An unusual sapphire–zircon–magnetite xenolith from the Chanthaburi Gem Province, Thailand

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Abstract

A sapphire, zircon and magnetite-bearing xenolith from Khao Wua, near Chanthaburi in Thailand, conclusively demonstrates a common origin for the sapphire, zircon and magnetite found in alluvial deposits in the Chanthaburi gem fields. The original aluminium- and titanium-rich octahedral magnetite crystal in the xenolith exsolved into hercynite, magnetite and hematite during cooling. It includes minor anhedral jarosite–alunite, possibly originating as an iron-sulphide-rich immiscible liquid. Uranium-lead isotope dating of zircon in the xenolith gives an age of 1–2 (± <1) million years (Ma). This falls within fission track ages for alluvial zircons (2.57 ± 0.20 Ma) from the Chanthaburi–Trat gem fields and within the potassium-argon ages of 0.44 to 3.0 Ma for the alkali basaltic volcanism in the Chanthaburi Province. These data suggest a common origin for sapphire, zircon and magnetite, and link them with the processes involved in alkali basaltic magma generation. The high iron and zirconium, low magnesium, and the inferred sulphides suggest pegmatite-like crystallization in an incompatible-element enriched, silica-poor magma (partial melt or fractionation product) in the deep crust or upper mantle. Etch features on exposed surfaces of the xenolith indicate that it was transported out of its equilibrium environment by the rise of later magma.

KEYWORDS: sapphire, zircon, uranium-lead dating, xenolith, Khao Wua, Chanthaburi, Thailand.

Introduction

THAILAND has long been renowned as a supplier of gemstones, and over the past few decades has emerged as one of the world's coloured stone centres. The principal gemstones are ruby, sapphire, garnet and zircon, among which ruby 'Siam Ruby') and sapphire are today the best known and constitute the majority of gems sold in foreign markets. The main suppliers of precious corundum are the mines of Chanthaburi, Trat and Kanchanaburi, which account for some 90–95% of the total production, and the remaining 5–10% come from Phrae, Si Sa Ket, Ubon Ratchathani and Sukhothai (Vichit, 1987, 1992).

In Thailand, rubies and sapphires are released by weathering and erosion of basalt (Taylor and Buravas, 1951; Charaljavanaphet 1951; Aranyakanon *et al.*, 1970). Distribution of basalts and gem corundum localities (Vichit, 1987, 1992), are shown in Fig. 1 and the common minerals

