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Mineralogy and petrology of gneiss hosted corundum deposits from the Day Nui Con Voi metamorphic range, Ailao Shan–Red River shear zone (North Vietnam)

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With 10 figures and 6 tables

Abstract: Corundum deposits and occurrences are typically associated with marbles in northern Vietnam. Relatively little attention has been paid to corundum hosted by partly migmatized gneisses and pegmatoids of the Day Nui Con Voi range, Ailao Shan–Red River shear zone, North Vietnam. The partly migmatized gneisses contain gray, grayish white to bluish, and yellowish gray sapphires (*type 1*) while dark red to pinkish rubies occur in feldspathic pegmatoid rocks (*type II*). Corundum crystals from both types are short prismatic with partly hexagonal tabular shape considerably varying in size. Common inclusions are ilmenite, magnetite, rutile, plagioclase, muscovite, biotite, apatite, zircon, boehmite and iron stains. Growth structures and deformed twinning with star effect can be observed as well. *Type I* corundum is noted for high content of total Fe (5500 to 7133 ppm), low content of Cr and Ti (59 to 65 and 40 to 58 ppm, respectively), whereas, in corundum of *type II* the Fe and Cr contents are medium (1028 and 940 ppm, respectively), with low content of Ti (42 ppm). Gneisses hosting *type I* corundum are characterized by three different mineral parageneses (1) sillimanite+corundum+K-feldspar+biotite; (2) sillimanite+garnet+spinel+corundum+biotite+K-feldspar+plagioclase+ilmenite, and (3) sillimanite+garnet+spinel+corundum+clinopyroxene+ilmenite. *Type II* corundum occurs in feldspathic pegmatoid rocks consisting of a paragenesis garnet+biotite+plagioclase+K-feldspar+corundum. Sapphire in gneisses (*type I*) crystallized during regional metamorphism of silica undersaturated metapelites and metapsammites at upper amphibolite to lower granulite facies conditions. Ruby found in desilicated feldspathic rocks (*type II*) probably formed at the contact of migmatitized pegmatoid bodies with either metabasic to metaultrabasic rocks or marbles. The metamorphic P-T condition of corundum formation was estimated with 650 to 760 °C and 5.0 to 7.6 kbar based on thermobarometric calculations. $^{40}K/^{40}Ar$ cooling ages obtained from biotite in gneisses indicate that the rocks reached ~300 °C at ~23 Ma.

Key words: corundum deposit, gneiss, Day Nui Con Voi range, Ailao Shan–Red River shear zone, mineralogy, petrology, paragenesis, genetic aspects.

Introduction

For more than two decades, Yen Bai and especially the Luc Yen gem districts are well known to the international gem community for their high gem-quality corundum deposits (Fig. 1). Vietnam geologists found corundum and spinel for the first time in the An Phu marble, Luc Yen district, in 1983. At the beginning of 1987, Geological Expedition No. 3 (Geological Survey of Vietnam) discovered gem-quality corundum in alluvium at the Khoan Thong location. From this moment, a large number of gem occurrences and deposits hosted in marbles and placers were discovered in the Luc Yen district (Henn & Bank 1990, Kane et al. 1991, Pham Van Long 2003, Pham Van Long et al. 2004, Garnier et al. 2002, 2003, 2005, 2008, Giuliani et al. 2007, Nguyen Ngoc Khoi 2004, 2005, Nguyen Ngoc Khoi et al. 2010a, b).

From 1994 to 1995 several new mining sites including Tan Huong, Truc Lau, Km 13, Tan Dong, Hoa Cuong, Cam An, Bao Ai, Ngoi Nhau, Ngoi Hop (Fig. 1) were discovered to the right bank of Chay river. Additional finds in this area have continued to the present time (Tran Ngoc Quan et al. 2000). This region can be considered as the type locality for the gneiss-hosted type of corundum deposits with entirely different characteristics in Vietnam (Simandl & Paradiss 1999, Long et al. 2004, Nguyen Ngoc Khoi et al. 2010a, b, 2011, 2013).

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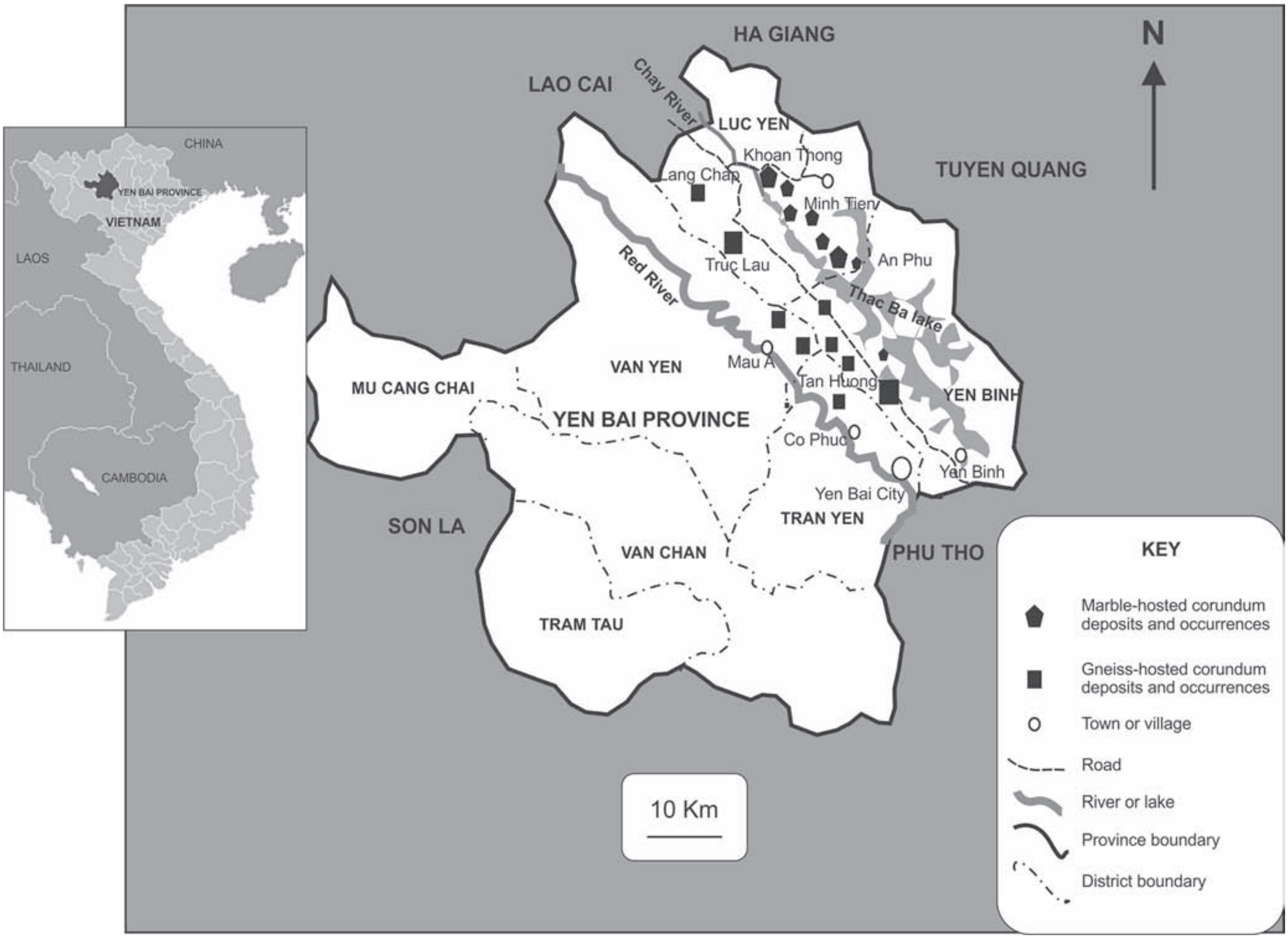

Fig. 1. Map displaying areas of marble-hosted and gneiss-hosted corundum deposits and occurrences in Yen Bai province (North Vietnam). Modified from the Yen Bai electronic map in http://www.yenbai.gov.vn.

Some aspects of this type of corundum deposits have been investigated and documented to different extents up to now. The first investigation of this type of corundum deposits in the Day Nui Con Voi range started in 1995 by Nguyen Kinh Quoc (1995), who suggested that corundum formation was related to the Tan Huong magmatic complex (Fig. 2) and is of little economic importance. Later, from 1995 to 1998, numerous corundum occurrences were documented by Vietnam National Gem and Gold Corporation (VIGEGO) with the aim to put them into production (To Xuan Voi 1991, Nguyen Huu Thang 1998). The economic potential of this deposit type was also mentioned by Tran Ngoc Quan et al. (2000), Hofmeister (2001a, b), Pham Van Long et al. (2004). Specifically, Phan Trong Trinh et al. (1998, 1999), Garnier et al. (2002, 2003, 2005, 2008), and Giuliani et al. (2007) clearly showed the relationship of the ruby-bearing formation with the high-temperature metamorphism of the Ailao Shan–Red River shear zone during the Neogene.

Corundum deposits in the gneisses of the Day Nui Con Voi (DNCV) range have supplied rubies (especially star rubies), and a few fancy-colored sapphires with mineralogical and gemmological characteristics essentially different from those rubies and sapphires coming from the marble-hosted deposits in the nearby Lo Gam tectonic zone. This is because they have formed in different geological units and different protoliths due to different sedimentation and paleogeography. Until now, no systematic investigation and documentation of this type of corundum deposits was undertaken. Thus, this article describes the general geology of the Day Nui Con Voi range, reports the mineralogical characteristics of primary corundum and the P-T conditions of metamorphic overprint of gem-bearing rocks. Finally we discuss the formation of the gneiss-hosted corundum deposits and compare it with those from the marble-hosted type of the nearby Lo Gam structural zone.

