* 2012).

The two diamonds also presented similar UV-Vis-NIR absorption spectra at ambient temperature, with a very broad transmission window around 600 nm, consistent with their desaturated colour (Figure 5). The general grey colour arises from the continuum rising towards the UV region (responsible for a brown hue) combined with the type IIb brown continuum (due to deformation; Hainschwang *et al.* 2020) rising towards the infrared region. Two large bands were observed at around 395 and 680 nm. The latter broad band might be a GR1 vibronic structure (the GR1 defect was recorded in PL spectra; see below), but we could not confirm this in the limited time allowed for examination.

In rare cases, type IIb diamonds may show a greenish (Scarratt 1989; Breeding *et al.* 2018) or brownish (Hainschwang *et al.* 2020) colour. The presence of brown graining in a type IIb diamond yields a combination of blue and brown. The

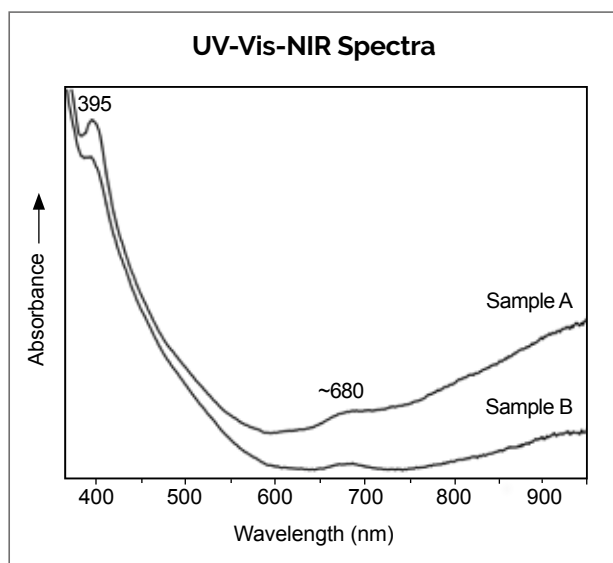


Figure 5: The UV-Vis-NIR absorption spectra (365–950 nm) of the two diamonds are very similar, showing the same features in approximately the same relative strengths. The spectra are offset vertically for clarity.

resulting desaturated colour is generally considered unattractive. As a result, such diamonds are commonly treated at high pressure and high temperature to remove the brown component. Thus, the two diamonds described here are believed to be untreated.

The PL spectra of both stones were also very similar (Figure 6). They are dominated by an intense GR1 doublet situated at around 741 and 744 nm (Figure 6a), with a weak band at approximately 648 nm due to the presence of boron (Figure 6b), as well as a series of other peaks tentatively attributed to boron and/or

deformation (Zaitsev 2001).

DiamondView luminescence images of both stones (Figure 7) showed a polygonal dislocation network characteristic of type II diamonds (Breeding & Shigley 2009). Intense graining, visible as dark lines/planes, revealed the presence of strong deformation, consistent with our observations between crossed polarisers. A sector of more intense blue luminescence was visible on the pavilion of both stones (again, see Figure 7).

The nearly identical gemmological and spectroscopic features exhibited by these two rare diamonds mounted together in the brooch raise the possibility they might have originated from the same rough. There are several examples in the literature of stones proven to come from the same crystal, either by X-ray topography (e.g. Sunagawa *et al.* 1998) or via a series of spectroscopic and luminescence imaging techniques (e.g. Hainschwang *et al.* 2024).

The sector of more intense blue luminescence seen with the DiamondView in both gems seems to be limited to the near-surface and, with proper positioning of the two stones, can be shown to align (Figure 8). Fitting the luminescence images together as if in a puzzle, two hypotheses may be proposed: (1) the tables of the cut gems were partly facing (Figure 8a), and (2) the gems' girdle planes were in approximately the same plane in a relatively elongated rough diamond (Figure 8b).

When the two stones were observed face up and oriented as in Figure 3, the graining was more significant on one side of sample A and on the other

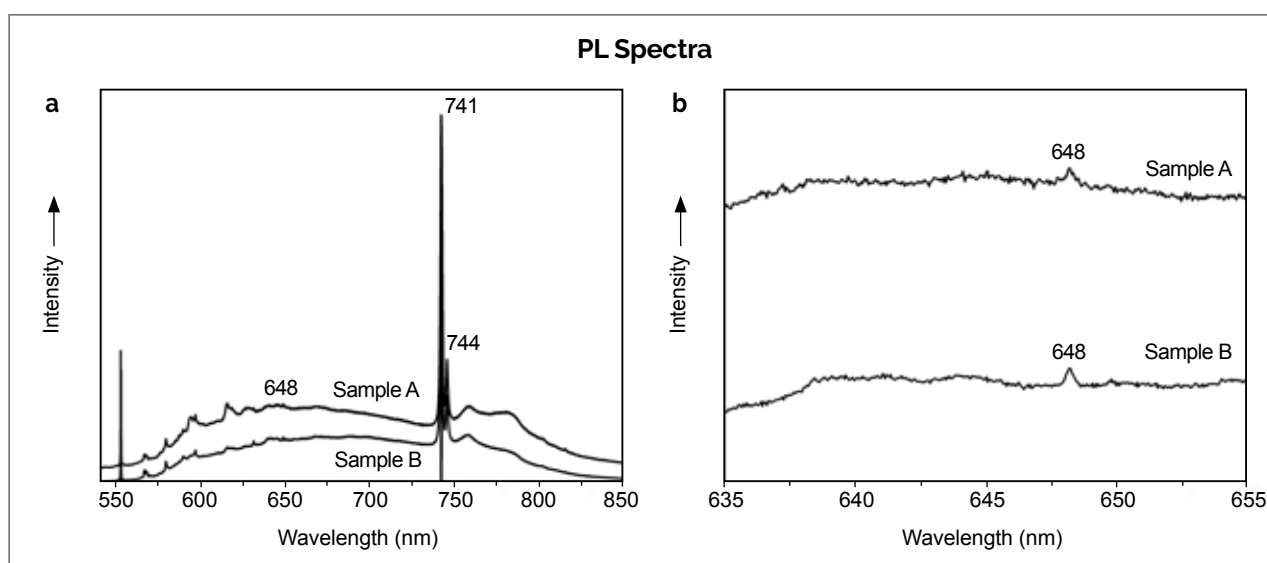


Figure 6: (a) PL spectra in the 540–850 nm range (514 nm laser excitation) of the two diamonds both show the main GR1 peak at around 741 nm, along with the smaller GR1 line at around 744 nm. For sample B, the line at 741 nm is saturated. A minute peak at approximately 648 nm is also seen. Only minor differences are present between the spectra. (b) An expanded view of the same PL spectra from 635 to 655 nm shows the weak peak at approximately 648 nm that is linked with the presence of boron. The spectra are offset vertically for clarity.

