

Distinction of Gem Spinel from the Himalayan Mountain Belt

Anna Malsy^{*ab} and Leonhard Klemm^b

Abstract: Gem spinel deposits in Myanmar, Vietnam and Tajikistan have their formation in association with Himalayan orogenesis. Gem-quality orange, pink, red and purple spinels from deposits at Mogok (Myanmar), Luc Yen (Vietnam), and Kuh-i-Lal (Tajikistan) have been investigated by 'standard' gemological testing and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Microscopic examination yielded apatite and calcite inclusions together with octahedral negative crystals to be most frequently present in Mogok spinels. The presence of dislocation systems and titanite inclusions are indicative inclusion features for spinels from Luc Yen. Trace elements such as Ti, Fe, Ni, Zn, Zr and Sn differ slightly in spinels from the sources investigated. A distinction of spinels from these deposits is therefore possible by trace element chemistry. This is especially helpful for gem spinels, which often show few inclusions or completely lack inclusion features.

Keywords: Gemstones · LA-ICP-MS · Origin determination · Spinel

Introduction

Natural magnesium-aluminum spinel (MgAl_2O_4) as a gemstone comes in a wide palette of attractive colors. Most appreciated are red spinels, but also pink to purple and blue are amongst the favorite colors on the gemstone market. Spinel is commonly associated with ruby and occurs in metamorphic rocks as gneisses, marbles or calc-silicate felses. Most important spinel findings are in Sri Lanka, Myanmar, Afghanistan, Vietnam, Tajikistan, Madagascar, Tanzania and China. Synthetic spinel of reasonable size has been commercially produced since 1908 by the flame fusion method. Synthetic spinel is often used to imitate a variety of other gemstones due to the ease of producing different colors with the addition of various metal oxides.

The purpose of the present study is the characterization of gem spinels from the deposits at Mogok, Myanmar, Luc Yen in Vietnam and Kuh-i-Lal mines in Tajikistan. These deposits are associated with the formation of the Himalayan Mountain Belt. Criteria for a proper assignment of gem spinel to these sources were investigated.

History

The curriculum vitae of spinel is a story full of misunderstandings. Two thousand years ago, Plinius the Elder described in his encyclopedia *Naturalis Historiae* (liber XXXVII) the *carbunculus* (from Latin meaning small piece of carbon) as the first-order red gemstone. Thus, the term *carbunculi* was a collective designation of red gems and further descriptions of *carbunculi* presumably include ruby, garnet, and probably spinel and hyacinth (yellow, brown to reddish brown variety of zircon).^[1] It was not until the twelve century that Albertus Magnus, a German bishop, mentioned a sub-division of *carbunculus* into *balagius*, *granatus* and *rubinus* and it is suggested that these indeed correspond to today's spinel, garnet and ruby, respectively. Names sounding quite similar to *balagius* appear in different literature, e.g. *balchasch* in some Arabic literature or *balassi* in the documentations of Marco Polo's travels.^[2] The latter texts both refer to gemstones coming from the mountains of Badakhshan province in today's northern Afghanistan, which is documented to be an early source of the finest quality ruby and spinels. Thus, it can be assumed that these more ancient names and finally 'balas ru-

by', a term which today is particularly used for pale or rose-tinted spinel, derive from an ancient word for Badakhshan. The name spinel possibly originates from the Latin *spinella*^[3] for little thorn or Greek σπινθήρ meaning spark. However, it was not until the end of the 18th century, that spinel was distinguished from ruby by chemical composition. Thus, the unreliability of its name and the lack of distinction from ruby made spinel's acceptance and recognition difficult. Even the discovery of many important historical treasures to be spinel instead of ruby, as for example the famous *Black Prince's ruby* in the Imperial state crown and the *Timur ruby* of the royal collection of the Queen of England, did not increase spinel's prestige.

Today, spinel benefits from other colored gemstones falling out of favor due to artificial treatments and market rumors. With its high diversity in color, all variants from pink to red, and its amazing transparency, spinel is gaining greater commercial importance.

Materials and Methods

For the present study, a total of 131 spinels from Burma, Tajikistan and Vietnam were characterized. All samples, ranging from 0.1 to 8.2 ct, were of 'gem quality' with colors of orange, red, pink or purple as the main hue.