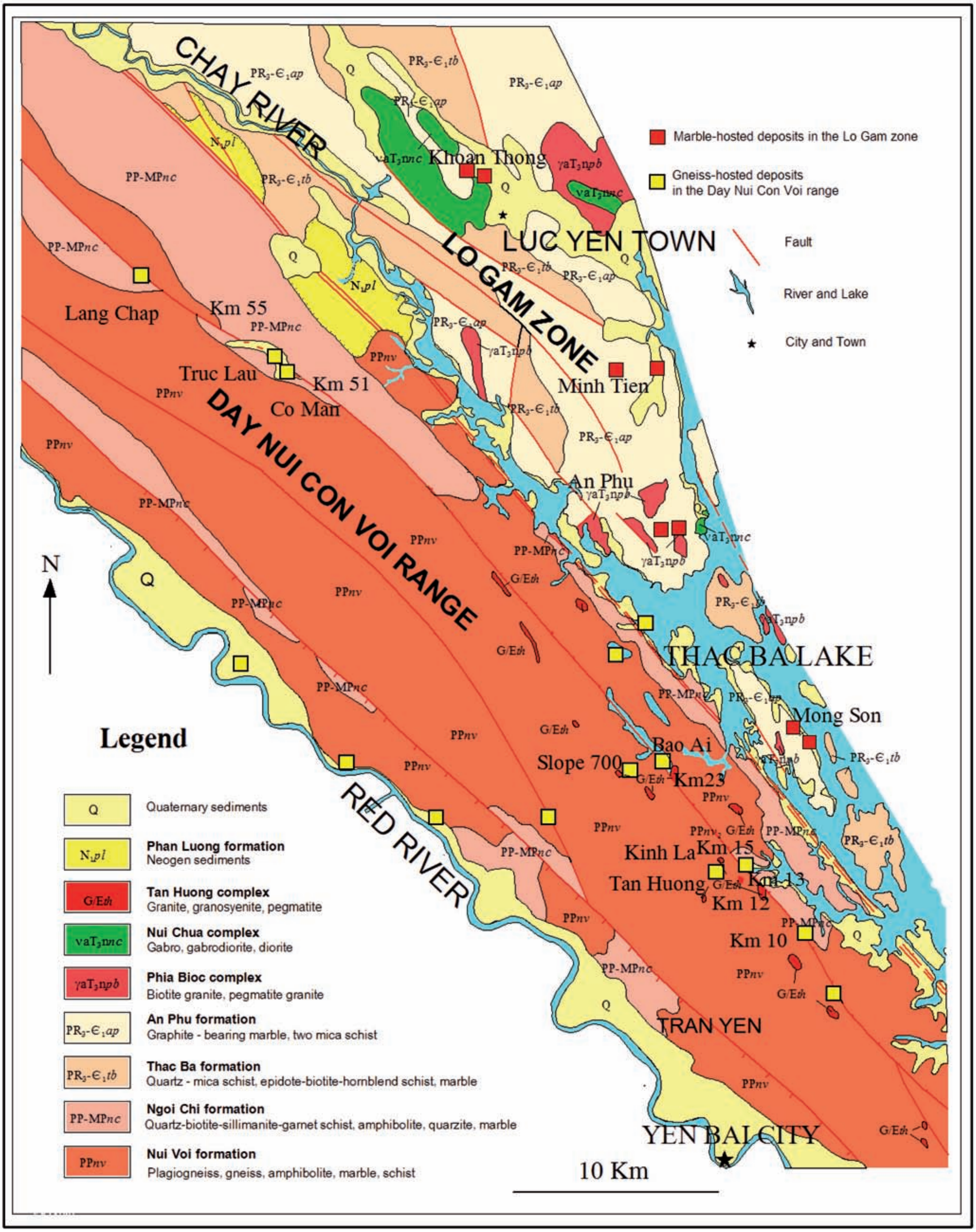

Fig. 2. Simplified geologic map showing the locations and rock formations of the gneiss-hosted corundum deposits and occurrences in the Day Nui Con Voi range and marble-hosted deposits and occurrences in the adjacent Lo Gam structural zone. (Modified after Geological and Mineral Resources Map of Vietnam, scale 1:200.000, sheet Bac Quang 2000, ed. Tran Xuyen, and sheet Yen Bai 2005, ed. Nguyen Vinh).

Geological setting

Gneiss-hosted corundum deposits and occurrences are located mostly within the Day Nui Con Voi range, which stretches from Lao Cai province southeastward to Yen Bai province. This mountain range is bound by lateral strike-slip faults (Fig. 2) forming a major Cenozoic geological discontinuity in Southeast Asia known as the Ailao Shan–Red River shear zone (Tapponier et al. 1990, Phan Trong Trinh et al. 1999, Leloup et al. 2001).

Rock types within the Day Nui Con Voi range are mainly plagioclase-rich gneiss, diopside gneiss, biotite-garnet gneiss, and quartz-sillimanite-garnet gneiss intercalated with biotite-sillimanite schist and lenses of amphibolite and marble; they are grouped as the Nui Voi Formation (Fig. 2). These rocks lie underneath the Ngoi Chi Formation, which comprises quartz-mica schist, sillimanite schist, and garnet schist (Pham Van Long et al. 2004, Nguyen Van Nam 2012, Garnier et al. 2008). Both rock formations were intruded by granite, syenite, and pegmatoid of the Tan Huong magmatic complex, which crystallization age is about 270–245 Ma (Garnier et al. 2003). However, Ar/Ar cooling ages on mica gave 22–25 Ma which is related to the activity of the Red River shear zone (Garnier et al. 2002, Nguyen Van Nam 2012).

Corundum-bearing, stratabound and discontinuous layers and lenses in gneisses are essentially from tens of centimeters to a few meters in thickness and may reach tens of meters along strike (e.g. Co Man). These layers are commonly strongly deformed, with coarse-grained “sweat outs” which may cut across the schistosity of the surrounding rocks. According to our observations, primary corundum in the Day Nui Con Voi range can be grouped into three main types, which are found in three different kinds of host rock and at different locations (Figs. 1 and 2):

– *Type I:* Gray, grayish white to bluish, and yellowish gray sapphires, with some pinkish sapphires, embedded in gneisses and migmatitized gneisses, e.g., Co Man outcrop at Truc Lau valley (Fig. 3a), Khe Nhan and Kinh La (Fig. 3b), Km51, Km 53, Km55 (National road 70), Tang Chang, and Lang Chap outcrops (Fig. 2; Pham Van Long et al. 2004, Nguyen Van Nam 2012, Nguyen Thi Minh Thuyet 2008).

– *Type II:* Dark red to pinkish, sometimes centimeters to tens of centimeters-sized, ruby crystals in weathered feldspathic (pegmatoid) rocks, developed in gneisses, e.g., Slope 700 occurrence (Fig. 3c), occurrences Km 13, Km 15, Km 23, etc. along National Road 70 (Nguyen Van Nam 2012).

– *Type III*: Rubies in marble lenses intercalated within gneiss, mica schist, and amphibolite, e.g., Slope 700 outcrop (Bao Ai occurrence), Tan Huong drill core (Pham Van Long et al. 2004), and DOJI’s Truc Lau mine.

For this study, corundum bearing rocks with embedded rubies and sapphires only from *type I* and *type II* were documented in detail from 4 outcrops which are located mainly along the National road 70 from Yen Bai city to Lao Cai, e.g. outcrops Km 10, Km 13 (Kinh La), Km 19, Km 20 (Cam An), Km 23 (slope 700 or Bao Ai), Km 51, Km 53, Km 55 (Truc Lau) (Fig. 2).

(1) Km 10 outcrop (type I): This outcrop is located at 104° 54′ 30″ N; 21° 47′ 59″ E. Corundum-bearing lenses are found in partly migmatized biotite-sillimanite-garnet gneisses of Con Voi formation. Most corundum crystals are of small size (0.5–2 cm), gray to black gray in color (Fig. 4a).

(2) Kinh La (Km 13) outcrop (type I): This outcrop is located 2 km southwest of Tan Huong mine, at 21° 48′ 55″ N, 104° 52′ 12″ E. The gem-bearing body is 0.1–1 m thick and 100 m long. Corundum ranges in color from black to bluish gray, and from 0.1 to 5 cm in size (Fig. 3b, Fig. 4 a).

(3) Slope 700 (Km 23) occurrence (type II): The occurrence is located at 21° 52′ 28″ N, and 104° 59′ 50″ E, 10 km north-west of Tan Huong mine, and consists mainly of quartz-biotite-sillimanite ± garnet gneiss, intercalated with sillimanite ± garnet schist and amphibolite lenses. Ruby crystals were found embedded in leucosome, pegmatite-like (pegmatoid) bodies which developed within the migmatized gneiss (Fig. 3c). These ruby-bearing irregular shaped bodies protruded amphibolite and schist and are 10 to 50 m long, and 0.5 to 2 m thick. Ruby crystals usually have a large size (Fig. 4b).

(4) Co Man – Km 51 outcrop (type I): The outcrop is located at 22° 02′ 05″ N, 104° 40′ 46″ E, and consists of biotite, biotite-sillimanite ± garnet gneisses. Corundum crystals were found in plagioclase-rich zones, which are up to 50 m long and 1 m wide (Fig. 3a, Fig. 4 a).

In contrast, the marble-hosted corundum deposits in the nearby Lo Gam structural zone (Khoan Thong-An Phu area or Luc Yen area) occur in a thick metasedimentary sequence of Cambrian sedimentation age, composed of marble and overlying sillimanite-biotite-garnet schist (Fig. 2). These units, bounded by left-lateral faults, are intruded by granitic rocks and related pegmatoids of Triassic age (Phan Trong Trinh et al. 1998, 1999). Primary ruby occurs (a) as crystals disseminated in marble and associated with phlogopite, magnesian tourmaline, margarite, pyrite, rutile and graphite; (b) in veinlets, associated with calcite, magnesian tourmaline, pyrite, margarite and phlogopite, and (c) in fissures, associated with graphite, pyrite, phlogopite and margarite (Pham Van Long 2003, Garnier 2003, Garnier et al. 2005).

Analytical methods

For this study, corundum material of the *types I* and *II* with their host rocks, and also corundum from placer deposits of Tan Huong and Truc Lau, were collected over several years during various scientific projects from different places within the Day Nui Con Voi range.

Mineral chemical analyses were performed by EPMA with a JEOL JXA-8200 electron microprobe at the UZAG Eugen Stumpfl Electron Microprobe Laboratory (University of Leoben, Karl-Franzens University of Graz, Graz University of Technology) in Leoben. An accelerating voltage of 15 kV, a beam current of 10 nA, count times of 60 seconds on peaks and 30 seconds on background, and a beam diameter of ~1 µm were used. Typical detection limits for most elements were in the range of 0.01–0.02 wt.%. Mineral formulae were calculated with the PET Mathematica package (Dachs 1998).

Trace elements in corundum were measured quantitatively using an Agilent 7500 ICP-MS joined to an ESI NWR193 laser-ablation sampling system at the NAWI Graz Central Lab for Water, Minerals and Rocks, University of Graz and Graz University of Technology. The laser was operated at a wavelength of 193 nm with He as carrier gas (flow rate of ~0.6 liter/minute). Laser-ablation parameters were as follows: 40 µm spot diameter, ~8 J/cm^2 laser energy density (fluence), 10 Hz repetition rate, and 60 seconds laser dwell time. For calibration, NIST SRM 610, 612, and 614 glass reference materials (Pearce et al. 1997) were used as external standards, while Al was used as internal standard.

Spectroscopical investigations were carried out at the Institute of Geosciences, Johannes Gutenberg-University Mainz, Germany. Ultraviolet/visible/ near-infrared (UV-Vis NIR) spectroscopic measurements over 250–900 nm range were performed with a PerkinElmer Lambda 950 spectrophotometer, equipped with an integrating sphere and operating with a spectral resolution of 0.05 nm for UV-Vis and 1 nm for NIR.