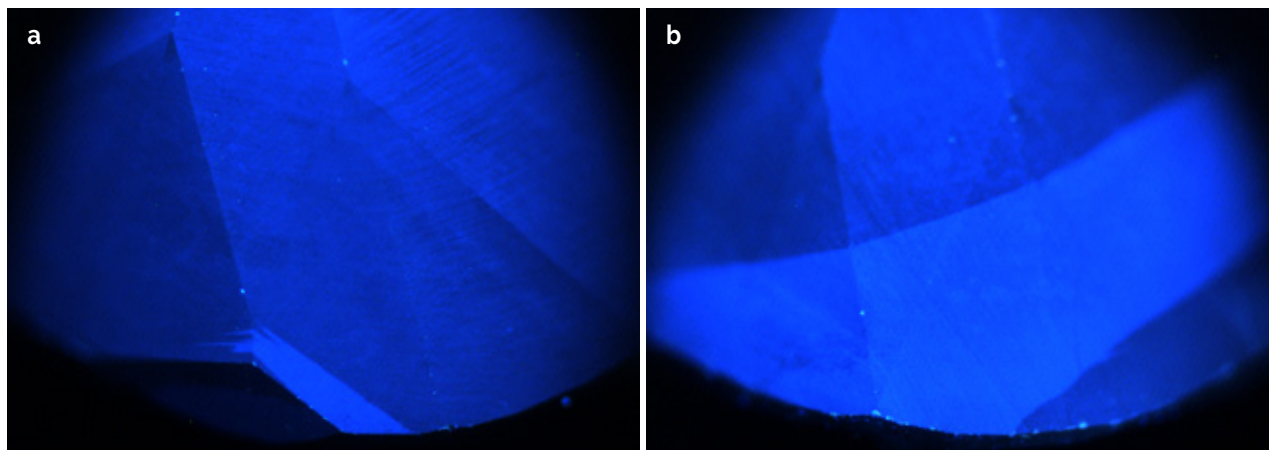


Figure 7: DiamondView luminescence images of the two diamonds show very strong deformation with intense graining in several directions in both samples. (a) A small sector of more intense blue luminescence is visible on the pavilion of sample A, and (b) a larger sector of intense blue luminescence is present on the pavilion of sample B. Photos by A. Delaunay, © LFG; image widths 6 mm.

side of sample B. This means that one part of the original rough would have been more deformed than the rest. Since the fluorescence band is not present on the crown of either stone, and there

is no apparent match between the DiamondView patterns of the two tables, the second hypothesis mentioned above appears more likely, although further investigation would have been required to resolve this. The second hypothesis would require a piece of rough that must have been very elongated and deformed, which is not uncommon for type II diamond rough (King *et al.* 1998). In this second case, the two stones can be positioned so that the zone of more intense luminescence is continuous, thus connecting the two diamonds (and their areas of more significant graining) in a way that they could have been positioned within a single rough diamond.

CONCLUSIONS

Two pear-shaped coloured diamonds (7.79 and 5.90 ct—dark greenish brownish grey and dark greenish grey, respectively) were submitted to LFG for grading in early May 2024. FTIR spectroscopy proved both to be rare type IIb diamonds, possibly of super-deep origin (cf. Smith *et al.* 2018). Both diamonds contained about 0.1 ppm uncompensated boron. Their colour makes them rarer than other diamonds of this type, which very infrequently display a greenish component (Breeding *et al.* 2018).

The two diamonds also presented strikingly similar IR, UV-Vis-NIR and PL spectra, as well as matching strain characteristics between crossed polarisers, strongly suggesting they were cut from the same rough. Luminescence imaging permitted the proposal of two hypotheses about the positions of the stones within a single rough diamond, as well as the potential shape of the rough.

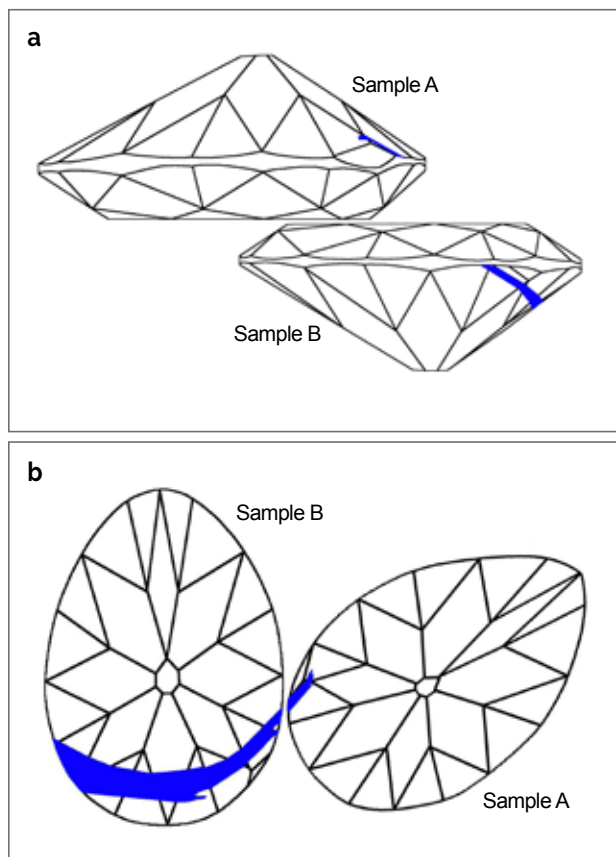


Figure 8: (a) One hypothesis of the possible orientation of the two diamonds within the original rough is that they lay on top of one another, tables facing and partly overlapping, with the zone of intense blue luminescence making the link between the two stones. (b) A second hypothesis proposes that the diamonds lay with their girdle planes in roughly the same plane. Drawings by A. Delaunay, © LFG.