The fluorescence behavior to standard 365 nm long-wave and 254 nm short-wave ultraviolet radiations was observed in a darkened room. Internal features were observed with a standard gemological microscope (GIA Gemolite Ultima B, Bausch & Lomb optics) and photomicrographs were

*Correspondence: A. Malsy^{ab}

Tel.: +41 41 429 17 17

Fax: +41 41 429 17 34

E-mail: a.malsy@gubelingemlab.ch

^aMineralogical Crystallography

Institute of Geological Sciences

University of Bern

^bGübelin Gem Lab Ltd

Maihofstrasse 102

CH-6006 Lucerne

taken by a Nikon D80 camera. Mineral inclusions were analyzed using a Renishaw Raman 1000 spectrometer with Ar⁺ laser at 514 nm excitation wavelength. Ultra-violet-visible-near infrared (UV-Vis-nIR) absorption spectra were recorded with a Perkin Elmer Lambda 19 spectrometer, in the range of 280–880 nm. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) was performed on a Perkin Elmer ELAN DRC-e single collector quadrupole mass spectrometer combined with a CETAC LSX-213 Nd:YAG laser ablation system. Helium was used as carrier gas. The LA-ICP-MS system performance was optimized to maximum intensities at Th/ThO >200 and U/Th ~ 1. Instrument settings were similar to those presented by Pettke *et al.*^[4] A set of four single-spot (100 µm in diameter) analyses per sample was performed on each sample at 10 Hz laser frequency. The calculation of concentration follows the equations given by Longerich *et al.*^[5] Multielement glass standard reference material NIST610 was used for external standardization; internal standardization was done by normalization to 100% cations of pure stoichiometric spinel.

Geology and Mining

Spinel deposits from central to South-east Asia are located within the Himalayan mountain belt which formed during the Tertiary continental collision between the Indian subcontinent and Eurasia.^[6] Spinel and/or ruby occur in platform carbonate series that underwent high-temperature amphibolite to lower granulite grade regional metamorphism.^[7] These marbles consist of calcite, dolomite, phlogopite, margarite, amphibole, chlorite, forsterite, and titanite ± graphite ± garnet ± pyrite. The marble units are generally associated with intercalations of garnet-biotite-sillimanite- or biotite-kyanite-bearing gneisses, schists, quartzites and amphibolites. Dikes of granite and/or pegmatite intruded these metamorphosed rocks.^[8]

Myanmar – Mogok

Burma, nowadays Myanmar, is not only famous for its finest rubies of so-called ‘pigeon blood’ color, but also for intensely red-colored spinels. The deposits around Mogok have been exploited for rubies since the sixth century,^[9] as documented by ancient legends. Mogok rubies are still today some of the highest priced gemstones of the world. The ‘Mogok Stone Tract’ is located in the Mandalay division and comprises several localities surrounding Mogok. Significant amounts of spinel

are found at virtually all of the corundum mines,^[10] from primary as well as secondary deposits.

Geological mapping of the ‘Mogok Stone Tract’ was done by Iyer in the 1950s.^[11] More recent investigations are lacking, as access to the mining area is limited to foreigners due to political changes in 1960s. The gem deposits occur in the Mogok Metamorphic Belt (MMB). This belt is marked by high-temperature ductile deformation from Oligocene stretching to post-Miocene brittle dextral faults resulting from the oblique Indio-Asian collision.^[6,12] Ruby and spinel are disseminated within marbles in a mineral association with phlogopite, muscovite, scapolite, margarite, titanite, pyrite, and graphite.^[8,13] The marble units consist of discontinuous horizons up to 300 m in thickness, interbedded with calc-schists or sillimanite-bearing gneisses.^[6] They are generally coarsely crystallized and typically pure white in color.^[14] Dikes of granite, minor syenite, and associated pegmatites intruded into the metamorphic rocks. The influence of the latter intrusives on the formation of gem ruby was discussed by several authors.^[11,14,15] Most recent investigations^[6] indicate that ruby formation was probably strictly associated with high-temperature metamorphism.

The tropical climate with high rainfall and strong weathering leads to residual accumulation of chemically and mechanically resistant minerals and ultimately to the formation of secondary gemstone deposits. Gem-bearing beds are characteristically brown and yellow and contain clays, iron oxides and sometimes sandy material, locally known as ‘byon’.^[14] With today’s political situation in Myanmar there is unfortunately no firsthand information on mining activities and production. Previous information on mining production gives only distinctive details on ruby and sapphire. However, Mogok spinels are available on the gemstone market in a variety of color hue, saturation and tone, from intense red to orange and purple, as well as pink from very light tones to intense pink.

Vietnam – Luc Yen

Luc Yen is located in the northern part of Vietnam in the Yen Bai province. The city of Luc Yen is the center of gemstone mining and trading in the area. The first discovery of ruby in northern Vietnam was in 1983. Serious mining of the occurrences did not start before 1988,^[16] but spinel findings are reported from that time.