Corundum has been indirectly dated using the $^{40}K/^{40}Ar$ laser stepwise heating technique on purified syngenetic biotite from corundum deposits in Tan Huong–Truc Lau

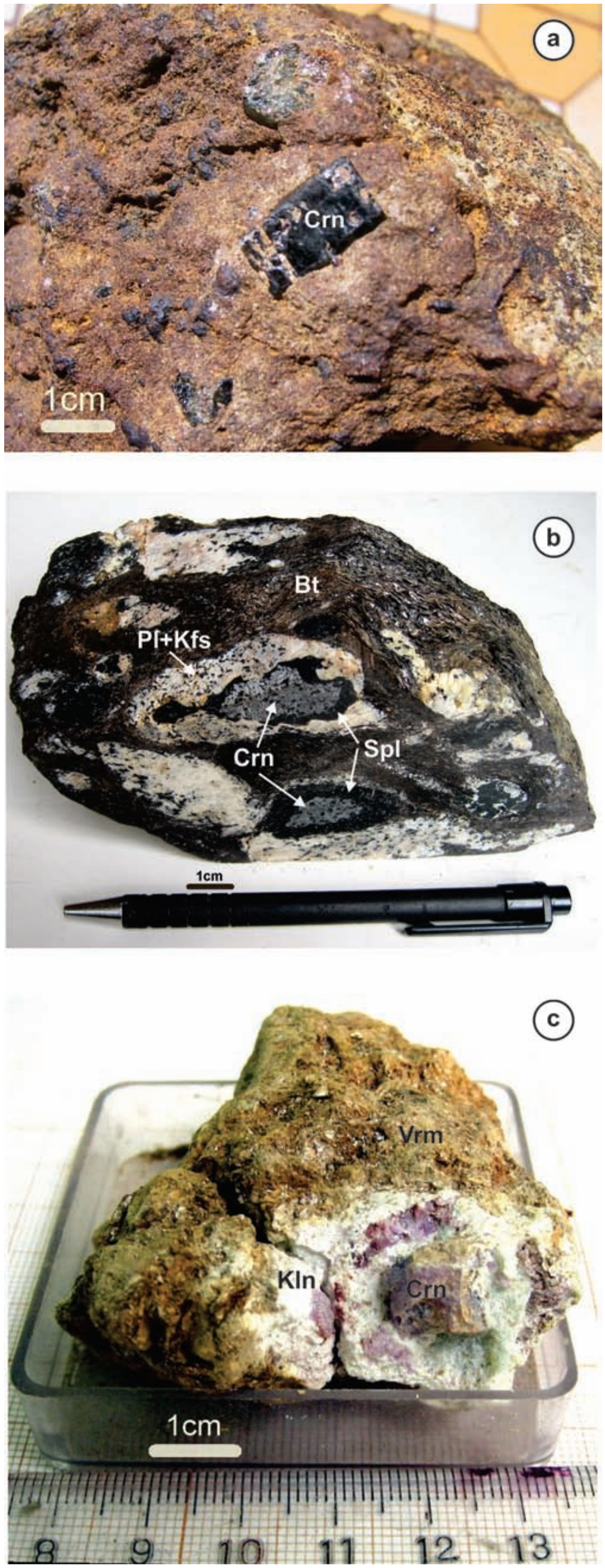

Fig. 3. Photographs of the main gem-bearing rocks with primary corundum from Day Nui Con Voi range. (a) Gneiss from Co Man (sample 5046Co/2), containing idiomorphic, prismatic crystals of sapphire. The size of the biggest sapphire crystal (in front) is about 20 × 7 mm. (b) Migmatic gneiss from Kinh La (sample H. 7005). Corundum (gray, in center) is rimmed by a spinel (hercynite) layer (black), which is again surrounded by feldspar. (c) Ruby-bearing feldspathic pegmatoid rock from Slope 700 occurrence (sample SH700). Symbols: Crn: corundum, Pl: plagioclase, Kfs: K-feldspar, Bt: biotite, Spl: spinel, Vrm: vermiculite, Kln: kaolinite.

area. Biotite was separated from the fresh host gneisses by crushing with a jaw crusher and enriching with gravitational and magnetic methods. After selection under a binocular, the samples (grain size 200–400 µm) were cleaned with deionized water, acetone and alcohol. Analyses of K and Ar from biotite separates and calculation of ages and errors were carried out at the Research Institute of Natural Sciences, Okayama University of Science (Japan), following the methods described by NAGAO et al. (1984) and ITAYA et al. (1991). Potassium was analyzed by flame photometry using a 2000-ppm Cs buffer with an analytical error within 2 % at a 2 σ confidence level. Argon was analyzed on a 15-cm radius sector type mass spectrometer with a single collector system using the isotopic dilution method and ^{38}Ar spike. Multiple runs of the standard (JG-1 biotite, 91 Ma) indicate that the error of argon analysis is about 1 % at a 2 σ confidence level (ITAYA et al. 1991). The decay constants of ^{40}K to ^{40}Ar, and ^{40}Ca, as well as the ^{40}K content in potassium used in the age calculations are 0.581×10^{-10}/year, 4.962×10^{-10}/year, and 0.0001167, respectively (STEIGER & JAGER 1977).

Characteristics of primary corundum from the Day Nui Con Voi range

Being found in different host rocks, primary corundum of the two above-mentioned types have different mineralogical and gemmological characteristics, which are listed in Table 1.

Crystal structure, morphology and visual appearance

Two main crystal forms dominate the morphology of primary corundum of *type I* (colored sapphires) and *type II* (rubies): (1) Prismatic crystal habits composed of hexagonal prism a {1120} and basal pinacoid c {0001} and (2) a modification of this habit, with the addition of positive rhombohedron r {$10\bar{1}1$} (Figs. 4a, b). Crystal size varies considerably from several millimeters to tens and sometimes hundreds of millimeters. The color of corundum crystals is gray, white, yellowish (*type I*) (Figs. 4a, c) as

Table 1. Characteristics of primary corundum from the Day Nui Con Voi range, North Vietnam.

Properties	Type I	Type II
Color	Colorless, spotted gray to spotted yellowish gray, spotted bluish or greenish gray	Dark red, red to pink, violetish pink
Diaphaneity	Poor to moderate clarity and opaque to translucent.	Poor to moderate clarity and opaque to translucent; sometime semitransparent to transparent
Specific gravity	3.95–4.02	3.91–3.99
Refractive Indices	n_e = 1.762–1.765 n_o = 1.768–1.772	n_o = 1.762–1.763 n_e = 1.770–1.772
Birefringence	0.008–0.009	0.008–0.009
Optic character	Uniaxial negative	Uniaxial negative
Pleochroism	Weak to moderate *Yellowish gray*: gray to yellowish, gray to greenish	Moderate *Dark red to red, pink*: violet to violetish red, orange to orangy red
UV luminescence	Inert under both LW and SW	–LW: Moderate to weak red –SW: Weak red
Optical absorption spectrum	*Bluish to bluish gray and bluish white (Fig. 6d):* 375, 388 nm, 450 nm (Fe^{3+}) and 550 nm (Fe^{2+}/Ti^{4+})	*Purplish red to purplish pink (Fig. 6a, b, c):* 388 nm (Fe^{3+}), 411 nm and 548 nm (Cr^{3+})
Internal features	Weak to prominent growth structures, parting, rarely color zoning. Biotite, ilmenite, magnetite, zircon, plagioclase, muscovite, apatite, chlorite, rutile. Fractures, deformation twinning, “fingerprints,” primary and secondary liquid and liquid-gas inclusions	Weak to prominent growth structures, parting, rarely color zoning. Rutile (“silk”, cloud”, “star”), plagioclase, zircon, spinel, muscovite, biotite, ilmenite, apatite, boehmite, diaspore. Fractures, deformation twinning, “fingerprints,” primary and secondary liquid (feathers) and liquid-gas inclusions

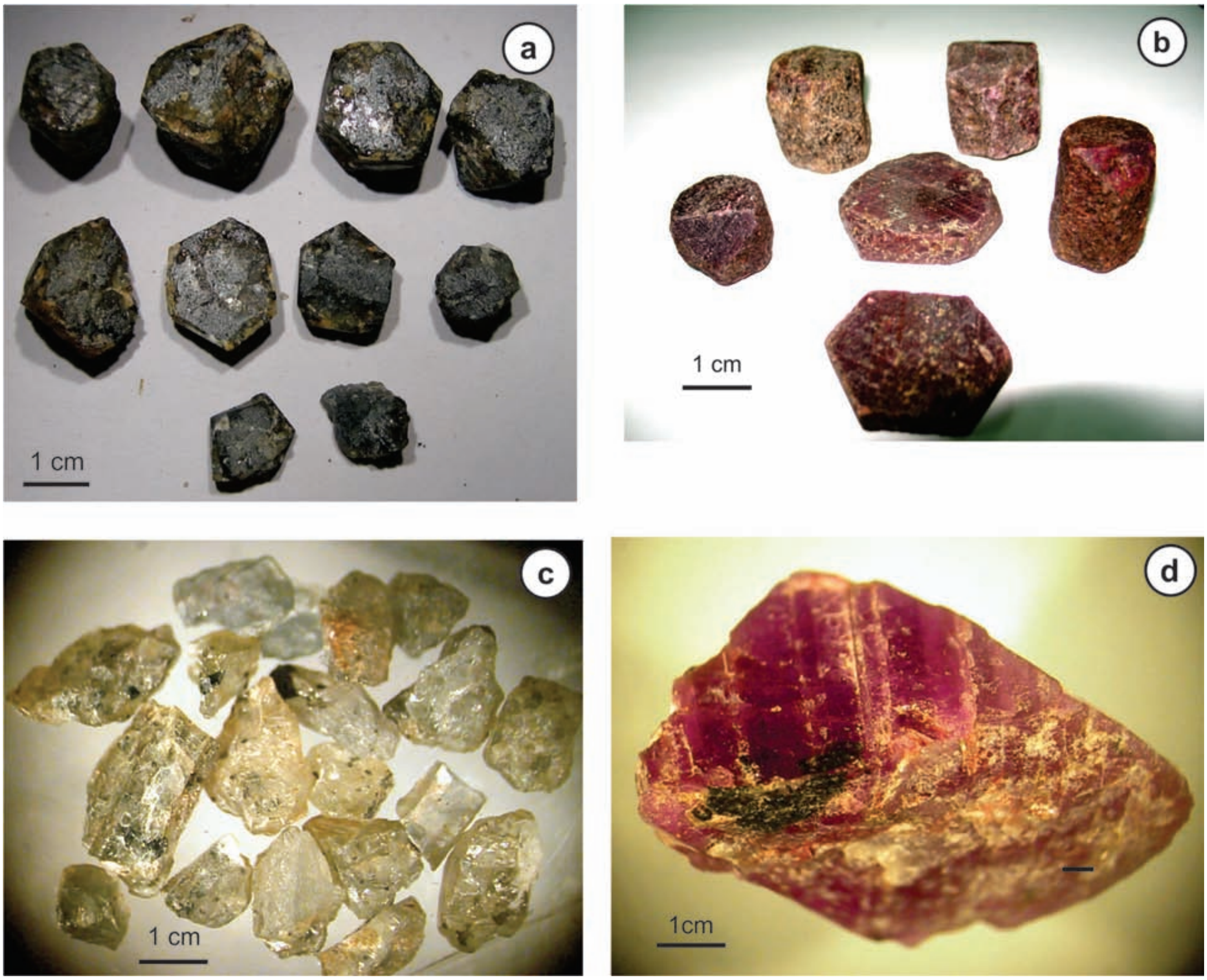

Fig. 4. Typical short prismatic shape of primary corundum of type I (a) and of type II (b). The various colorations of these corundum vary from dark bluish gray (a) and yellowish gray (c) for type I to dark brownish red (b) and pink to pinkish red (d) for type II.

well as dark red, pink to purplish or brownish pink (*type II*) (Figs. 4b, d). "Pure" red and blue are much rarer than pink and other colors, green and yellow almost absent. Most samples range from semitransparent, translucent to nearly opaque. A remarkable feature of primary corundum from the Day Nui Con Voi range is growth zoning (straight and angular) and asterism; about 30 % of the gem-quality stones from the area show a star effect. Both phenomena can be observed in the same stones. Other color irregularities such as spots, streaks, and patches do not occur in these corundums. Another distinct visual characteristic is a coronitic aggregate layer of spinel coating some of the corundum crystals which may have a deep red color (Häger et al. 2010, Hauzenberger et al. 2010).