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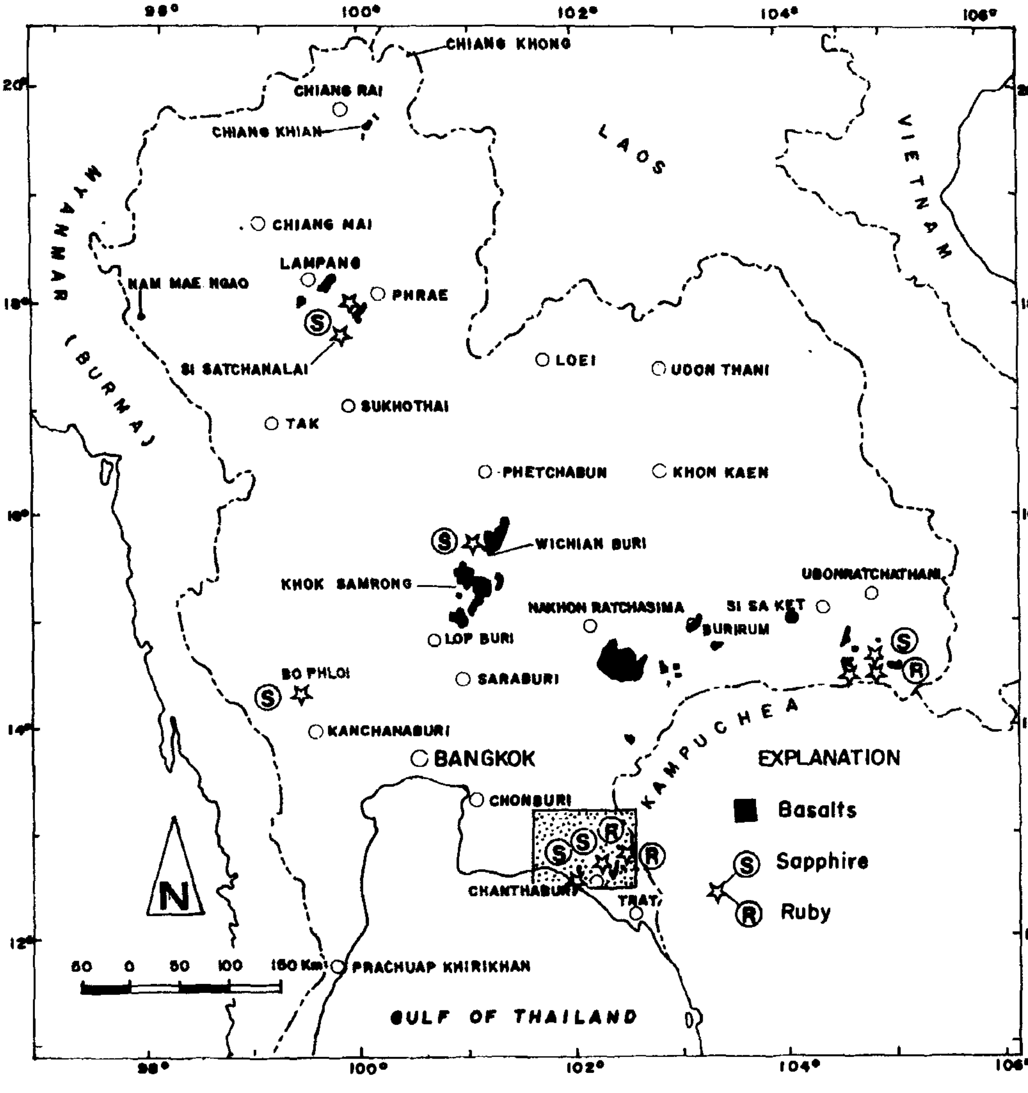

FIG. 1. Distribution of basalts and gem corundum localities in Thailand (Vichit, 1987, 1992). The heavy minerals associated with each of the gem provinces are listed in Table 1. The Chanthaburi-Trat Gem Province is within the rectangle, shown enlarged in Fig. 2.

associated with each gem province are summarized in Table 1.

Corundum-bearing basalts are found throughout the world. They are generally alkaline (e.g. nephelinite, nepheline hawaiite, basanite, basanitoid) and usually carry spinel-lherzolite xenoliths and megacrysts of spinel, clinopyroxene, ilmenite, magnetite, garnet, and in some places, feldspars including sanidine and anorthoclase (Barr and Macdonald, 1978, 1981; Vichit *et al.*, 1978; Yaemniyom, 1982; Vichit, 1987, 1992). Similar xenoliths and megacrysts are, however, also common in alkaline provinces lacking corundum. In contrast to other megacrysts, corundum in fresh basaltic rock is extremely rare in Thailand, but is found at the Bo Phloi sapphire field in Kanchanaburi, the Denchai district in Phrae, and Ban Bang Kacha in Chanthaburi (Vichit *et al.*, 1978; Vichit, 1987, 1992).