The deposits from Luc Yen are located in weakly deformed marble units hosted by metamorphic belts associated with the southern Red River Shear zone, which was active during the Cenozoic.^[17] Geothermo-

barometric studies revealed a peak metamorphism at amphibolite-facies conditions.^[18] Amphibolite bodies are alternated with calcitic and/or dolomitic marble.^[8] Surrounding gneisses or schists show assemblages of biotite-garnet-sillimanite ± scapolite ± kyanite ± amphibole ± clinopyroxene.^[6] For the gem-bearing marbles, literature data agree on two different types or assemblages. Garnier *et al.*^[13] indicate a marble-parageneses of spinel + ruby ± chlorite ± amphibole ± olivine ± humite ± graphite ± pyrite. A second, spinel-free paragenesis, is given as ruby + phlogopite + feldspar ± muscovite ± paragonite ± amphibole ± graphite ± tourmaline ± apatite ± titanite ± pyrite ± pyrrhotite. These authors further state a destabilization of spinel in contact with calcite during retrograde metamorphism as the principle reaction for ruby formation. A more distinct separation into spinel- and ruby-bearing marbles is stated by other authors.^[19,20]

Placer deposits are the main source for gem spinel. The secondary deposits consist of gravel fillings in karst pockets or are located in alluvial fans of the Luc Yen valleys. Open-pit mining is the dominant method used and associated gem minerals are pink to red corundum, yellow and green tourmalines and garnets.^[16] Vietnamese spinels are known for both their bright and pastel-pink color. There is, however, a broad variety of colors from orange to pinkish-red and purple, but also pale blue spinel is available. Pure red spinels are rather rare from Vietnam.

Tajikistan – Kuh-i-Lal

The Kuh-i-Lal mines are situated on the Tajik side of the Badakhshan region, which comprises parts of today’s north-eastern Afghanistan. The historic mine is amongst the oldest of the world and source of the so-called ‘Balas Rubies’, which are actually pale rose-tinted spinel.

The Kuh-i-Lal deposits are situated within southwest Pamir Mountains, which are designated by extensive development of ultra-magnesian metamorphic assemblages^[21] in the Goran series. The Goran series consists of metasedimentary rocks, dominantly biotite gneiss and migmatite, marble and calc-silicate rocks, and subordinate quartzite and amphibolites.^[22] The ultra-magnesian rocks include ‘white-schist’ (talc-kyanite rocks), enstatite- and forsterite-rich skarns, and kornepine-bearing skarns and schists.

Results

Results for microscopic and spectroscopic features, as well as chemical com-

Table 1. Summary of gemological properties (color, refractive index, specific gravity, fluorescence, microscopic features)

Property	Mogok, Myanmar	Luc Yen, Vietnam	Kuh-i-Lal, Tajikistan
Color	Red, orangey red, pinkish red, pink (light or medium in tone), orangey pink, purple, orange	Red, orangey red, pink (light or medium in tone), orangey pink, reddish pink, purple, orange	Pink (light in tone) 'rose'
Refractive index (RI)	n = 1.715 (pink, light in tone) to n = 1.719 (pink)	n = 1.714 (pink, light in tone) to n = 1.719 (pink)	n = 1.712 to 1.713
Specific gravity (SG)	3.59–3.61	3.59–3.61	3.58–3.59
UV fluorescence			
Long-wave	inert to strong; red	inert to strong; red	medium to strong; red
Short-wave	inert to weak red	inert to very weak; red	weak; orange, yellow (at surface)
Internal features	apatite ('belly button') calcite dolomite anhydrite magnesite graphite potassium feldspar chondrodite Partially healed fissures Octahedral negative crystal : filled by calcite or dolomite; isolated with cross cutting needle-like inclusion; perching on a partially healed fissure; with equatorial tension disc; circled by accretion clouds; lined-up in rows	apatite calcite dolomite zircon (tension crack; cluster) magnesite graphite potassium feldspar titanite ("sphene") Partially healed fissures composed of arranged fluid inclusions Monodirectional, parallel blades of short needles (högbomite?) Primary two-phase inclusions Dislocation channels: bands or as stellate networks; outgoing from fluid inclusions; with cut-off by growth steps	zircon Poorly healed fissures with coarse texture, cavities partially filled by double refractive substance and "tails" Planes of negative crystals Octahedral negative crystal : isolated with cross cutting needle-like inclusion; with attached black platelet Crystal inclusion associated with particulate trails = "comet-tails"

position by LA-ICP-MS are given in the following section. A summary of gemological features is given in Table 1.

Microscopic Features

Mineral inclusions and octahedral negative crystals are the most prominent features in Mogok spinels. The appearance of slightly rounded, more or less spherical apatite crystals with a black graphite or ilmenite platelet attached on a basal pinacoid (Fig. 1) is quite specific and often characterized as a highly diagnostic feature for spinel from Mogok.^[23] However, these so-called 'belly-button' inclusions were observed in some of the spinels only,



Fig. 1. Rounded apatite inclusion with attached black graphite platelet. This inclusion feature is also described as 'belly button' and is considered a diagnostic inclusion in spinel from Mogok, Myanmar.

more specifically in samples from the former Dr. Gübelin collection. These samples further show rows of lined-up negative crystals, as well as negative crystals encircled by accretion clouds. All other spinels are characterized by calcite of variable appearance and octahedral negative crystals as dominant inclusion features. Octahedral negative crystals may be transparent or of more turbid white aspect and are partly filled by calcite and/or dolomite substance. Occasionally they are accompanied by an equatorial stress crack, partially healed fissure or accretion clouds of minute light scattering particles. Some octahedral negative crystals are also penetrated by a needle-like crystal. Isolated graphite platelets are observed and less frequently mineral inclusions of anhydrite, magnesite, feldspar, and chondrodite.