Physical properties and internal features

Refractive indices, birefringence, and specific gravity of corundum samples fall within the reported range for corundum (Webster 1994, Hughes 1997, Nguyen Ngoc Khoi et al. 2011). In corundum from both types we discovered various mineral inclusions: ilmenite (Fig. 5a), magnetite (Fig. 5b), zircon (Fig. 5c), plagioclase, muscovite, biotite, rutile ("silk", "cloud" and "star"), apatite, chlorite, diaspore, etc. Of these, the darker inclusions (biotite, ilmenite, and magnetite) are more common in *type I*. Also frequently encountered are liquid, liquid/gas (Fig. 5d) inclusions, growth structures, fractures and fissures, as well as orange coloured iron stains. We observed a wide range of fluid inclusions that showed various stages of healing,

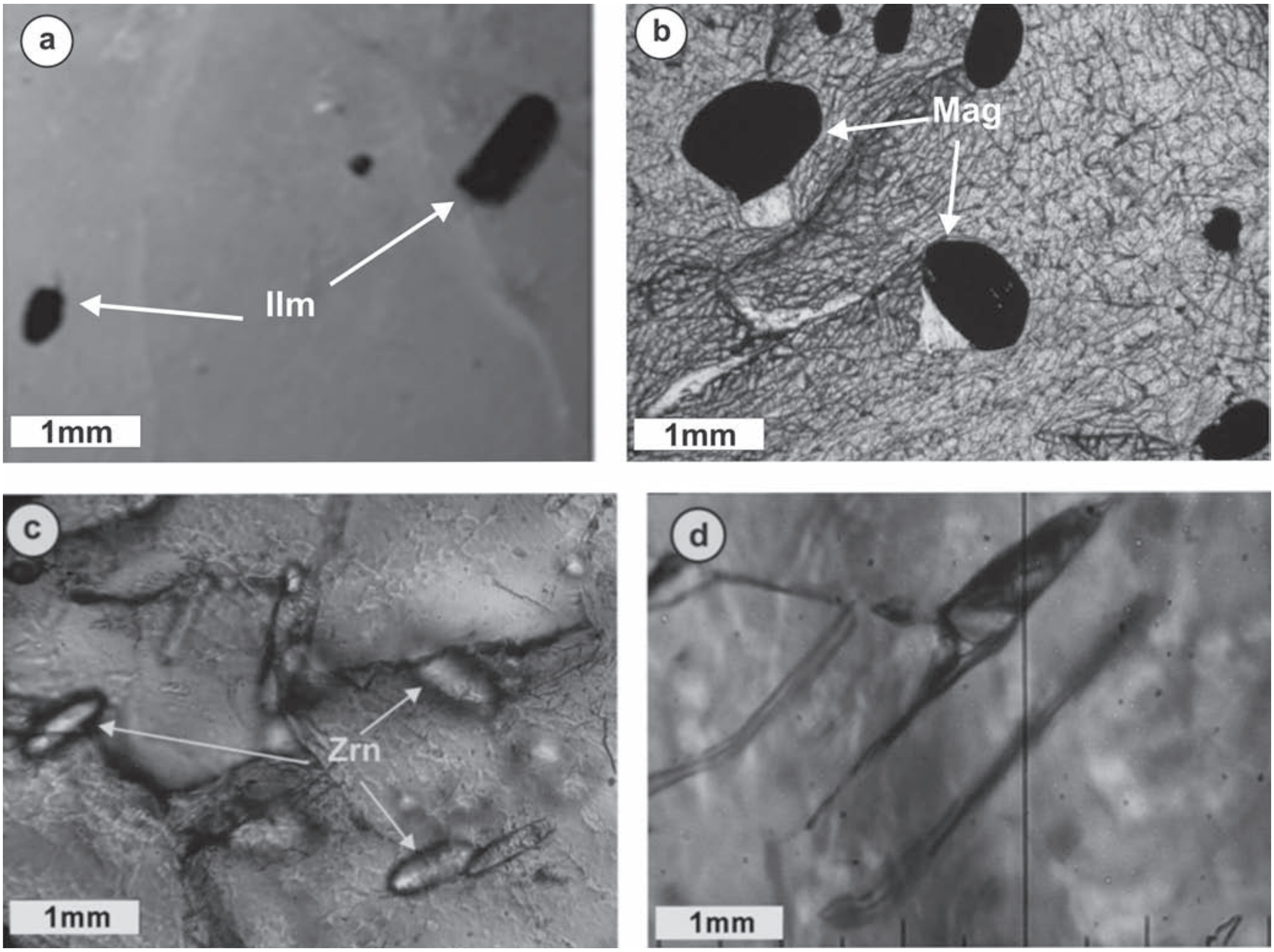

Fig. 5. Photographs of various inclusions in primary corundum from the Day Nui Con Voi range. (a) Under stereomicroscope, in cabochon-cut stone of type II corundum, sample TH2/2, magnified 64×. Ilmenite inclusions. (b) Under polarizing microscope, transmitted light, nicols //, sample H7005. Magmetite inclusions in type I corundum. (c) Under polarizing microscope, transmitted light, nicols //, sample H5046Co. Zircon inclusion in type I corundum. Note the prismatic shape of zircon crystals. (d) Under polarizing microscope, transmitted light, nicols //, sample H5046Co. Gas-liquid inclusions, sample H5046/Co. Symbols: Mag: magnetite, Ilm: ilmenite, Zrn: zircon.

forming negative crystals, feathers, folded patterns, and irregular fluid droplets. A more detailed study about the gem properties and inclusions is found in Nguyen Ngoc Khoi et al. (2011, 2013).

Chemistry

The chemical data for trace elements in primary corundum from the DNCV range are summarized in Table 2 a. In general, primary corundum of *type I* shows high contents of Fe (5500 to 7133 ppm) and low contents of Ti and Cr (59 to 65 and 40 to 58 ppm, respectively). In contrast, primary corundum of *type II* contains the high levels of both Cr and Fe measured in this study (940 and 1028 ppm, respectively) with low content of Ti (42 ppm). Other elements, such as Ga, Mg and V, were found in all samples of both corundum types, although with low contents. It is interesting to note here that ruby and pink sapphire from placer deposits in the Day Nui Con Voi range (Table 2 b) also contain high contents of both Cr and Fe (1077 to 1249 ppm for Cr, and 880 to 1325 for Fe).

The presence and valence state of trace elements in corundum from the Day Nui Con Voi range have been proved by absorption spectra. In *type I* corundum most of the Fe occurs as Fe^{3+} (sample H5406, Fig. 6d). Fe^{2+} is only detectable in blue sapphires via the Fe^{2+}/Ti^{4+} IVCT (Fritsch et al. 1988a). In *type II* corundum Fe mostly occurs as Fe^{3+} (samples H700/1, H700/3 and TH2, Fig. 6a–c), and red to pink color of this type is caused by dispersed Cr^{3+} ions (Fritsch et al. 1987). The presence of Fe^{3+} ions here appears to make the tone of the stones darker (Hughes 1997).

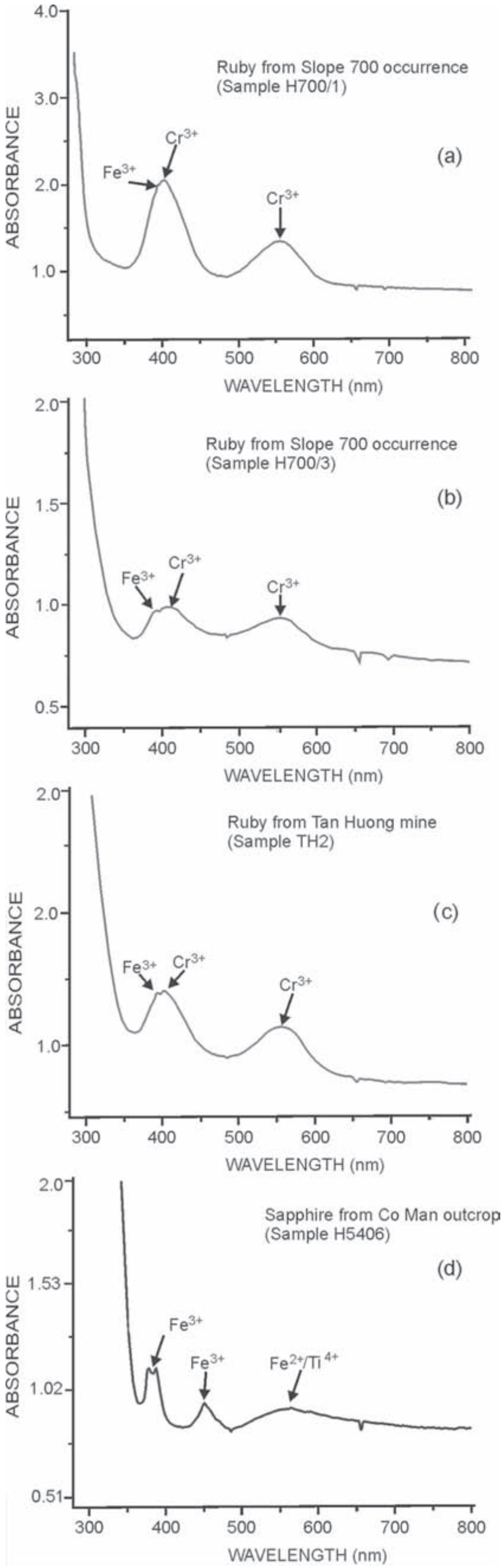

Fig. 6. UV-VIS absorption spectra of rubies and sapphires of type II (a-c) and type I (d) from the Day Nui Con Voi range.

Petrography of host rocks and mineral parageneses

Partly migmatic gneisses hosting *type I* corundum (Figs. 7a, b) are described in detail for the first time. They are characterized by the following parageneses: (1) sillimanite+corundum+K-feldspar+plagioclase+biotite, (2) sillimanite+garnet+spinel+corundum+biotite+K-feldspar+plagioclase+ilmenite, and (3) sillimanite+garnet+spinel+corundum+muscovite+ilmenite (Figs. 7a–f). Feldspathic pegmatoid rocks, due to high level of weathering alteration, could only be studied to some extent (Fig. 3c).