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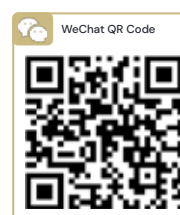
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Letters

CORRECTION OF THE SITE FOR THE Fe^{3+} ION IN THE DARK BLUE CHROMOPHORE OF BERYL

The structure of beryl ($\text{Be}_2\text{Al}_3\text{Si}_6\text{O}_{18}$) is described by the space group $P6/mcc$. In this space group, the site halfway between two Be ions in the c -axis direction is designated by the crystallographic notation 6g, and the site halfway between two Al ions in the c -axis direction is 4d (see International Union of Crystallography 2006). This is correctly described by the distances listed in the abstract of the publication by Groat *et al.* (2010), but is wrongly illustrated in figure 1 of their article. They show that the colour of dark blue beryl is due to intervalence charge transfer (IVCT) between an Fe^{3+} ion located halfway between two Al sites in the beryl structure and an Fe^{2+} ion substituting at one of the Al sites (the valences of these two iron ions is rapidly interchanging during IVCT). Following their figure 1, Groat *et al.* (2010) incorrectly referred to the site for the Fe^{3+} ion in this IVCT pair as 6g. As a result, this error has been repeated in many subsequent publications, including this writer's recent review article (Andersson 2023).

In summary, the correct site of the Fe^{3+} ion in the IVCT pair giving rise to the dark blue colour in beryl is 4d.

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Editor's note: An updated PDF file of Andersson (2023) showing the corrections for the 4d site has been posted online. Also included is a correction for a typographical error on p. 770.

ERRATUM

In the article by F. Blumentritt *et al.* titled 'Properties and Colouration of Orange Hackmanite from Afghanistan' (Vol. 39, No. 2, 2024, pp. 160–170), the last sentence of the Conclusion on p. 168 should have read: 'Gemmologists should therefore be alert to the possibility that deep orange hackmanite could be artificially irradiated.'



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Conferences

SWISS GEMMOLOGICAL SOCIETY CONFERENCE

On 8–11 June 2024, the Swiss Gemmological Society (SGS) held its 82nd annual conference in Nottwil on beautiful Lake Sempach in Switzerland. As in previous years, the event was well attended with around 80 Society members and guests (e.g. Figure 1). This year's theme focused on the historical aspects of the use, significance and trade of gemstones. The conference was chaired by SGS president Martin Julier (Bucherer AG, Lucerne, Switzerland) and author MH (SGS director; see Figure 2).

Catherine DeVincenti (CdV Consulting, Lausanne, Switzerland) presented an overview of the historical development of gem examination methods, and placed them in the context of typical jewellery styles of the respective eras. She showed that the characterisation of gems in earlier eras was typically based on experience and arbitrary criteria. It was only over time and with the associated development of optical and technical devices (and scientific knowledge) that modern gemmology emerged.

Dr Laurent Cartier (Swiss Gemmological Institute SSEF, Basel, Switzerland) provided an overview of the history and development of gem treatments, imitations and synthetics since Egyptian times. He also drew parallels between the rise of synthetic rubies in the late nineteenth century and recent developments in the production and trade of synthetic diamonds. This historical tour also showed how and why gemmology emerged as a scientific discipline over time, largely fuelled by the difficulties the trade faced in identifying cultured pearls and synthetic rubies in the early twentieth century.

Helen Molesworth (Victoria & Albert Museum, London) explored the background of people's appreciation of gems in a presentation titled 'Sex, Death, Money and Religion: A History of Gemstones, a History of Humanity'. She described the role of gems in burial rituals, their representation of wealth and power, their use in religious rites and, of course, as a symbol of love—the 'ultimate definition of



Figure 1: The audience at the 2024 Swiss Gemmological Society conference heard a diversity of lectures, most of which focused on the historical aspects of the use, significance and trade of gem materials. Photo by Daniela Bellandi, *Gold'Or* magazine.

humanity'. On this occasion, she also presented her newly published book, *Precious: The History and Mystery of Gems Across Time*, which explores the theme of her talk in detail.

Dr Hanco Zwaan (Netherlands Gem Laboratory, Leiden) gave two presentations on diamonds. In the first, he provided an overview of the current knowledge about natural and synthetic diamonds. In particular, new insights into the dating of diamonds and their deposits have been gained in recent years. For example, radiometric dating of inclusions in the centre and edge of a diamond crystal has revealed a difference in age of about 1 billion years, corresponding to the growth duration of the host crystal. While most diamonds formed 1–3 billion years ago, their associated kimberlites are generally much younger (less than 252 million years), so it is clear that the kimberlite magmas merely acted as 'means of transport' for the older diamonds. In the case of synthetic diamonds, a massive increase in production, combined with a reduction in production costs of around 90% over the past 10 years, has led to a major drop in prices. Dr Zwaan's second presentation focused on the history and gemmological characteristics of the Banjarmasin diamond. Weighing 38.23 ct, this diamond was cut from a 70+ ct octahedral crystal mined at Karang-intan in Borneo at the beginning of the nineteenth century, and came into the possession of the Dutch colonial government after the dissolution of the Sultanate of Banjarmasin. It has been in the collection of the Rijksmuseum in Amsterdam since 1902. (For more on this diamond, see the article in *The Journal*, Vol. 38, No. 7, 2023, pp. 662–677.)

Michael Hügi presented an account of the formation of Alpine quartz deposits and the significance of the crystals as raw material for artefacts throughout history. The formation of rock crystal and smoky quartz in the Alps is the result of tectonic processes that occurred during the uplift of the mountains approximately 20 million years ago. These processes led to the formation of Alpine fissures and the recrystallisation of quartz within these cavities. In contrast to the rapid growth of quartz in pegmatitic deposits, the crystallisation of Alpine quartz was subject to the influence of regional uplift and associated cooling over a period of approximately 7 million years. The search for high-quality rock crystal constituted an important source of income for the mountain population, with the crystals being processed into objects of considerable value in stone-cutting workshops in various European cities from the Middle Ages onwards.

In his market report on the current coloured stone



Figure 2: Martin Julier and Michael Hügi were the co-chairs of the SGS conference. Photo by Daniela Bellandi, *Gold'Or* magazine.

trade, **Hans Pfister** (Lugitrade, Geneva, Switzerland) explained that brands are exerting an increasingly significant influence on the gem trade. Gem production from many classic deposits is now dwindling, so larger, untreated stones of good quality are primarily sourced from pre-existing stocks and mostly traded at auction. Price increases in recent years have been correspondingly profound. For instance, the price of fine, unheated Burmese rubies in the 3 ct range has increased five-fold over the past two decades. The production of large, high-quality sapphires from Kashmir and Myanmar has effectively ceased, and the availability of fine, untreated sapphires from Sri Lanka will likely also decline significantly in the coming years. Regarding emeralds, Colombia is still considered to be the most highly valued origin in the trade; however, high-quality and large stones have become scarce and expensive, particularly ones with no or only minor clarity enhancement.