Since 1978, numerous brief reports on the petrography, geochronology and major and trace

TABLE 1. The Thai Gem Provinces: minerals associated with some sapphire and ruby deposits

Location	Setting	Gem corundum							Remarks
		Ruby	Sapphire	Black spinel	Clinopyroxene	Garnet	Zircon	Magnetite	
CHANTHABURI PROVINCE									
Tha Mai District									
(The First or Western Zone)									
-Khao Phloi Waen-Khao Wua-Bang Kacha area	residual basaltic soil, eluvium and alluvium	–	x	x	x	x	x	x	garnet > zircon, clinopyroxene > spinel, phlogopite is also common at Khao Wua-Khao Phloi Waen
CHANTHABURI-TRAT PROVINCES									
Khlung and Kriao Saming District									
(The Second or Middle Zone)									
-Bo Welu-Ban Si Siat-Tok Phrom-Bo Khlang-Nong Pia Lai-Ang Et area	residual basaltic soil, eluvium and alluvium	x	x	–	x	Tr	x	–	zircon is abundant
-Bo i Rem area		–	x	–	–	–	Tr	–	
-Bo Na Wong-Nong Noi area		x	–	–	x	Tr	Tr	–	
TRAT PROVINCE									
Bo Rai District									
(The Third or Eastern Zone)									
-Nong Bon-Sua Dao-Khao Pik Ka area	stream gravels and residual basalt soil	x	–	–	x	x	–	x	garnet and clinopyroxene are abundant large grains of ilmenite, magnetite and hematite are also abundant
-Bo Rai-Ban Thung Satharana Ban Ta Bad area	alluvium	x	Tr	–	x	x	–	–	
-Ban Sra Yai-Ban Non Tri-Ban Ta-Ngam	alluvium	x	Tr	x	x	–	x	–	
Ban Khlong Aeng (Rubywell Mine)	stream gravels	x	Tr	x	–	x	–	–	sapphirine and ilmenite are also found
PHRAE PROVINCE									
Denchai-Wang Chin District									
-Ban Bo Khaeo Huai Mae Sung area	stream and terrace gravels	Tr	x	x	x	Tr	x	x	spinel and clinopyroxene are abundant spinel > clinopyroxene
SUKHOTHAI PROVINCE									
Si Satchanalai District									
-Ban Huai Po-Ban Pak Sin-Ban Sam Saen area	stream and terrace gravels	–	x	x	–	–	–	–	spinel is common
PHETCHABUN PROVINCE									
Wichian Buri District									
-Ban Khok Samran-Ean Marp Samo-Khlong Yang area	residual basaltic soil and stream gravels	–	x	x	x	Tr	x	x	spinel and magnetite are abundant spinel > clinopyroxene
KANCHANABURI PROVINCE									
Bo Phloi District									
-Bo Phloi-Ban Chong Dan area	alluvium, eluvium and residual basalt soil	Tr	x	x	x	Tr	–	x	spinel and clinopyroxene are abundant sanidine is also common
UBON RATCHATHANI-SI SA KET PROVINCES									
Nan Yun and Kantharalak Districts									
-Ban Saen Thawon-Ban Ta Kao-Ban Ta Koi-Ban None Yang-Huai Pho	alluvium	x	x	–	–	–	x	–	zircon is abundant
-Huai Ta-Aek-Lam Som area	stream gravels	x	x	–	–	–	x	–	

x observed
Tr trace
– not observed

element chemistry of basalts in Thailand have been published (Barr and Macdonald, 1978, 1979, 1981; Vichit *et al.*, 1978; Sirinawin, 1981; Yaemniyom, 1982; Jungyusuk and Sirinawin, 1983; Barr and