Corundum bearing gneisses (type I)

Samples from three different outcrops, Co Man (Truc Lau mine), Kinh La and KM10, were investigated in detail:

(1) *KM10 outcrop:* Besides corundum bearing gneisses, corundum bearing feldspathic-pegmatoid rocks and corundum free ultramafic rocks occur. The partly migmatic gneisses contain the mineral assemblage sillimanite +biotite+plagioclase+ilmenite+garnet+hercynite+apatite ± magnetite. The samples show cm sized garnet crystals with abundant ilmenite and apatite inclusions (Figs. 8a, b). Corundum and spinel occur within the plagioclase matrix as 0.5–2 cm sized crystals. Garnet is iron rich with X_{Alm} of ~0.88. Biotite has a low X_{Mg} with ~0.2 and TiO_2 content of up to ~4 wt%. Again no F and Cl could be detected. Spinel is a nearly pure hercynite with low MgO content (< 2 wt.%) and very low contents of Cr and V. The matrix consists mainly of plagioclase, which contains ~77 mol.% albite. Selected mineral analyses are presented in Tables 3 a–d.

(2) *Co Man (Truc Lau mine):* The main rock type at Co Man outcrop comprises mainly sillimanite+biotite+ilmenite ± garnet ± hercynite ± magnetite bearing migmatic gneiss which contains a lot of bluish to whitish gray prismatic sapphire crystals. The size of the corundum crystals varies from millimeters to 6–7 cm occurring in a plagioclase ± K-feldspar rich matrix (Fig. 3a). Garnet (sample KM55) is almandine and pyrope rich (X_{Alm} = 0.63, X_{Prp} = 0.28) while grossular and spessartine components are very low (< 0.05). The garnet composition across a ~0.5 cm large garnet crystal (sample KM55) displays a homogeneous central part but an increase in Alm and to a lesser extent in Sps and decrease in Prp and Grs component at the rim. Spinel is always nearly pure hercynite without Zn and Cr. Biotite occurs as mm sized flakes, has a X_{Mg} of ~0.40 and variable TiO_2 contents between different samples from the same outcrop of c. 1.7–4.5 wt.%. Plagioclase is albite rich (X_{Ab} = 0.63–0.76),

Table 2. a. Trace elements contents of corundum from primary deposits in the Day Nui Con Voi range[a].

Element (ppm)	Type I		Type II
Locality	Co Man outcrop	Kinh La outcrop	Slope 700 outcrop
Color	Bluish gray	Bluish gray	Dark to purplish red
No of samples	9	3	9
Ti	29–97 (58)	16–81 (40)	41–42 (42)
Cr	37–109 (65)	55–62 (59)	908–984 (940)
Fe	5923–8012 (7133)	5119–5717 (5500)	981–1075 (1028)
V	5–10 (8)	18–20 (19)	65–71 (67)
Ga	70–115 (95)	49–50 (49)	48–55 (51)
Mg	5–74 (33)	2–4 (4)	27–92 (50)

[a] Analyzed by LA-ICP-MS, average of 3 analyses per sample. In parentheses: average contents of elements.

Table 2. b. Trace elements contents of corundum from placer deposits in the Day Nui Con Voi range[a]

Element (ppm)	Tan Huong placer		Truc Lau placer
Color	Pink to red and dark red	Gray to dark blue	Pink to red
No of samples	8	5	7
Ti	49–422 (150)	28–512 (221)	42–534 (187)
Cr	247–2121 (1077)	7–167 (65)	250–4160 (1249)
Fe	17–2241 (880)	68–7529 (2243)	179–3356 (1325)
V	5–157 (65)	5–62 (23)	6–238 (108)
Ga	27–100 (52)	21–93 (58)	21–68 (34)
Mg	23–88 (51)	17–739 (216)	41–1121 (234)

[a] Analyzed by LA-ICP-MS, average of 3 analyses per sample. In parentheses: average contents of elements.

K-feldspar contains up to 22 mol.% albite component. Accessory minerals are magnetite, ilmenite, and zircon. Quartz is usually not present. Selected mineral analyses are presented in Tables 3 a–d.

(3) *Kinh La occurrence:* corundum occurs in a sillimanite+biotite+plagioclase+K-feldspar+ilmenite ± garnet ± hercynite ± magnetite migmatic gneiss. In some samples a hercynite corona forms around corundum (Fig. 3b). In general, minerals from this outcrop are extremely iron rich. Magnetite and ilmenite are frequently encountered either as inclusions in corundum, spinel and garnet or as single phases in the matrix. Garnet was only observed in one sample and has an almandine content of c. 80 mol.%, grossular and pyrope content of c. 10 mol.% each while spessartine component is lower than 5 mol.%. Biotite is nearly pure annite with some Tschermak substitution and up to 5 wt.% TiO_2. No F and Cl could be detected. Spinel is nearly pure hercynite with very low V and no Cr and Zn contents. The feldspathic matrix consists usually of plagioclase with X_{Ab} of ~0.75 and K-feldpsar with albite content of about 25 to 30 mol.%. Selected mineral analyses are presented in Tables 3 a–d.

Associated ultrabasic rocks

Within the KM10 outcrop, mafic rocks occur which are described as amphibolites in geological maps. However, the investigated sample (KM10 a) is an ultrabasic rock containing the assemblage olivine+orthopyroxene+magnesiohornblende+spinel (Fig. 8c). Orthopyroxene occurs as mm-sized grains and has a X_{Mg} of ~0.84. Olivine is found as 0.5–1 mm grains without any inclusions and has a X_{Mg} of 0.8. Amphibole is the dominant mineral in the sample with prismatic grains of max. several mm. According to Leake et al. (2004), it can be classified as magnesiohornblende with a X_{Mg} of 0.95. Spinel is found as intra-cumulus phase with small elongated grains. It displays a X_{Mg} of 0.65 and a X_{Cr} (= Cr/[Cr+Al]) of > 0.1. Selected mineral analyses are presented in Table 4.

Table 3. a. Representative garnet analyses from the DNCV range.

	KM10 g12	R7005	504660	H70052d
Locality	km10	Con Ma	Con Ma	Kinh La
SiO_2	36.21	38.87	38.88	37.26
Al_2O_3	20.69	21.86	22.16	21.08
FeO	39.24	29.23	28.04	33.67
MnO	0.46	1.25	0.96	1.19
MgO	1.77	7.37	8.87	2.68
CaO	1.00	2.21	2.06	3.13
Total	99.37	100.79	100.97	99.01
Si	2.971	3.007	2.973	3.015
Al	2.001	1.990	1.995	2.010
Fe^{3+}	0.058	0.000	0.067	0.000
Fe^{2+}	2.634	1.889	1.724	2.278
Mn	0.032	0.082	0.062	0.082
Mg	0.216	0.849	1.010	0.323
Ca	0.088	0.183	0.169	0.271
Sum	8.000	8.000	8.000	7.979
X_{mg}	0.076	0.310	0.369	0.124
X_{alm}	0.887	0.629	0.581	0.771
X_{prp}	0.073	0.283	0.341	0.109
X_{grs}	0.030	0.061	0.057	0.092
X_{sps}	0.011	0.027	0.021	0.028

Table 3. b. Representative biotite analyses from the DNCV range.

	KM10b13	R7005	504621	H70052d	H7005bt3
Locality	km10	Con Ma	Con Ma	Kinh La	Kinh La
SiO_2	31.92	35.69	39.73	34.14	32.02
TiO_2	3.80	4.52	1.68	4.82	5.08
Al_2O_3	18.34	17.17	16.54	17.60	18.75
FeO	27.02	14.52	20.70	26.50	29.90
MnO	< 0.15	0.02	0.17	0.24	0.00
MgO	4.10	12.83	7.99	4.42	0.60
CaO	0.09	< 0.1	< 0.1	< 0.1	< 0.1
K_2O	8.89	9.39	8.62	7.67	9.02
Na_2O	0.29	0.14	1.00	1.13	0.24
Total	94.45	94.28	96.43	96.52	95.61
Si	2.568	2.687	2.972	2.652	2.576
Ti	0.230	0.256	0.094	0.282	0.307
Al	1.739	1.524	1.458	1.612	1.778
Fe^{3+}	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	1.818	0.914	1.295	1.722	2.012
Mn	0.000	0.001	0.011	0.016	0.000
Mg	0.492	1.440	0.891	0.512	0.072
Ca	0.008	0.000	0.000	0.000	0.000
K	0.912	0.902	0.823	0.760	0.926
Na	0.045	0.020	0.145	0.170	0.037
Sum	7.812	7.744	7.689	7.726	7.708
X_{mg}	0.213	0.612	0.408	0.229	0.035

Table 3. c. Representative feldspar analyses from the DNCV range.

	KM10pl5	504621	504664	H70052d	H70052d
Locality	km10	Con Ma	Con Ma	Kinh La	Kinh La
SiO_2	62.66	60.74	64.66	65.11	62.44
Al_2O_3	23.33	23.93	18.26	18.90	23.01
FeO	0.11	0.93	0.15	0.14	0.14
CaO	4.33	5.98	0.11	0.23	5.16
K_2O	0.42	< 0.1	13.97	12.50	< 0.1
Na_2O	9.26	8.67	1.90	3.31	8.84
Total	100.10	100.25	99.05	100.19	99.59
Si	2.776	2.703	2.995	2.973	2.778
Al	1.218	1.255	0.997	1.017	1.207
Fe^{3+}	0.004	0.034	0.006	0.005	0.005
Ca	0.205	0.285	0.006	0.011	0.246
K	0.024	0.000	0.826	0.728	0.000
Na	0.795	0.748	0.170	0.293	0.763
Sum	5.022	5.025	5.000	5.027	4.999
X_{ab}	0.776	0.724	0.170	0.284	0.756
X_{an}	0.200	0.276	0.006	0.011	0.244
X_{kfs}	0.023	0.000	0.824	0.705	0.000

Table 3. d. Representative spinel analyses from the DNCV range.