Willy Bieri (GRS GemResearch Swisslab AG, Lucerne) presented a comprehensive overview of Australian opal deposits and their history. A highly esteemed gem material since antiquity, opal's popularity declined in the nineteenth century due to the novel *Anne of Geierstein* by Walter Scott, in which it was portrayed as a harbinger of misfortune. Bieri also presented a detailed account of the formation of different types of opal, which depends on the presence of Si-rich solutions, dehydration and the arrangement of silica spheres. He also illustrated ongoing mining activities in Australia's renowned opal deposits: Lightning Ridge, Yowah, Quilpie and Coober Pedy. These regions continue to serve as important suppliers

of high-quality opals.

Dr Peter Janowski and Leander Schorr (Ceylons Munich, Germany) described their mining project in Sri Lanka, which prioritises the highest standards of environmental sustainability and socially responsible working conditions. This was accomplished by establishing an autonomous supply chain in which the stones are delivered directly to Ceylons Munich by joint-venture partners, eliminating the need for intermediaries. This framework has been used to ensure the miners are appropriately compensated, while also facilitating the development of an environmentally friendly mining infrastructure.

Tobias Lanz (Bucherer AG) presented an analysis of the current diamond market. As a consequence of excess supply and elevated stock levels among retailers, prices for natural diamonds have declined by approximately 30% since 2008, according to the RapNet Diamond Index, and this trend persists. The market is currently undergoing a fundamental change. Banks have modified their lending policies, the purchasing behaviour of millennials is more discerning and the increase in synthetic diamonds on the market is presenting the trade with significant challenges. The price of synthetic diamonds has experienced a dramatic decline over the past several years, and Lanz predicted that in the future they will likely be used only in fashion jewellery. The presentation also highlighted interesting aspects of setting a market price and price negotiation, demonstrating that the information on a laboratory report alone is not sufficient for serious pricing.

Dr Thomas Hainschwang (GGTL Laboratories, Balzers, Liechtenstein) presented the findings of an analysis of green diamonds in the collection of the Museum of Natural History in Vienna, Austria, in order to help distinguish between natural and artificially irradiated green diamonds. The Vienna museum has a notable collection of green diamonds that were acquired before 1950 and are, therefore, unlikely to have been subjected to artificial irradiation. As the diamonds are not permitted to leave the museum, the extensive examination had to be conducted on-site. Characterisation of these green diamonds and yellow diamonds with green fluorescence ('emitter' diamonds) using the latest UV-Vis and PL spectroscopy yielded detailed spectra, providing a positive step forward for differentiating between naturally coloured and treated diamonds.

Dr Klaus Schollenbruch (Gübelin Gem Lab, Lucerne) described his 2023 visit to several areas where Co-blue spinel is mined in the Luc Yen region of Vietnam. He documented the mining activities

and obtained a substantial number of samples for characterisation. He presented some initial results, in particular on their inclusions. Distinguishing between Co-blue spinels and those that are blue but coloured by Fe is relatively straightforward through a combination of chemical analysis and UV-Vis spectroscopy. As blue spinels generally contain both Co and Fe, he proposed that Co-spinels be defined by a Fe/Co ratio of <110 and a Cr/Co ratio of <4 .

The newly appointed head of the German Gemmological Association, **Dr Tom Stephan** (DGemG, Idar-Oberstein, Germany), provided insights into the historical gem deposits in the Czech Republic and Slovakia. Cr-bearing pyrope has been mined in Bohemia since the Middle Ages, and is still produced today from two locations (Podsedice and Dolní Olešnice), where the garnet crystals are extracted from sediments in open-pit mining. The current annual production of both mines is approximately 350 kg, predominantly as pieces measuring 2–5 mm. (See the article in this issue of *The Journal*, pp. 242–258.) Moldavite is extracted from sediments in the vicinity of Chlum, situated in the southern region of the Czech Republic. These green, transparent stones with their distinctive furrowed surface structure represent a variety of tektite ejected during the impact of the meteorite in the Nördlinger Ries 14 million years ago. (See the article in *The Journal*, Vol. 38, No. 7, 2023, pp. 696–707.) Dr Stephan also visited the opal mines in the Prešov Region in Slovakia, which have been known since the Middle Ages. In the second half of the nineteenth century, in particular, opal was intensively mined underground. Currently, underground mining has ceased but one company still processes the tailings.

In his presentation titled 'Old Gems – New Thoughts', **Dr Jack Ogden** (jewellery historian and independent researcher, London) provided a comprehensive overview of early gem deposits and the historical use of gem materials (Figure 3). Notable discoveries, such as the Vajrasana Throne deposit in India, yielded a considerable quantity and variety of gems, thereby providing insight into the range of gem species mined and utilised during the third century BCE. The deposits in Egypt, referred to as the 'emerald mines of Cleopatra', were known long before the birth of the famous Egyptian queen. (See the article in *The Journal*, Vol. 38, No. 2, 2022, pp. 156–170.) The processing techniques available at the time permitted only the crude polishing of rough, and drilled hexagonal crystals were frequently used in jewellery. During the Middle Ages, emeralds were regarded as aesthetically unappealing in Europe.



Figure 3: Dr Jack Ogden delivers his presentation at the Swiss Gemmological Society conference. Photo by M. Hügi.

Even the discovery of South American deposits by Spaniards in the sixteenth century had a limited impact on their appeal. Consequently, emeralds were predominantly exchanged for rubies in India and Burma. Dr Ogden also provided insights into the processing techniques, historical gem prices and the formerly prevalent use of powdered stones for medical applications.

Dr Michael Krzemnicki (SSEF) offered insights and case studies of interesting diamonds, coloured

stones and pearls tested at SSEF over the past year, with a special emphasis on historical items. He provided examples of how cutting and manufacturing techniques evolved over time, and also covered modern techniques to analyse gems, such as age dating (e.g. of zircon inclusions in heated Greenland rubies that are about 2.7 billion years old), as well as recent advances in diamond and coloured stone traceability (GemTrack).

In addition to the numerous engaging presentations, the conference also facilitated valuable informal dialogue and networking opportunities. One of the notable highlights was the conference dinner, featuring an exceptional barbecue buffet and dance music, which was enjoyed by many participants well into the night.