The most striking inclusion feature of spinels from Luc Yen is the presence of dislocation systems. These appear as intersecting bands of iridescent parallel oriented channels (Fig. 2) or build three-dimensional stellate networks. Single bands with distinct cut-offs can be observed and are most probably generated by bisecting growth steps. In a few samples, mono-directional parallel blades of needles (possibly högbomite) can be observed. A wide variety of mineral inclusions were identified by Raman spectroscopy; these are zircon, apatite, calcite,

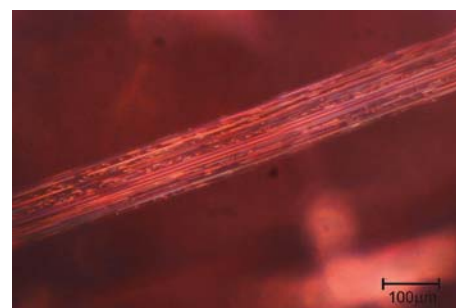


Fig. 2. Band of an oriented dislocation system within spinel from Luc Yen, Vietnam.

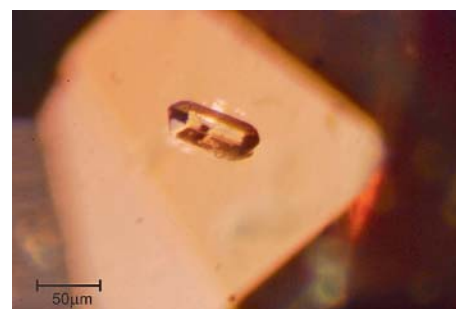


Fig. 3. Well-developed zircon inclusion with tension crack within a spinel from Luc Yen, Vietnam.

dolomite, titanite, graphite, and potassium feldspar (75% orthoclase). Zircon crystals (Fig. 3) occur slightly rounded

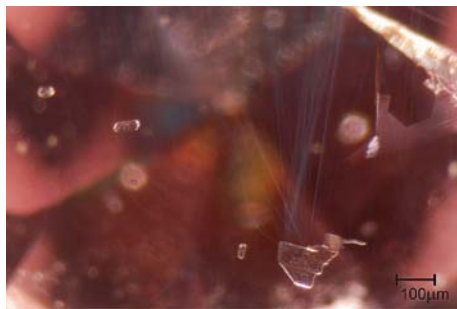


Fig. 4. Inclusion scene in a spinel from Tajikistan with small prismatic zircon crystals. An unknown colorless crystal inclusion is accompanied by divergent particulate trails forming so-called 'comet-tails'.

in clusters or as well-developed prisms accompanied by tension cracks. Partially healed fissures with fluid inclusions arranged in a pattern are rarely seen.

Spinel investigated from Tajikistan have few inclusions. Negative octahedra were observed. These can be associated with a needle-like inclusion at the octahedron's tip or a black graphite platelet. Planes of elongated negative crystals are common. Euhedral zircon crystals and tabular to prismatic colorless mineral inclusions (most probably phlogopite) were observed. In association with mineral in-

clusions, diverging stringers of delicate light-scattering particles (Fig. 4) were seen in some samples. Poorly developed healed fissures with coarse constituents are sometimes present.

Chemical Composition

In Table 2, selected LA-ICP-MS data are summarized and given as ranges, mean values and standard deviations. The elements V, Cr, Fe and Zn were commonly present in highest concentrations whereas Ti, Ga, and Mn contents were generally low. Traces of Li, Be, Co, Ni, Cu, Zr and Sn were detected, other investigated elements were below the detection limits (Table 1). Highest Zn concentrations have been observed for Mogok spinels. Spinel from Mogok are further characterized by the highest Ti, V, Cr, Ga and Sn contents. Investigated samples from Luc Yen stand out by having the highest Fe content (up to 2.2 wt% Fe₂O₃), as well as low Ti (<0.04 wt% TiO₂) and Sn (<0.5 µg/g) concentrations. Samples from Tajikistan show intermediate values for Ti, V, Cr, Fe, Zn, and Ga. Nickel and Zr are typically close or below the detection limit in Tajik spinels. The homogeneity of trace elements within all individual samples is generally quite high, with mean variations of <7% for V, Zn, Ga, and mean variation of <10% for Li, Ti, Cr, Mn and Fe. The variation of trace element

concentrations is strongest for Mogok spinels.