	KM10sp8	5046	H70052d	H7005sp1
Locality	km10	Con Ma	Kinh La	Kinh La
TiO_2	< 0.1	0.17	0.17	0.13
Al_2O_3	52.85	55.37	55.37	51.90
Cr_2O_3	0.22	< 0.1	< 0.1	< 0.1
V_2O_3	0.28	< 0.1	< 0.1	< 0.1
FeO	42.03	42.68	42.68	44.69
MnO	< 0.1	0.13	0.13	0.31
MgO	1.73	< 0.1	< 0.1	< 0.1
Total	97.11	98.35	98.35	97.03
Ti	0.000	0.004	0.004	0.003
Al	1.861	1.935	1.935	1.854
Cr	0.005	–	–	–
V	0.007	–	–	–
Fe^{3+}	0.127	0.058	0.058	0.138
Fe^{2+}	0.923	1.001	1.001	0.995
Mn	0.000	0.003	0.003	0.008
Mg	0.077	0.000	0.000	0.000
Sum	3.000	3.001	3.001	2.998

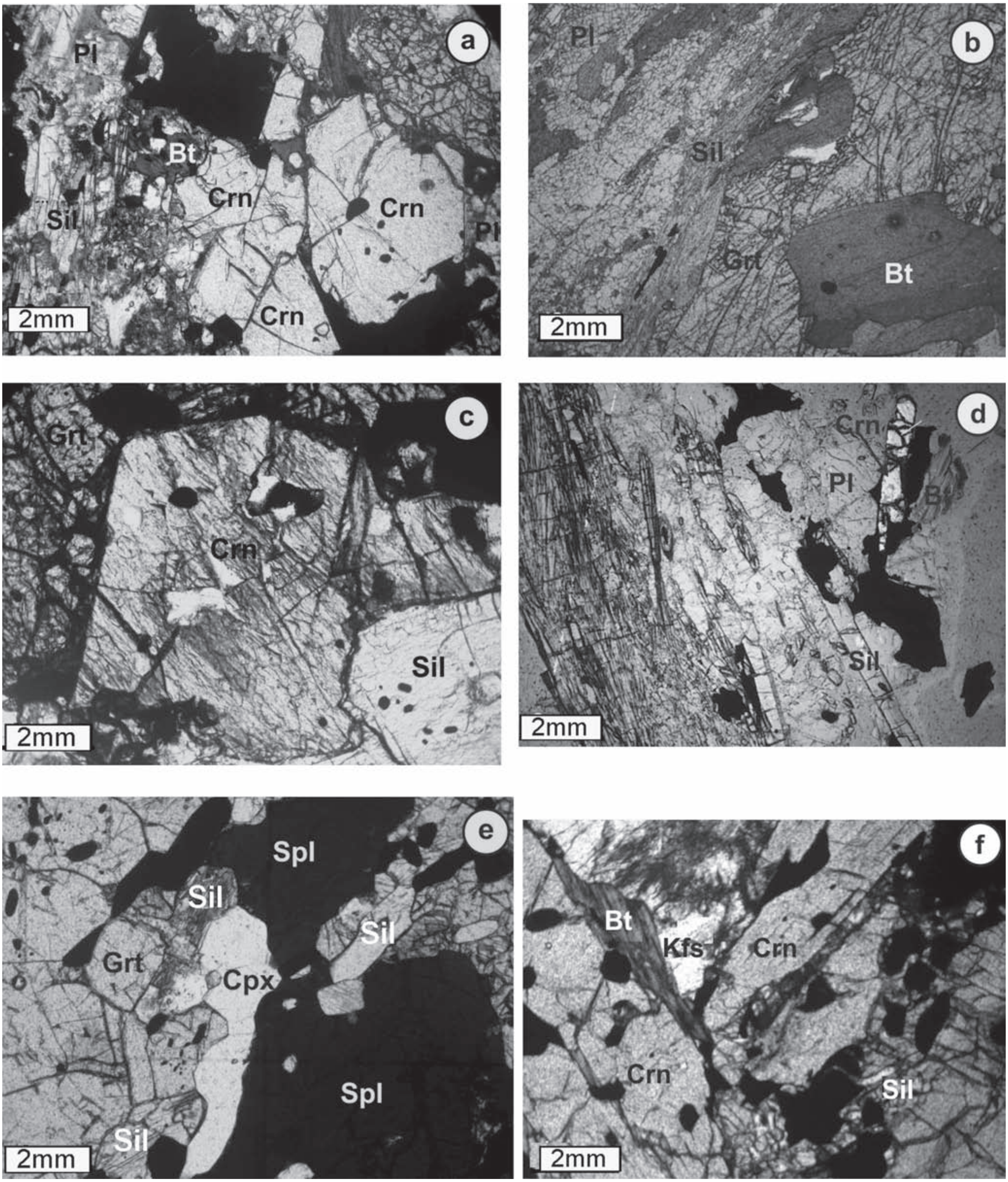

Fig. 7. Photomicrographs of some mineral assemblages, typical for gem-bearing gneisses and migmatic gneisses from Co Man outcrop in the Day Nui Con Voi range. (a) Sample 5046Co/1. Assemblage plagioclase+sillimanite+corundum+biotite. (b) Sample 5046/3. Assemblage biotite+sillimanite+garnet. (c) Sample 5046/R. Assemblage garnet+corundum+sillimanite. (d) Sample 5046/Co. Sillimanite+plagioclase+corundum assemblage. (e) Sample 5046/R. Garnet+spinel+sillimanite+clinopyroxene assemblage. (f) Sample 5046/Co. Assemblage corundum+K-feldspar+biotite+garnet+sillimanite. Symbols: Crn: corundum, Pl: plagioclase, Kfs: K-feldspar, Bt: biotite, Spl: spinel, Grt: garnet, Sil: sillimanite, Cpx: clinopyroxene.

Table 4. Mineral analysis of the ultrabasic sample KM10 a.

	KM10ao2	KM10aa4	K10aol5	KM10as9
Mineral	opx	magnesio-hornblende	ol	spin
SiO_2	54.78	47.26	39.29	< 0.1
TiO_2	0.19	0.87	< 0.1	< 0.1
Al_2O_3	1.65	11.60	< 0.1	56.70
Cr_2O_3	0.15	0.33	< 0.1	7.07
FeO	11.67	5.50	19.04	18.26
MnO	0.24	< 0.1	0.23	0.10
MgO	30.51	19.00	41.75	15.95
ZnO	–	–	–	< 0.1
CaO	0.26	11.43	< 0.1	–
K_2O	< 0.1	0.35	–	–
Na_2O	< 0.1	1.11	–	–
Total	99.45	97.45	100.31	98.08
Si	1.944	6.596	1.001	0.000
Ti	0.005	0.091	0.000	0.000
Al	0.069	1.908	0.000	1.797
Cr	0.004	0.036	0.000	0.150
Fe^{3+}	0.028	0.445	0.000	0.052
Fe^{2+}	0.318	0.197	0.406	0.358
Mn	0.007	0.000	0.005	0.002
Mg	1.614	3.953	1.586	0.639
Zn	–	–	–	0.000
Ca	0.010	1.709	0.000	0.000
K	0.000	0.062	–	0.000
Na	0.000	0.300	–	0.000
Sum	3.999	15.297	2.998	2.998
X_{mg}	0.835	0.953	0.796	0.641

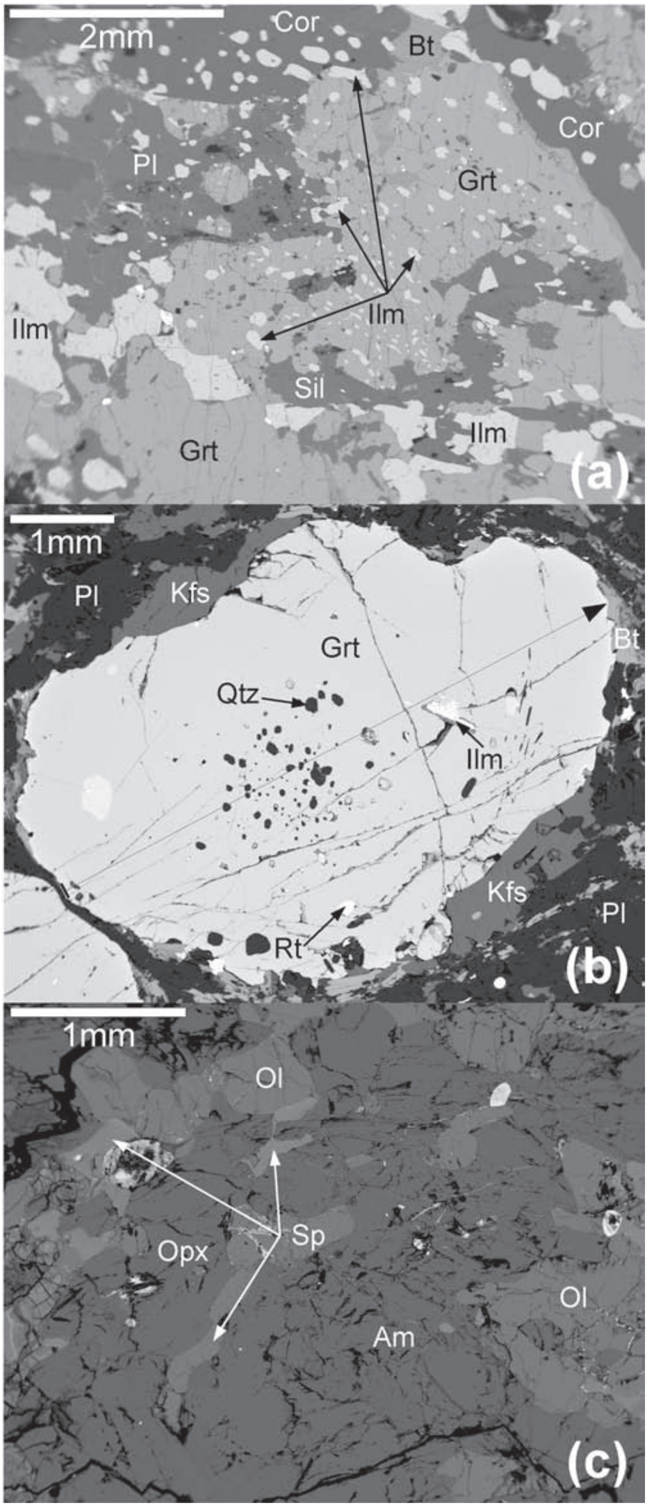

Fig. 8. BSE images of corundum bearing gneiss samples from different outcrops. (a) corundum bearing gneiss sample KM55 (Co Man outcrop, Truc Lau mine) with a typical mineral assemblage garnet+corundum+ilmenite+sillimanite+plagioclase. (b) migmatic corundum bearing gneiss sample KM10 showing a garnet cryst with ilmenite inclusions, spinel, corundum, biotite and plagioclase. (c) ultrabasic sample from the same outcrop with the mineral assemblage olivine+orthopyroxene+magnesiohornblende+spinel.

Corundum bearing feldspathic (pegmatoid) rocks (type II, Slope 700 occurrence)

One of the most remarkable features of the corundum-bearing feldspathic rocks is their migmatic texture with noticeable textural zonation around large corundum crystals, from the center to periphery: ruby, sapphire => K-feldspar, plagioclase => biotite, vermiculite ± garnet (Fig. 3c). Ruby and sapphire occur as idiomorphic, prismatic crystals, from some millimeters to 4–5 centimeters in diameter, and from 1–2 centimeters to 20 centimeters in length. Their color is from red, dark red to violetish red or pinkish red. Corundum crystals usually are surrounded by a rim of K-feldspar and plagioclase.

Age and P-T conditions of corundum formation

Primary corundum from the Day Nui Con Voi range has been indirectly dated using the $^{40}K/^{40}Ar$ laser stepwise heating technique on biotite samples collected from different localities (Table 5). The obtained ages of 22.17–24.52 Ma represent an age where the host rock reached a temperature of about 300–350 °C depending on various factors such as grain size and cooling rate. Since corundum forms at higher temperatures (> 450 °C, GARNIER 2003) these ages represent minimum ages of corundum formation. Similar cooling ages from phlogopite in ruby bearing marbles from the Lo Gam zone were also reported by GARNIER et al. (2002).