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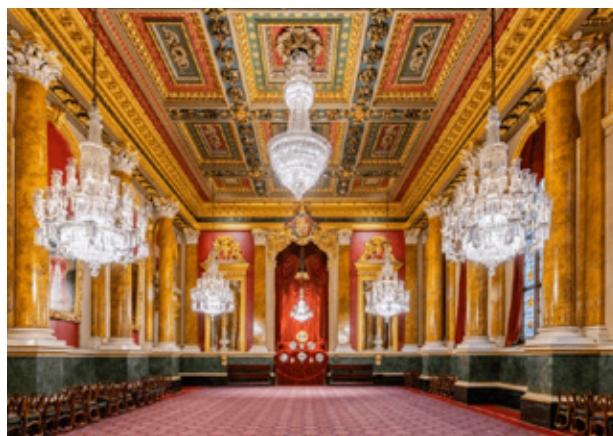
The Gem-A Conference will take place on Saturday and Sunday 2–3 November 2024 at etc.venues County Hall, which overlooks the River Thames



and the Houses of Parliament in London. This year's event will feature two full days with 12 international speakers. Gem-A will host an informal cocktail party on the evening of 2 November, which will provide a fantastic opportunity to network with other gemmologists and jewellery professionals. On Monday 4 November, attendees will have the option to attend various workshops and field trips, in order to make the most of their visit to London. More information and a link to register are available at <https://gem-a.com/resources/conference-2024>.

GEM-A GRADUATION AND PRESENTATION OF AWARDS

The Gem-A Graduation and Presentation of Awards ceremony will be held at Goldsmiths' Hall in London on Monday 4 November 2024. This important event will celebrate the achievements of our most recent graduating class, including special awards and prize winners. Goldsmiths' Hall, positioned at the junction of Foster Lane and Gresham Street, opened in 1835 and is one of London's hidden treasures. The Livery Hall is an awe-inspiring space and a magnificently proportioned room with Corinthian columns and a richly moulded ceiling decorated with gold leaf. We look forward to acknowledging our newest graduates on this special evening.



GIFTS TO THE ASSOCIATION

Gem-A is most grateful to the following for their generous donations, which will support continued research and education:

Eric Emms, London, for a collection of more than 100 specimens consisting of natural, synthetic, treated and imitation coloured stones and biogenic gem materials.

Claire Scragg, Tucson, Arizona, USA, for a fibre-optic lamp.

Richa Goyal Sikri, Singapore, for a copy of her 2024 book *No Stone Unturned: The Hunt for African Gems*.

Learning Opportunities

CONFERENCES AND SEMINARS

Geological Society of America Annual Meeting (GSA Connects 2024)

22–25 September 2024

Anaheim, California, USA

<https://community.geosociety.org/gsa2024/home>

Session of interest: Gem Minerals, Localities and Geological Significance

16th GeoRaman Conference

24–27 September 2024

Rhodes, Greece

<https://georaman2024.ntua.gr>

Note: Gemmology is one of the conference themes.

25th Federation for European Education in Gemmology (FEEG) Symposium

19 October 2024

Brussels, Belgium

<https://www.facebook.com/profile.php?id=100057188270879>

Canadian Jewellers Association (CJA) Industry Summit

21 October 2024

Toronto, Ontario, Canada

<https://canadianjewellers.com/2024-industry-summit>

44th New Mexico Mineral Symposium

1–3 November 2024

Socorro, New Mexico, USA

<https://geoinfo.nmt.edu/museum/nmms/home.cfm>

Gem-A Conference

2–3 November 2024

London

<https://gem-a.com/resources/conference-2024>

CIBJO Congress 2024

2–4 November 2024

Shanghai, China

<https://www.cibjo.org/congress-2024>

Treasures: Royal Gems & Jewellery International Colloquium

8–9 November 2024

Lisbon, Portugal

<https://www.treasures-colloquium.com>

FACETS2024 Diamond Conference

26–27 November 2024

Antwerp, Belgium

Email: facets@awdc.be

Note: Hosted by the Antwerp World Diamond Centre, which will also hold its Diamond Days event on 27–28 November.

NAJA 63rd Annual ACE®It Winter Education Conference

1–2 February 2025

Tucson, Arizona, USA

<https://najaappraisers.com/event/63rd-annual-aceit-winter-education-conference>

AGTA Gemfair Tucson

3–9 February 2025

Tucson, Arizona, USA

<https://agta.org/agta-gem-fair-tucson>

Note: Includes a seminar programme

43rd FM-TGMS-MSA Tucson Mineral Symposium

15 February 2025

Tucson, Arizona, USA

<https://www.friendsofmineralogy.org/call-for-papers>

Inhorgenta Munich

21–24 February 2025

Munich, Germany

<https://inhorgenta.com/en>

Note: Includes a seminar programme

Independent Jewelers Organization (IJO) Conference

1–4 March 2025

Palm Springs, California, USA

<https://www.ijo.com/events/conferences>

Hong Kong International Jewellery Show

4–8 March 2025

Hong Kong

<https://www.hktdc.com/event/hkjewellery/en>

Note: Includes a seminar programme

Hasselt Diamond Workshop 2025 (SBDD XXIX)

19–21 March 2025

Hasselt, Belgium

<https://tinyurl.com/txrnzcv8>**GemGenève**

8–11 May 2025

Geneva, Switzerland

<https://gemgeneve.com>*Note:* Includes a seminar programme**German Gemmological Association Conference**

23–25 May 2025

Idar-Oberstein, Germany

Email: info@dgemg.com*Note:* This event will celebrate the 50th anniversary of the Association's training centre in Idar-Oberstein.**JCK Las Vegas**

6–9 June 2025

Las Vegas, Nevada, USA

<https://lasvegas.jckonline.com>*Note:* Includes a seminar programme**Independent Jewelers Organization (IJO) Conference**

19–22 July 2025

Indianapolis, Indiana, USA

<https://www.ijo.com/events/conferences>**OTHER EDUCATIONAL OPPORTUNITIES****Gem-A Workshops and Courses**

Gem-A, London

<https://gem-a.com/education>**'Meet the Author Series' Hosted by Gemmological Instruments at Gem-A**

Held in the Webster Room at Gem-A's headquarters in London at 6:00 pm, various authors will discuss their books with the audience. Tickets are GBP18.00 for Gem-A Members and students, and GBP25.00 for others. Email: shop@gem-a.com

- Cally Oldershaw—*Gemstones*
19 September 2024
- Richa Goyal Sikri—*No Stone Unturned* (held remotely via webinar; tickets are GBP5.00)
26 September 2024
- Helen Molesworth—*Precious*
3 October 2024
- Robin Hansen—*Gemstones: A Concise Reference Guide*
10 October 2024
- Colin Winter—*A Students' Guide to Spectroscopy*
17 October 2024
- Justin Prim—*The Secret Teachings of Gemcutting: 50 Classic Gemstone Designs*
21 November 2024

Gemstone Safari to Tanzania

8–25 January 2025 and 2–19 July 2025

<https://www.free-form.ch/tanzania/gemstonesafari.html>**Lectures with The Society of Jewellery Historians**