The color of Mogok spinel strongly depends on Cr, with minor influence of Fe and V concentrations (Fig. 5a). The Cr content of the investigated spinels shows variations from 0.001 wt% in light orange up to 2.6 wt% Cr₂O₃ in red samples. The Fe content ranges from 0.002 to 1.2 wt% Fe₂O₃. Red to pinkish red samples generally contain more Cr than Fe whereas Fe significantly exceeds Cr concentrations in purple spinels. Lower variation in the concentration of chromophores Cr and Fe is observed for spinels from Luc Yen, Vietnam and Kuh-i-Lal, Tajikistan (Fig. 5b). Samples investigated from Vietnam showed Cr contents from 0.05 wt% Cr₂O₃ in light pink to 1.3 wt% Cr₂O₃ in pinkish red samples. The Fe content ranges from 0.18 to 2.2 wt% Fe₂O₃ and equals or exceeds the Cr concentration with the exception of one sample. Orange spinels investigated from Myanmar and Vietnam typically have higher V than Cr contents. As expected from their quite uniform light pink color, spinels from Tajikistan are most homogeneous regarding chromophore contents (Cr₂O₃: 0.04–0.13 wt% and Fe₂O₃: 0.13–0.52 wt%).

UV-Vis Spectroscopy

According to the dominant color-causing trace elements, different types of

Table 2. Chemical composition by LA-ICP-MS given as ranges, mean values (mean) and standard deviation (sdev)

wt% ^a	Mogok, Myanmar		Luc Yen, Vietnam		Kuh-i-Lal, Tajikistan	
	range	mean + sdev	range	range + sdev	range	mean + sdev
V ₂ O ₃	0.004–1.019	0.261 ± 0.202	0.004–0.323	0.101 ± 0.099	0.028–0.068	0.048 ± 0.010
Cr ₂ O ₃	0.001–2.614	0.497 ± 0.550	0.053–1.271	0.291 ± 0.251	0.036–0.127	0.059 ± 0.016
Fe ₂ O ₃	0.002–1.217	0.226 ± 0.235	0.182–2.228	0.722 ± 0.463	0.134–0.523	0.330 ± 0.075
ZnO	0.045–2.757	0.461 ± 0.546	0.014–0.889	0.222 ± 0.243	0.045–0.144	0.108 ± 0.022
µg/g ^b						
Li	0.14–343	43 ± 63	2.3–814	115 ± 211	7.1–21	15 ± 2.3
Be	< ^c 0.14–141	17 ± 24	2.4–34	10 ± 7.0	5.9–13	9.3 ± 1.4
Ti	4.0–1566	370 ± 355	0.78–194	60 ± 33	47–114	84 ± 12
Mn	2.6–812	51 ± 137	3.1–179	56 ± 42	67–120	92 ± 11
Co	<0.024–14	2.1 ± 2.5	0.28–15	4.5 ± 3.7	0.40–1.5	0.85 ± 0.20
Ni	<0.49–78	35 ± 41	<0.43–245	37 ± 51	<0.33–2.0	0.58 ± 0.39
Cu	<0.18–1.2	0.40 ± 0.19	0.13–5.0	0.35 ± 0.43	<0.15–1.4	0.30 ± 0.22
Ga	1.3–401	137 ± 79	21–355	137 ± 79	136–275	180 ± 129
Zr	<0.024–0.43	0.041 ± 0.039	<0.016–0.086	0.025 ± 0.018	<0.013–0.047	0.020 ± 0.015
Sn	<0.14–26	1.1 ± 3.2	<0.11–0.49	0.16 ± 0.073	<0.084–0.71	0.31 ± 0.028

^a weight percent; ^b 1 µg/g = 1 part per million by weight; ^c < = value below the detection limit.