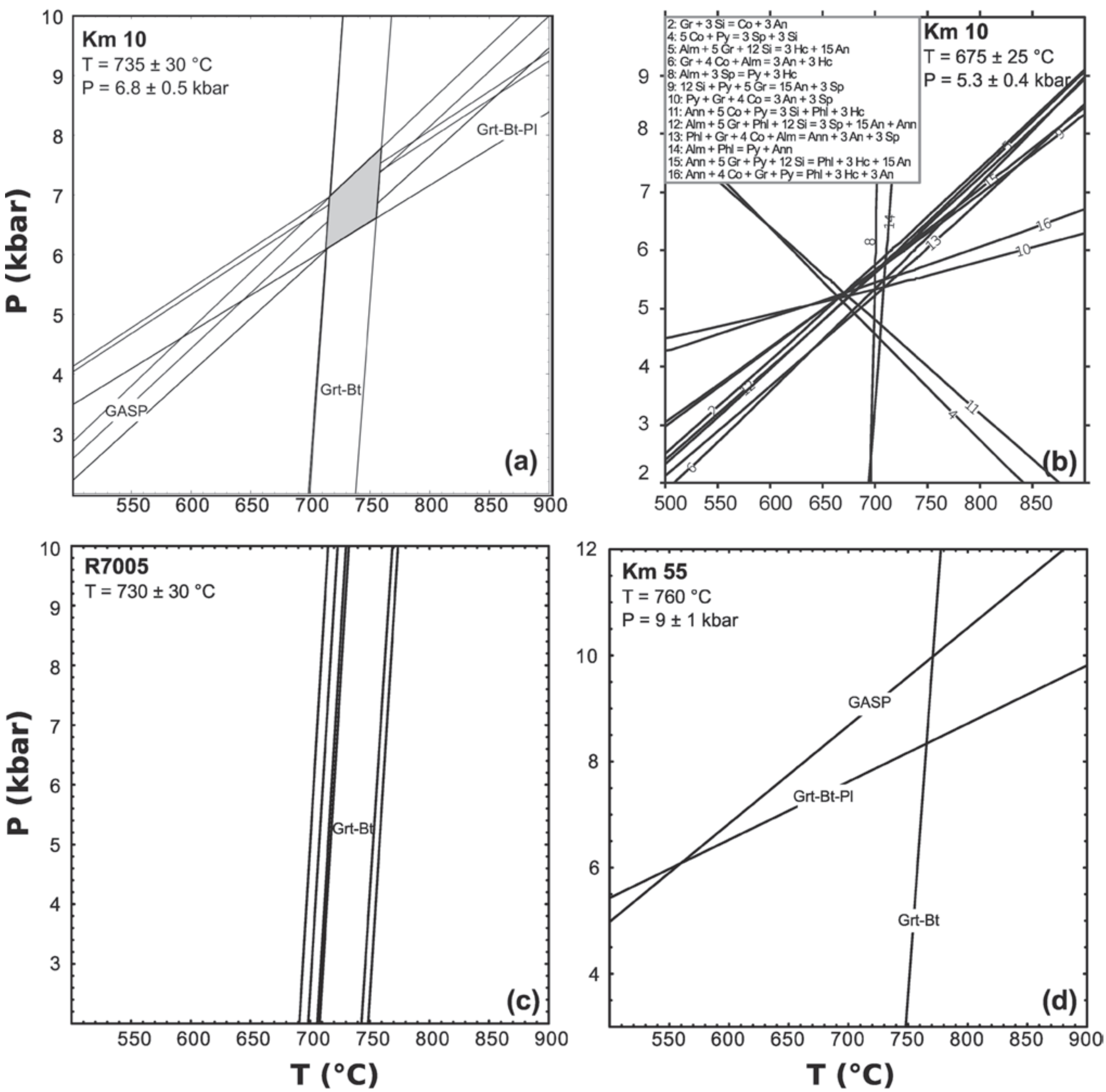

Fig. 9. Migmatic gneisses and schists from KM10, Kinh La (sample R7005), and Co Man area (sample Km55) were used in order to constrain the P-T conditions of metamorphic overprint. (a) The Grt-Bt, GASP and Grt-Bt-Pl reactions from sample Km10 constrain a P-T field of 700–760 °C and 6.3–7.3 kbar. (b) By using the full mineral assemblage, the TWQ calculation yields slightly lower conditions of 650–700 °C and 4.9–5.7 kbar. (c) Sample R7005 from Kinh La did not allow to constrain pressure, however, the Grt-Bt thermometer gives similar results of c. 700–750 °C. (d) For the Co Man area (Km55) slightly higher P-T conditions of c. 760 °C and 9 ± 1 kbar were determined.

Table 5. Results from ^{40}K–^{40}Ar age dating of biotite from different samples of corundum bearing gneiss.

Sample Name	Locality	Analyzed mineral	K (wt. %)	^{40}Arrad (ccSTP/g)	Rad ^{40}Ar (%)	Age (Ma)	Error (Ma)
K7005	Kinh La	Biotite	7.231 ± 0.145	679.7 ± 7.4	9.8	24.06	0.54
SH12	Tan Huong	Biotite	7.122 ± 0.142	682.4 ± 7.5	10.6	24.52	0.56
TL1	Truc Lau	Biotite	6.909 ± 0.138	598.1 ± 6.7	12.1	22.17	0.51
K8	Truc Lau	Biotite	7.371 ± 0.147	677.1 ± 7.9	15.6	23.52	0.54
SH. 4007	Truc Lau	Biotite	7.080 ± 0.142	658.9 ± 7.7	15.1	23.82	0.55
K5046/1	Truc Lau	Biotite	6.854 ± 0.137	625.6 ± 7.4	16.6	23.37	0.54
K5046/2	Truc Lau	Biotite	6.854 ± 0.137	625.6 ± 7.4	16.6	23.37	0.54

The widespread occurrence of migmatites clearly displays high grade metamorphism of the Day Nui Con Voi range. In order to constrain P-T conditions of metamorphism and corundum formation conventional geothermobarometry and thermodynamic equilibrium calculations (TWEEQU, Berman 1991) were applied (Fig. 9). The Grt-Bt (Holdaway 2000), GASP (Koziol 1989) and Grt-Bt-Pl (Hoisch 1990) reactions from sample Km10 constrain a P-T field of 700–760 °C and 6.3–7.3 kbar. By using the full mineral assemblage, the TWEEQU calculation yields slightly lower conditions of 650–700 °C and 4.9–5.7 kbar. Sample R7005 from Kinh La did not allow to constrain pressure. However, the Grt-Bt thermometer gives similar results of c. 700–750 °C. For the Co Man area (Km55) slightly higher P-T conditions of c. 760 °C and 9 ± 1 kbar were determined.

Discussion

Comparison to marble-hosted corundum deposits in nearby Lo Gam structural zone

As mentioned previously, corundum deposits and occurrences were found not only in gneisses of the Day Nui Con Voi range of Ailao Shan-Red River shear zone (Tan Huong-Truc Lau area), but also in marbles of the nearby Lo Gam structural zone (Khoan Thong-An Phu area, see Fig. 2).

Gneiss-hosted corundum deposits in Tan Huong–Truc Lau area occur in high-grade, mainly granulite facies, regional metamorphic environments. Corundum occurs as porphyroblasts or idiomorphic, xenomorphic or skeletal crystals, confined to specific metamorphic layers and concordant lenses of alumina-rich gneisses and schists. Gem corundum and spinel are the essential products (Nguyen Ngoc Khoi et al. 2010b). Khoan Thong–An Phu area is situated at the southern edge of Lo Gam structural zone, to the east of Ailao Shan-Red River shear zone. Ruby and sapphire occur as idiomorphic crystals within or at the contact of marble layers with magmatic rocks (pegmatite, syenite) or schists, while fancy sapphire occurs only in pegmatite bodies in association with tourmaline, amazonite, etc. (Pham Van Long 2003, Garnier 2003, Garnier et al. 2005, Nguyen Ngoc Khoi 2004).

Corundum from gneiss-hosted deposits shows a color variation from gray, white, and yellowish to dark red, pink to purplish or brownish pink. Color zoning is uncommon. Diaphaneity is semitransparent to translucent or opaque because of fracturing and the abundance of inclusions. By contrast, the majority of stones from marble-hosted deposits range from "pure" red or pink to purplish red or pink; other hues such as blue, orangy red, violet, or multicolored are also found with varying tones and saturations. Strong color zoning is commonly visible with the unaided eye.

Inclusions and growth structures are typical features to differentiate gneiss-hosted corundums from marble-hosted ones. The most common inclusions in gneiss-hosted corundums are ilmenite, magnetite, rutile, plagioclase, muscovite, biotite, apatite, zircon and boehmite. Although, straight and angular growth structures are quite common, color zoning and color irregularities are rare (Nguyen Ngoc Khoi et al. 2010a, 2010b, 2011, 2013). "Trapiche"-like rubies and sapphires have also been found (Schmetzer et al. 1996) in some stones from this type of deposits. On the other hand, corundums from the marble-hosted deposits contain mineral inclusions that are slightly diversified. The most frequent inclusions found here are calcite, rutile, apatite, spinel, zircon, corundum, pyrrhotite, graphite, boehmite, hematite, phlogopite, muscovite, hercynite and tourmaline; straight and angular color zoning, color patches, dots and spots are usually recognized in most of stones whereas swirl growth marks are sometimes observed (Henn & Bank. 1990, Kane et al. 1991, Hoang Quang Vinh 2000, Pham Van Long 2003, Nguyen Ngoc Khoi 2004, 2005). Summary of mineral inclusions and growth features in corundums reported from these two deposit types are present in Table 6.

Table 6. Mineral inclusions and growth features identified in corundums from gneiss-hosted and marble-hosted deposits in Yen Bai Province, North Vietnam.

Deposit type, area	Gneiss-hosted, Tan Huong-Truc Lau, Type I	Gneiss-hosted, Tan Huong-Truc Lau, Type II	Marble-hosted, Khoan Thong-An Phu
Mineral inclusions			
Allanite (?)		2	
Anatase			4
Apatite		2	6
Biotite	2	2	
Boehmite		1	6
Brookite			4
Calcite			6
Chlorite	2		
Corundum			4
Diaspore		1	4
Dolomite			5
Graphite			4
Halite			8
Hematite			4
Hercynite			4
Ilmenite	2	2	
Limonite	2	2	7
Magnetite	2	2	
Margarite			5
Monazite			7
Muscovite	3	2	4
Nepheline			7
Nordstrandite			6
Phlogopite			6
Plagioclase	1	2	
Pyrite			5
Pyrrhotite			6
Rutile	2	2	6
Spinel	2	3	4
Titanite			7
Tourmaline			4
Zircon	3	2	4
Growth structures, liquid-gas inclusions			
Color zoning	3	2	6
“Fingerprints”	2	2	
Fractures, feathers	2	2	
Growth structures	2	2	6
Liquid-gas inclusions	2	2	
Negative crystals	2	2	
Na, Ca, K-Cl salts			8
Swirl growth marks			6
Twinning	2	3	6
Wedged-shaped growth features			6

1: This study; 2: Khoi et al. (2011); 3: Nguyen Van Nam (2012); 4: Long et al. (2004); 5: Hoang Quang et al. (1999); 6: Kane et al. (1991); 7: Dao et al. (2001); 8: Giulliani et al. (2003)

In terms of mineral chemistry, in general, our results are well consistent with those published previously by Pham Van Long et al. (2004). The high content of Fe (5500 to 7133 ppm) with low content of Ti (59 to 65 ppm) is the main cause of the observed bluish to greenish gray color in primary corundums of *type I* in the Day Nui Con Voi range. High levels of both Cr and Fe (940 and 1028 ppm, respectively) in *type II* corundum (see Table 2 a) are responsible for dark pink to red color, while primary corundum from marble-hosted deposits in Khoan Thong-An Phu area contains less Fe, that is why the red color is lighter and more vivid (Hughes 1997).