Society of Antiquaries of London,

Burlington House

https://www.societyofjewelleryhistorians.ac.uk/current_lectures

- Jane Kershaw—Viking-age Jewellery
24 September 2024
- Claudine Seroussi—Jewellery at the 1925 'Exposition Internationale des Arts Décoratifs et Industriels Modernes'
22 October 2024
- Tonia Marek—African Beads and Their Roles in Rituals
26 November 2024
- Ragnall Ó Floinn—Late Medieval Jewellery in the 15th and 16th Century in Gaelic Ireland and Scotland
28 January 2025
- Emma Rutherford—Portrait Miniatures 1550–1850
25 February 2025
- Beth Wees and Sheila Smithie—Marcus & Co.: An American Art Nouveau Jeweller
25 March 2025
- Cristina Filipe—An Aspect of Contemporary Portuguese Jewellery
27 May 2025

New Media



Decoding the Jewels: Renaissance Jewellery in Scotland

Ed. by Anna Groundwater, 2024. Sidestone Press (for National Museums Scotland), Leiden, The Netherlands, 200 pages, illus., ISBN 978-9464262582 (hardcover), 978-9464262575 (softcover) or 978-9464262599 (PDF eBook), <https://doi.org/10.59641/oo901ra>. EUR95.00 hardcover, EUR40.00 softcover, EUR15.00 PDF or read online for free.

Renaissance jewellery—that is, European jewellery produced between about 1450 and 1650—has been underrepresented in academic study. What has been written has mainly focused on stylistic developments and relationships, as well as contemporary documentary sources. Technical study has been limited, with the most work being done on enamels. Renaissance jewellery was copied to a huge extent in the nineteenth century, and analysis of the enamelwork is one of the primary ways to help determine authenticity.

The inspiration for the present book was the acquisition by National Museums Scotland of the Fettercairn Jewel, an extraordinary enamelled locket dating to the sixteenth century (likely 1560–1580). This enamel-and-gold masterpiece was found in 2017, wrapped in paper and forgotten, in a drawer in Fettercairn House in Aberdeenshire, Scotland. It came up for auction at Sotheby's, London, in March of that year and was acquired by the museum, with the aid of the Art Fund, the Heritage Lottery Fund and the National Museums Scotland Charitable Trust.

The book consists of eight chapters written

by different specialists who describe the jewel, explain its iconography and put it in the context of similar jewels, concluding with an analysis of its materials and techniques: (1) 'The Renaissance in Scotland: Historical and Cultural Contexts' by Dr Anna Groundwater, principal curator of Renaissance and early modern history, National Museums Scotland; (2) 'The Fettercairn Jewel: An Interpretation' by Geoffrey Munn, a well-known jewellery historian; (3) 'The Mystery of the Fettercairn Jewel' by Helen Wyld, senior curator of historic textiles, National Museums Scotland; (4) "'A Most Extraordinary and Very Curious Jewel': The Darnley or Lennox Jewel' by Deborah Clarke, former senior curator at Holyrood House; (5) 'Scottish Renaissance Jewels in the National Collection' by Lyndsay McGill, former curator of Renaissance and early modern history, National Museums Scotland; (6) 'Jewels in Sixteenth-Century Scottish Portraits' by Kate Anderson, senior curator, National Galleries of Scotland; (7) 'Tracing Royal Stewart Jewels in the Archives' by Dr Anna Groundwater; and (8) 'Analysis of the Fettercairn Jewel and Comparative Scottish Renaissance Jewellery' by Dr Lore Troalen, analytical scientist, National Museums Scotland.

The Fettercairn Jewel is an elaborately enamelled, 21-carat gold locket, oval in shape, with a large rectangular flat garnet set in its front. It is missing the miniature portrait that it almost certainly contained originally. The reverse side of the locket bears an enamelled representation of the Roman god Mercury with a white dog, surrounded by a seemingly eclectic assortment of parrots, flowers and butterflies, with buildings in the background—a puzzling scene that Geoffrey Munn seeks to unravel in the second chapter, concluding that it was almost certainly to anticipate or commemorate a betrothal or marriage.

Helen Wyld, in her chapter on the 'mystery' of the jewel, discusses the likely significance of the use of a garnet in an ornament of this type. She says, 'Red garnets were in some contexts viewed as equivalent to rubies due to their red colour', which in this reviewer's opinion is seeing things from too modern a perspective. Today, the tendency is to consider our ancestors unable to distinguish among rubies, garnets and spinels. Of course, the average person then could not tell them apart, any more than the average person can today, but

there were those who could. In Renaissance time, *ruby* typically referred to any red stone, of which different varieties were known, including ruby (corundum), red garnets, ‘balas rubies’ and spinels (which were thought of as distinct). Garnets were considered one type of ‘ruby’.

The chapter that will likely be of most interest to readers of *The Journal* is the final one by Lore Troalen, which deals with the materials and technology of the Fettercairn and related jewels. The garnet on the front of the locket is described as a thin, flat rectangle about 3 mm thick with a bevelled edge, mounted over gold foil. Troalen gives the measurements as 8 × 6 mm, but this must be a printing error; judging from the photo of the jewel (given as 50 × 28 mm overall), the garnet looks to be nearer 18 × 13 mm. Semi-quantitative chemical analysis confirmed that the garnet was almandine and showed its trace-element composition to be consistent with Rajasthan, India, as a likely source. It has a somewhat unusual form for a Renaissance gem, so it may be a reused stone that graced some ornament from as much as a millennium earlier. Reused ancient emeralds and sapphires were commonly mounted in later Medieval pieces, so why not garnet?

Troalen also studied the construction of the locket and analysed its gold and enamels. The purity of the gold was measured at about 86–89%, but the analyses were carried out on unprepared surfaces, and manufacturing techniques and finishing can elevate the purity of surface gold. It is impossible to tell if all the gold was of identical composition originally. (When a crown was made for Margaret Tudor when she married James IV of Scotland in 1503, the gold was supplied as several distinct types of gold coins.) Troalen provides a chart with the Ag and Cu contents of the Fettercairn locket along with several other comparable Scottish Renaissance jewels, and the clustering of this data is remarkable. It is to be hoped that the National Museums Scotland reports soon on the more detailed analyses they carried out on these various jewels.

The analyses of the enamels provide no new insights, but are extremely useful in adding to the body of data. For example, changes in the sources of Co ores used for making blue enamel show up at the end of the Medieval period, from having traces of Zn to traces of Ni and As, and the Fettercairn blue enamel fits into this pattern perfectly. However, one intriguing feature is that the relative amounts of Na and K in the ruby-red enamels on

the locket differ from those of other red enamels of this period. The reasons are unknown, but this sort of detail may eventually allow us to distinguish individual workshops or work practices.