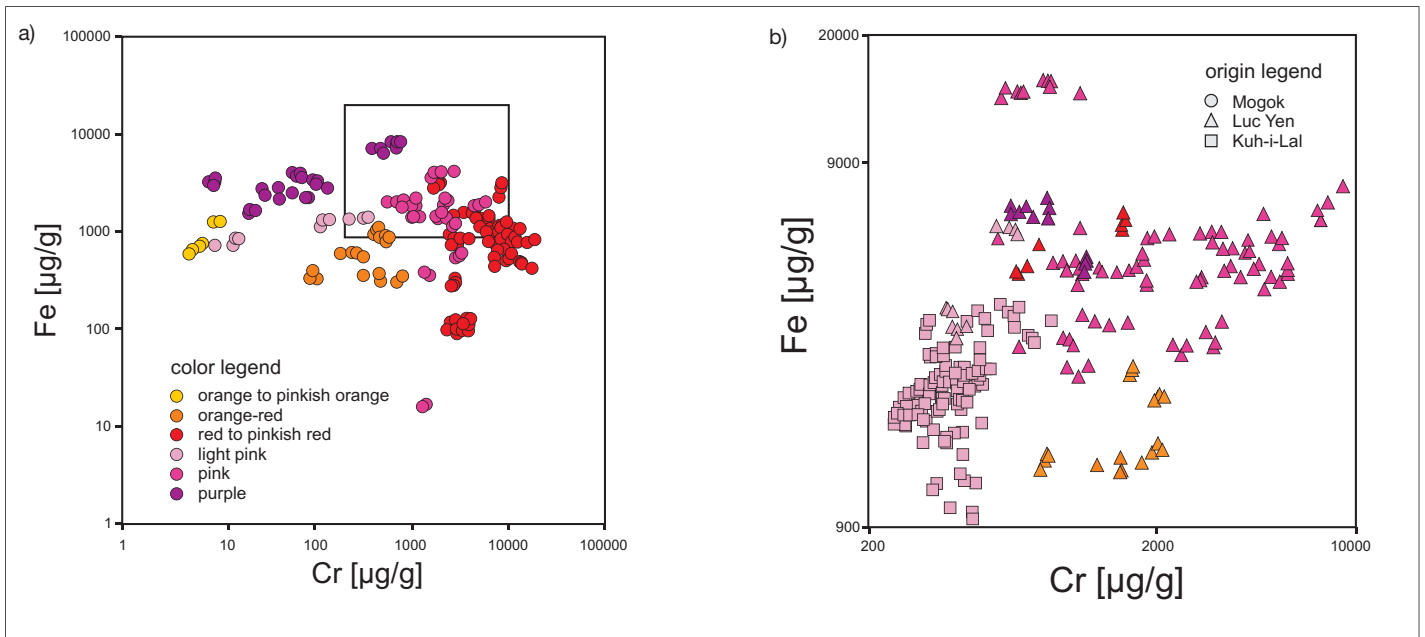


Fig. 5. Diagram showing Cr vs. Fe contents: a) Investigated spinels from Mogok show a wide range of Cr contents from 0.001 to 2.6 wt% Cr₂O₃ (5 to 18'000 µg/g), causing light pink to pink and red colors. The Fe content ranges from 0.002 to 1.2 wt% Fe₂O₃ (15 to 8'600 µg/g) and is responsible for purple colored spinels when significantly exceeding the Cr concentrations. b) Cr and Fe of spinels from Luc Yen have lower variation from 0.05 to 1.3 wt% Cr₂O₃ (346 to 8'700 µg/g) and higher Fe contents (up to 2.2 wt% Fe₂O₃) compared to samples from Mogok. Spinel from Kuh-i-Lal are quite homogeneous within Cr and Fe, as expected from their homogeneous color.

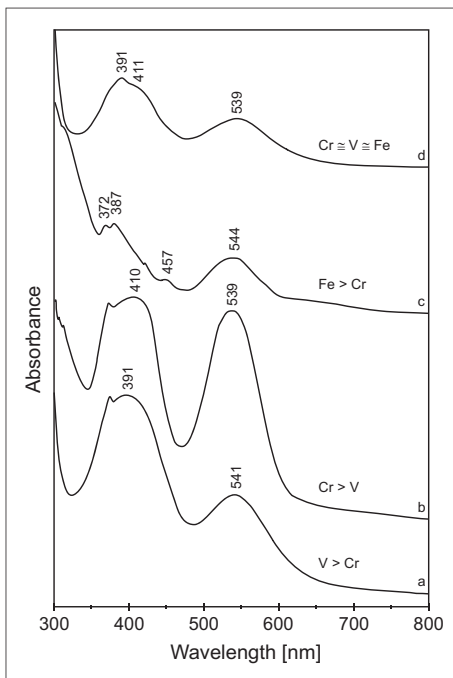


Fig. 6. Absorption spectra of spinels of type: a) V > Cr (orange-red spinel, Mogok); b) Cr > V (red spinel, Mogok); c) Fe > Cr (purple spinel, Vietnam); d) Cr ≈ V ≈ Fe. Absorption spectra b) and c) represent predominant Cr³⁺ and Fe²⁺ spectra, respectively. Absorption bands with maxima at 410, 411 and 539 nm are attributed to Cr³⁺ on octahedral sites and maxima at 372 and 457 to Fe²⁺. In spectrum a) the observed maximum at 391 nm (Cr³⁺ at 410 nm) is caused by V³⁺ [24] on octahedral sites whereas the absorption band at 539 nm represents superposition of V³⁺ + Cr³⁺ absorption. Spectrum d) shows superimposed Cr³⁺ + V³⁺ ± Fe²⁺ absorption features.