Concerning the economic factor, most of the gneiss-hosted primary deposits in the Day Nui Con Voi range contain only industrial grade corundum (*type I*) with little or no high gem-quality stones. Nevertheless, corundum from feldspathic rocks (*type II*) has higher gem quality and has been sporadically mined from host rocks in some places of the Day Nui Con Voi range.

Genetic model

The corundum-bearing host rocks from the Day Nui Con Voi range are of metamorphic genesis, with similar characteristics as described from other localities by several authors (e.g., Cooray & Kumarapeli 1960, Katz 1972, Dahanayake & Ranasinghe 1981, Simandl & Paradiss 1999, Mercier et al. 1999, Giuliani et al. 2007, Simonet et al. 2008). Nevertheless, the genesis of corundum, especially of gem quality, in these rocks has not yet been explained. While Phan Truong Thi (1978) suggested a formation of these corundum-bearing rocks at amphibolite facies conditions, Nguyen Kinh Quoc et al. (1995) proposed that alkaline magmatism and postmagmatic fluids, related to the Tan Huong Magmatic Complex, are responsible for the formation of the corundum-bearing “plagioclasite zones”. Other authors (Tran Ngoc Quan et al. 2000) concluded that rubies and sapphires in the Red River shear zone were formed by alteration of alumina-rich metapelites by pegmatoid bodies. Specifically, Phan Trong Trinh et al. (1998) related the formation of rubies and sapphires in the Day Nui Con Voi range with the Cenozoic tectonic activity of the Red River shear zone, where deep-rooted fluids caused partial melting and metasomatic interactions (desilification) between alumina-rich gneisses and metabasic rocks or metacarbonates (Ethridge et al. 1984).

The metamorphic origin of the primary corundum in the Day Nui Con voi range can be proved by both petrographic and geothermobarometric evidences. The investigated samples indicate that the coarse grained corundum-bearing metasediments formed at upper amphibolite to lower granulite facies conditions during the Cenozoic (Oligocene to Miocene) tectonic activity of the Ailao

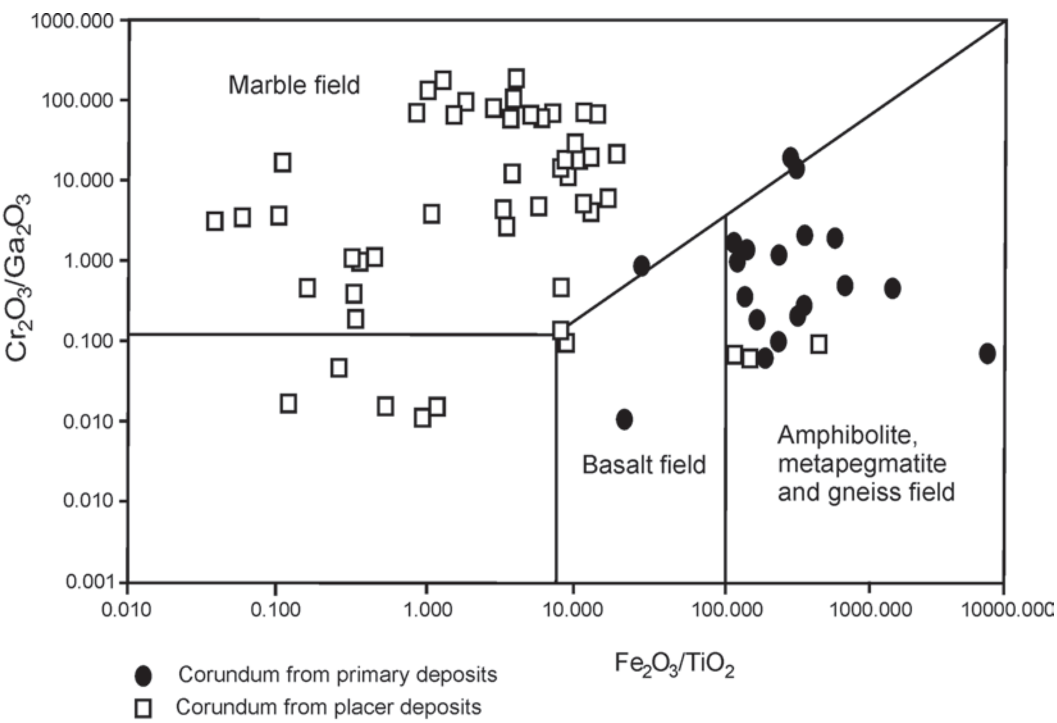

Fig. 10. Correlation diagram of Cr_2O_3/Ga_2O_3 vs Fe_2O_3/TiO_2 for corundums from primary and secondary deposits in the Day Nui Con Voi range (Sutherland et al. 1998, 2003)

Shan–Red River shear zone (Garnier 2003, Tenyakov et al. 1982). The correlation diagram of (Cr_2O_3/Ga_2O_3) vs (Fe_2O_3/TiO_2) for corundum from primary deposits in the Day Nui Con Voi range (Fig. 10) shows that most of samples (both *type I* and *type II*) fall into the metamorphic field, concretely into the gneiss, amphibolite and (meta) pegmatite field, which is quite consistent with the data obtained by Long et al. (2004). Nevertheless, almost all the samples from placer deposits in the Day Nui Con Voi range fall into the marble field (see Fig. 10), suggesting that gem material in placer deposits here might come from primary sources related directly to marble layers and lenses intercalated with gneisses in the region. This type of corundum (*type III*) should be the object of study in the future.

The common occurrence of corundum within the gneissic rocks (*type I*) indicates that probably weathering of the sedimentary protolith led to an enrichment of aluminum. The metamorphic overprint during the Cenozoic tectonic activity resulted in transformation of this Al-rich sediments into corundum bearing gneisses. The following reaction could be proposed for corundum formation:

$$2AlO(OH)\ \text{(diaspore)} = Al_2O_3\ \text{(corundum)} + H_2O$$

From field evidence small-scale desilification processes associated with metamorphism, migmatization and pegmatization at the contact with meta-basic/meta-ultrabasic and meta-carbonate rocks are probably responsible for a second mechanism of corundum crystallization (Altner et al. 1982, Phan Trong Trinh et al. 1998, Simonet 2008). This case can be seen clearly at Slope 700 occurrence where ruby crystals were found embedded in feldspathic (pegmatoid) rocks with migmatic texture and noticeable textural zonation from the periphery to the center of gem ore body: (1) quartz-biotite-sillimanite ± garnet gneis zone => (2) amphibolite zone => (3) biotite, vermiculite zone => (4) K-feldspar, plagioclase zone.

The age of corundum formation within the Day Nui Con Voi range (22.17 ± 0.51 to 24.52 ± 0.56 Ma) is well consistent with those previously published by Leloup et al. (2001) and Garnier et al. (2002, 2003) for the Lo Gam zone who report ages of 21.2 ± 0.2 to 24.9 ± 0.9 and 23.2 ± 0.6 to 24.4 ± 0.4 Ma, respectively. The deformation and metamorphism in the Day Nui Con Voi range occurred under upper amphibolite to lower granulie metamorphic conditions at temperatures between 600 and 750 °C (this study; Leloup et al. 2001), which is also supported by calcite–graphite isotope thermometry in marbles from the Tan Huong mine with temperatures of 600–625 °C (Giuliani et al. 1999). The obtained P-T conditions from three localities of this study are close to each other with 650–760 °C and 5–9 kbar and to values reported from literature (Nam et al. 1998, Leloup et al. 1999, 2001, Phan Trong Trinh et al. 1999, Nguyen Thi Huyen 2010, Nguyen Van Nam 2012). The Day Nui Con Voi range represents mid-crustal to lower crustal rocks which were exhumed by the activity of the Ailao Shan–Red River shear zone.

Conclusions

1) Corundum hosting lithologies around the Day Nui Con Voi range, Ailao Shan–Red River shear zone, comprise mainly plagioclase-rich gneiss, diopside gneiss, biotite-garnet gneiss, and quartz–sillimanite–garnet gneiss intercalated with biotite–sillimanite schist and lenses of amphibolite and marble of the Nui Voi Formation. These rocks lie underneath the Ngoi Chi Formation, which comprises quartz–mica schist, sillimanite schist, and garnet schist.

2) Primary corundum from the Day Nui Con Voi range can be grouped into three main types, where *type I* is sapphire varying from grayish, whitish, yellowish to bluish and greenish in colour, *type II*, ruby and purplish sapphire in feldspathic rocks at the contact with mafic/ultramafic rocks and *type III* which is related to metacarbonates. Corundum from the first two types differs from each other essentially in its trace element content with high Fe (5500 to 7133 ppm) and low Cr (59 to 65 ppm) and Ti (40 to 58 ppm) content in *type I* and higher Cr (940 ppm), medium Fe (1028 ppm), and low Ti (42 ppm) content in *type II*. Many stones have low transparency due to abundant fracturing and dark-colored inclusions such as ilmenite, magnetite, biotite, and the vast majority of gem corundum from this area is suitable only for cutting cabochons (especially star rubies).

3) Gneisses, hosting *type I* corundum, are characterized by three different mineral parageneses (1) sillimanite+K-feldspar+biotite; (2) sillimanite+garnet+spinel+biotite+K-feldspar+plagioclase+ilmenite, and (3) sillimanite+garnet+spinel+clinopyroxen+ilmenite. *Type II* corundum occurs in feldspathic pegmatoid rocks consisting of an assemblage garnet+biotite+plagioclase+K-feldspar.

4) Corundum from gneisses in the Day Nui Con Voi range has a metamorphic origin. Sapphire in gneiss (*type I*) formed during large-scale, regional metamorphism, whereas ruby in feldspathic rocks (*type II*) probably formed at the contact of migmatitized pegmatoid bodies with surrounding mafic-ultramafic or marble rocks causing small-scale desilification.

5) Temperatures of 650–760 °C and pressure of 5–9 kbar have been calculated for the metamorphism and corundum formation, which corresponds to upper amphibolite to lower granulite facies.

6) $^{40}K/^{40}Ar$ cooling ages obtained from biotite in gneisses indicate that the rocks reached ~300 °C at ~23 Ma.

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