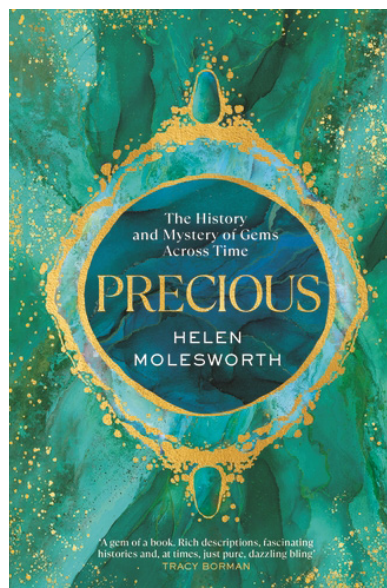
This reviewer would have liked slightly more description of the way the gold components were made and assembled. The manufacturing technology of Renaissance jewellery has received remarkably little attention over the years. On the other hand, in her chapter ‘Scottish Renaissance Jewels in the National Collection’, Lyndsay McGill provides an in-depth and fascinating study of what is known about actual makers of jewellery in Scotland during the period.

The other chapters of the book provide a combination of art-historical and technical studies, which tie together well to provide a wonderful overview of the locket and of Scottish Renaissance jewellery in general. The introductory chapter might have benefitted from a simple description of the jewel—which the reader has to piece together from various bits of the different chapters—along with the story of its recent discovery. Mention of it being found wrapped in paper in a drawer in a Scottish country house—and its subsequent appearance at auction—is not provided until chapter 3.

The book is beautifully illustrated—almost excessively so. The same image of the front of the locket appears four times in separate chapters (which may explain why it was not chosen for the front cover), but this repetition does save the reader from leafing backwards and forwards. This reviewer’s biggest gripe is the lack of an index. This is a common deficiency in books composed of chapters by different authors, but today there are relatively easy, semi-automated ways to construct an index once a PDF with final pagination is available.

In short, this is a brilliant addition to the literature on Renaissance jewellery, and a good demonstration of what a team of experts can create. This reviewer hopes it will be a spur to other museums to produce similar published research on their holdings. It is a visually attractive book, and one that should be on every jewellery historian’s bookshelf. It may not hold enough gemmological interest to loosen the purse strings of most readers of *The Journal*, but there is a version freely available for reading online. The publisher, the National Museums of Scotland and the authors all deserve our thanks and congratulations.

Dr Jack M. Ogden FGA
London



Precious: The History and Mystery of Gems Across Time

By Helen Molesworth, 2024. Penguin UK, London, <https://www.penguin.co.uk/books/451584>, illus., ISBN 978-0857529091 (hardcover, 336 pages), 978-1529177466 (softcover, 352 pages), 978-1529194487 (eBook) or ISBN 978-1529906813 (audio download). GBP30.00 hardcover, GBP10.99 softcover or eBook, or GBP14.00 audio download.

This is a book of facts and enthralling stories about amazing gems that is aimed at a wide readership, written by someone with the rare if not unique qualifications to write it. Unfortunately, the publishers have done neither her nor the subject justice. The reviewer had the hardcover version to review, and it appears that its shortcomings in design terms are because they also offer a far less expensive softcover version. By eyeing this cheaper softcover edition, the publishers seem to have misjudged the target audience and the opportunities this book could have provided. As it is, the cover bears no image of a gem or jewellery. They have allowed just 16 pages of plates clumped into two sections, a binding style that seems incredibly old-fashioned. And, most surprisingly, the plate pages (and the individual images on them) are left unnumbered and so, of course, the gems or jewels shown are not cross-referenced to the text or vice versa. As far as this reviewer could see, some of the pictured pieces are not even specifically mentioned in the text. There is no list of plates, and the captions are cursory in the extreme. This reviewer can't second-guess the publisher's marketing department and

their reasoning, but a more visually appealing version, albeit making the softcover edition more expensive, would have done credit to the subject matter and likely found a market just as wide, if not wider.

Now to the content. The book's author will be well known to many readers of *The Journal*. Molesworth's impressive career has ranged from the jewellery departments in top auction houses, to one of the world's most highly esteemed gemmological laboratories (in an educational capacity), to chief jewellery curator at the Victoria and Albert Museum in London. She also passed the Gemmological Association of Great Britain's (now Gem-A) gemmology diploma with distinction. It is a perfect résumé for the author of a book that promises to tell the reader about 'the history and mystery of gems across time'. The book is divided into ten chapters, each devoted to a single gem type: emerald, ruby, sapphire, garnet, pearl, spinel, quartz, diamond, coloured diamond and jade. Within these chapters, she interweaves information about each gem with anecdotes on the history of its use, its mines and some exceptional examples.

When describing mines and individual gems, she does so in a very personal manner, and it is this aspect that is one of the great strengths of the book. She talks of the many mines she has visited and her observations and experiences along the way, often sharing engaging tales and insights that will appeal particularly to the non-specialist reader. Her hands-on experience with notable gems and jewellery will enthrall readers, from the Wittelsbach (later Wittelsbach-Graff) blue diamond to the sapphire-and-diamond tiara that Prince Albert presented to Queen Victoria in 1840. She writes about it all in an easy-to-read, informal manner, so the reader can share some of the delight and awe she felt when first seeing and touching some of these objects.

Of course, all the main gem types are covered, and it is not necessary to report on all of them here. In particular, it is good to see a chapter on quartz. But of necessity, this is one of the more technical chapters in the book because that gem has many varieties (both macrocrystalline and microcrystalline). Strangely, however, rock crystal barely gets a mention.

The book has some weaknesses when it touches on the history of gems and, in most cases, these can probably be attributed to the author relying too much on secondary or outdated sources. For example, she refers to the 'first known reference to emeralds, and perhaps gemstones altogether' as

being in the Egyptian text known as the Maxims of Ptahhotep (around 2375–2350 BCE). It is seemingly a wonderful statement, but almost certainly incorrectly translated. The source she cites is Battiscombe Gunn's translation of the text from around 120 years ago. Our understanding of both gem history and Egyptian philology has advanced considerably since then, and more recent translations of this and other texts containing the same word indicate that it refers to malachite. This quibble about translation from a 4,400-year-old hieroglyphic text might sound like awful pedantry, but gem historians battle to lay down as accurate a history of gems as possible. In fairness, the author does raise the prospect of this quote being a mistranslation, but she brushes it aside because of the 'supporting evidence' for emerald mining in Egypt some 2,000 years later.