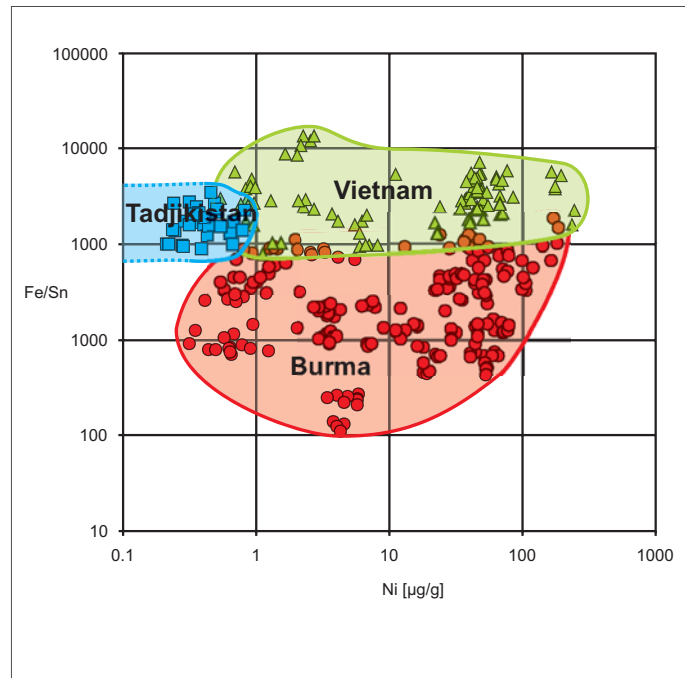


Fig. 7. Plot Ni [µg/g] versus Fe/Sn ratio by LA-ICP-MS data. Spinel from Mogok, Myanmar and Luc Yen, Vietnam show only slightly overlapping data in their Fe/Sn ratio. A proper distinction of spinels from these origins can be achieved by considering additional trace elements. Spinel from Tajikistan is characterized by Ni contents close to or below the detection limit (<0.2 µg/g).

spectra could be recorded (Fig. 6). Literature data^[24] indicate a grouping into predominantly Cr and V-bearing, Fe-bearing, Fe and Co-bearing and Fe and Mn-bearing spinels. Results of the present study comprise the first and second type only. Based on literature data,^[24] and the general principles of ligand field theory, the following assignment of absorption bands can be done. Absorption maxima at about 410 and 540 nm are attributed to Cr³⁺ (Fig. 6b) and maxima at 391 and 558

nm to V³⁺ at octahedral sites. As natural spinels usually contain both trace elements, a superposition of the individual absorption spectra is observed. Purple spinels with dominant amount of Fe showed absorption maxima at 372, 387, 457 and 544 nm (Fig. 6c). Investigations of Mössbauer spectroscopy^[25–27] indicate Fe²⁺ at tetrahedral sites to be responsible for these maxima, except the broad band at 544 nm, which results from superimposition of Cr and Fe.

Discussion

Chemical analysis showed gem-quality spinels to be almost pure $MgAl_2O_4$ end-members with Zn, Cr and Fe not exceeding 0.05 atoms per formula unit (apfu). Due to a limited presence of trace elements and similar formation condition, spinels display few origin-specific characteristics in their trace element pattern. Spinel from Luc Yen deposit in Vietnam differ mainly by high Fe and low Sn concentrations from spinels of the Mogok deposit (Fig. 7). By additionally considering V, Ti and Zr, a proper distinction of these two deposits can be achieved. The strong variation of trace elements within Mogok spinels obviously results from the widespread mining pits over a complex geological region. The dominant feature in spinels from Mogok are mineral inclusions (mostly apatite and calcite) together with octahedral negative crystals. In contrast to spinels from Vietnam and Tajikistan, no zircon inclusions were observed. However, the Mogok spinels had the highest zirconium concentrations. The presence of dislocation systems and titanite inclusions are strongly indicative features for Vietnamese spinels. The rose-tinted spinels from Kuh-i-Lal mines in Tajikistan show typically only few inclusions and generally have intermediate to low concentrations of trace elements compared to Mogok and Luc Yen spinels. A yellow surface fluorescence under short-wave UV was observed for samples from Tajikistan only. This specific fluorescence behavior was previously observed for purple-pink Tajik spinels.^[28]

In summary, it was found that despite of the quite similar geological setting, trace elements such as Ti, Fe, Ni, Zn, Zr and Sn differ for the deposits investigated. A careful examination of the trace element pattern therefore allows a differentiation of spinels from Mogok, Luc Yen and Kuh-i-Lal by chemistry only. This is a prerequisite for origin determination of spinels, which occasionally challenge gemologists by their absence of inclusions.

Acknowledgements

Hans-Georg Wild (Paul Wild OHG, Kirschweiler, Germany), Michael Hügi (Schweizerische Gemmologische Gesellschaft SGG, Switzerland), Dr. Michael Krzemnicki (Swiss Gemmological Institute SSEF, Basel, Switzerland), and Dr. Dietmar Schwarz (Gübelin Gem Lab GGL, Lucerne, Switzerland) are thanked for supplying us with additional samples. Mingling Zheng and Beryl Huber kindly performed UV-Vis spectra and refractive indices, respectively. Prof. Thomas Armbruster (Institute of Geological Sciences, University of Bern, Switzerland) kindly helped us with professional advice and discussions. Eva Wadoski is thanked for English corrections. Dr. Dietmar Schwarz is thanked for the review of the present article.

Received: June 23, 2010

- [1] R. Gerber, 'Apokalyptische Steine von Plinius und heute', Books on demand GmbH, **2002**.
- [2] C. Keferstein, 'Mineralogia Polyglotta', www.gutenberg.net, **2005**.
- [3] J. W. Anthony, R. A. Bideaux, M. C. Nichols, in 'Handbook of Mineralogy Vol. 3', Tucson, Arizona, Mineral Data Publishing, **1997**, 521.
- [4] T. Pettke, W. E. Halter, J. D. Webster, M. Aigner-Torres, C. A. Heinrich, *Lithos* **2004**, 333.
- [5] P. H. Longerich, E. S. Jackson, D. Günther, *J. Anal. At. Spectrom.* **1996**, 899.
- [6] V. Garnier, H. Maluski, G. Giuliani, D. Ohnenstetter, D. Schwarz, *Can. J. Earth. Sci.* **2006**, 509.
- [7] C. A. Hauzenberger, T. Häger, L. P. Baumgartner, W. Hofmeister, in 'International workshop on material characterization by solid-state spectroscopy: gems and minerals of Vietnam', Hanoi, **2001**.
- [8] G. Giuliani, D. Ohnenstetter, V. Garnier, A. E. Fallick, M. Rakootondrazafy, D. Schwarz, in 'Geology of gem deposits', Canada: Mineralogical Association of Canada, **2007**.
- [9] H. L. Chhibber, in 'The mineral resources of Burma', McMillan & Co, London, **1934**.
- [10] R. Kane, C. Kammerling, *Gems Gemol.* **1992**, 28, 152.
- [11] L. A. Iyer, *Memy India. Geol. Surve* **1953**, 82.
- [12] G. Bertrand, C. Rangin, *Geophysic. Res. Lett.* **2003**, 915.
- [13] V. Garnier, G. Giuliani, D. Ohnenstetter, A. E. Fallick, J. Dubessy, D. Banks, *Ore Geol. Rev.* **2008**, 169.
- [14] C. Keller, *Gems Gemol.* **1983**, 19, 209.
- [15] L. N. Rossovskiy, S. I. Konovalekno, S. A. Ananjev., *Geol. Rudnyh Mestorozhd.* **1982**, 57 (in Russian).
- [16] R. E. Kane, S. F. McClure, R. C. Kammerling, N. D. Khoa, C. Mora, S. Repetto, (1991) *Gems Gemol.* **1991**, 27, 136.
- [17] U. Schärer, P. Tapponnier, R. Lacassin, R. Leloup, D. Zhong, S. Ji, *Earth and Planetary Science Letters* **1990**, 65.
- [18] P. H. Leloup, J. R. Kienast, *Earth Planet. Sci. Lett.* **1993**, 213.
- [19] C. Suthirath, S. Lapngamchana, V. Pisutha-Armond, N. N. Khoi, in 'International symposia on geoscience Resources and Environments of Asian Terranes', Bangkok, **2008**.
- [20] D. P. Tien, W. Hofmeister, V. X. Quang, *Appl. Mineral.* **2000**, 281.
- [21] W. Schreyer, K. Abraham, K., *Contrib. Mineral. Petrol.* **1976**, 111.
- [22] M. S. Hubbard, E.S. Grew, K.V. Hodges, M. G. Yates, N. N. Pertsev. *Tectonophysics* **1999**, 325.
- [23] E. J. Gübelin, J. I. Koivula, 'Photoatlas of Inclusions in Gemstones Volume 2', Opinio Publishers, Basel, **2005**.
- [24] K. Schmetzer, C. Haxel, G. Amthauer, *Neues Jahrb. Mineral., Abh.* **1989**, 160.
- [25] K. Ono, L. Chandler, A. Ito, *Phys. Lett.* **1967**, 273.
- [26] B. Dickson, G. Smith, *Can. Mineral.* **1976**, 206.
- [27] V. V. Bukanov, A. N. Platonov, M. N. Taran, *Vses. Mineral. Osh.* **1977**, 565. (in Russian).
- [28] N. Sturman, *Gems Gemol.* **2009**, 57.