As another example, she quotes the rule imposed by Byzantine emperor Justinian that 'only the emperor was allowed to wear sapphires, pearls or emeralds...' This would surprise any reader acquainted with the wealth of such gems in the Byzantine gold jewellery preserved in museums. The actual law was much more specific: Justinian only banned the wearing of such gems when set in belts or horse trappings. A well-to-do Constantinopolitan lady could wear her splendid gem-set earrings without risk of the stipulated fine of fifty pounds' weight of gold, although her horse might feel miffed. The regulations are quite clear in the translation of the *Enactments of Justinian* that the

author cites (Scott 1932), but she seems to have followed the more curtailed version available on the internet.

The problem with such errors, minor as they may seem, is that repeating discredited or misquoted statements about gems in a book like this, by an author like this, will see them ricochet around the web and social media more than they do already. A cause of despair to some gem historians...

It would have been useful to have a brief additional section on 'further reading' listing the more accessible works on gems to allow the intrigued reader to follow up on the subject. It is good, however, to see that the book is fairly copiously referenced (although often to secondary sources), particularly for one aimed at a popular readership. The index is more comprehensive than expected for a book of this type.

The author has produced an enticing text for the general audience for which it was intended. It is a well-written, personal account of gems and a journey through the gem world that few could ever be privileged to match. This highly readable book will introduce many to the alluring world of gems, and may even prompt some to delve more deeply and one day study gemmology. It just needed a more visionary publisher, a more nit-picking editor and, perhaps, fewer time constraints on the author.

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Other Book Titles

COLOURED STONES

Broken Bangle: The Blunder-Besmirched History of Jade Nomenclature

By Shang-i (Edward) Liu, Richard W. Hughes, Zhengyu (Adam) Zhou and Kaylan Hourie, 2024. Lotus Publishing, Bangkok, Thailand, and RWH Publishing, Boulder, Colorado, USA, 120 pages, ISBN 978-0964509788. THB2100.00 hardcover.

Paraiba – The Legacy of a Colour

By Kevin Ferreira and Katerina Perez, 2024. Watchprint, La Croix-Sur-Lutry, Vaud, Switzerland, 195 pages, ISBN 978-2940506620. USD150.00 hardcover.

GENERAL REFERENCE

Gold: A Monograph

By Joaquim Callén, 2023. Self-published, 223 pages, no ISBN. USD100.00 hardcover.

The Handbook of Gemmology, 5th edn.

By Geoffrey M. Dominy, 2024. Amazonas Gem Publications, Mallorca, Spain, 1,236 pages, ISBN 978-0991888283. USD59.95 eBook (three-volume set).

JEWELLERY HISTORY

Antique Jewelry from 1800 to 1939:

Appreciating the Dreams

By Ioannis Alexandris, 2024. Gemolithos GmbH, Appenzell, Switzerland, 289 pages, ISBN 978-3831649679. USD69.00 hardcover.

Streeter of Bond Street: A Victorian Jeweller, 2nd edn.

By Patrick Streeter, 2024. Matching Press, Harlow, Essex, 269 pages, ISBN 978-0951866498 (hardcover) or 978-1399991629 (softcover). GBP25.00 hardcover or GBP20.00 softcover.

JEWELLERY AND OBJETS D'ART

Bizarre Beauty: The Art of William Harper

Ed. by Glenn Adamson and Martha J. Fleischman, 2024. Arnoldsche Art Publishers, Stuttgart, Germany, 248 pages, ISBN 978-3897907164. EUR48.00 hardcover.

Chanel: The Legend of an Icon

By Alexander Fury, 2024. Assouline Publishing, New York, New York, USA, 240 pages, ISBN 978-1649803443. USD120.00 hardcover.

For the Love of Diamonds:

The Fine Jewelry Book

By Rachel Tailor, 2024. teNeues Verlag GmbH, Augsburg, Germany, 224 pages, ISBN 978-3961716043. EUR60.00 hardcover.

Jewelry's Shining Stars: The Next Generation, 45 Visionary Women Designers

By Beth Bernstein, 2024. ACC Art Books, Woodbridge, Suffolk, 176 pages, ISBN 978-1788842402. GBP50.00 hardcover.

Masterpieces of Islamic Art from the Farjam Collection

Ed. by Sheila R. Canby, 2024. Yale University Press, New Haven, Connecticut, USA, 684 pages, ISBN 978-0300273519. USD250.00 hardcover (two-volume boxed set).

Meta Overbeck's Designs for Louis C. Tiffany Art Jewelry

By Meta Overbeck with Laurence Ruggiero and Jennifer Thalheimer, 2024. Applewood

Books, Carlisle, Massachusetts, USA, 64 pages, ISBN 978-1429096355. USD75.00 hardcover.

Sybil and David Yurman: Artists and Jewelers

By Sybil Yurman, David Yurman and Thierry-Maxime Loriot, 2024. Phaidon Press, London, 352 pages, ISBN 978-1838669058. GBP49.95 hardcover.

MISCELLANEOUS

Gem Characterisation

Ed. by Stefanos Karampelas and Emmanuel Fritsch, 2024. MDPI, Basel, Switzerland, 262 pages, ISBN 978-3725813339 (hardcover) or 978-3725813346 (PDF), <https://doi.org/10.3390/books978-3-7258-1334-6>. CHF85.25 hardcover or free PDF.

No Stone Unturned: The Hunt for African Gems

By Richa Goyal Sikri, 2024. Austin Macauley Publishers, London, 396 pages, ISBN 978-1035867844 or e-ISBN 978-1035867851. GBP13.99 softcover or GBP3.50 eBook.

ORGANIC/BIOGENIC GEMS

Amber for Artemis: Amber Finds from the Artemision at Ephesos

Ed by A. Naso, 2024. Austrian Academy of Sciences Press, Vienna, Austria, *Forschungen in Ephesus*, Vol. XII/7, 274 pages, ISBN 978-3700192824 or e-ISBN 978-3700192831, <https://doi.org/10.1553/978OEAW92824>. EUR150.00 hardcover or free PDF.

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By the International Amber Association, 2023. International Amber Association, Gdańsk, Poland, 160 pages, no ISBN. PLN100.00/EUR25.00 softcover.

ERRATUM

In the New Media section of *The Journal*, Vol. 39, No. 2, p. 188, the book review of *Star Gems: A Fascinating World* should have indicated that the price for the hardcover edition is EUR89.00 and the VIP edition is EUR190.00.

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COLOURED STONES

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