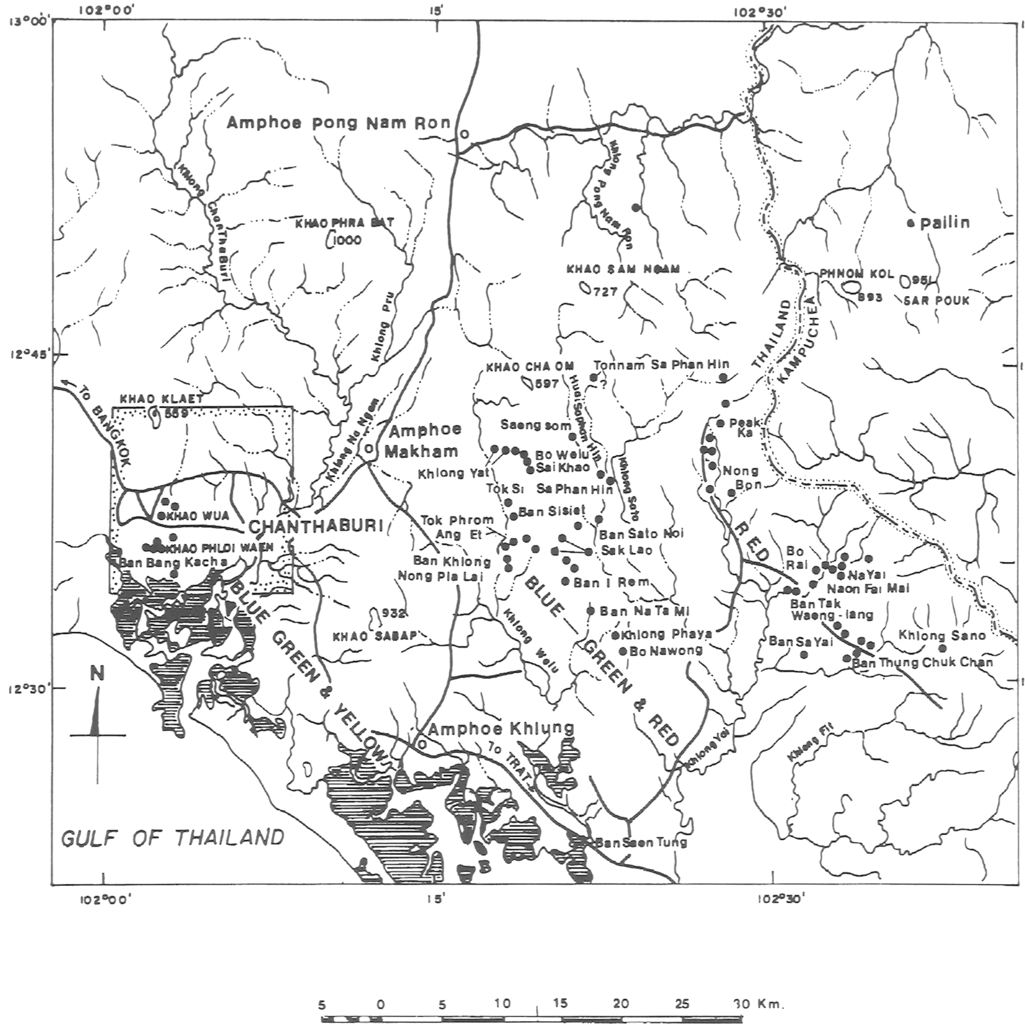

FIG. 2. The Chanthaburi-Trat gem fields (Vichit, 1987; 1992). A variation of gem colours in three distinctive geographic zones over a distance of 50 km is indicated. Khao Wua, in the First Zone (blue, green and yellow) is within the square, shown enlarged in Fig. 3.

Dostal, 1986; Barr and James, 1990). The genesis of corundum in relation to the host basalts, discussed by some authors, is still not clear. In general, more emphasis was placed on the basaltic rocks than the gem corundum and its associated minerals. Potassium-argon age determinations for the basaltic rocks range from 0.44±0.11 Ma to 11.29±0.64 Ma (Barr and Macdonald, 1981; Charusiri *et al.*, in prep.)

The most common minerals associated with sapphire in alluvial deposits are black spinel, black clinopyroxene, zircon, garnet, ilmenite, magnetite, olivine, and less commonly phlogopite and sanidine (Table 1). Some minerals occur in several deposits, but not all. Black spinel and zircon are abundant in many deposits in Chanthaburi, Trat, Phetchabun, Ubon Ratchathani and Si Sa Ket provinces (Vichit, 1987, 1992).

A xenolith containing octahedral magnetite intergrown with sapphire and zircon was found at the Nai Mod mine in the Khao Wua area, Chanthaburi province (Figs. 2 and 3), and suggests a common origin for these minerals. Its rarity is inferred as none

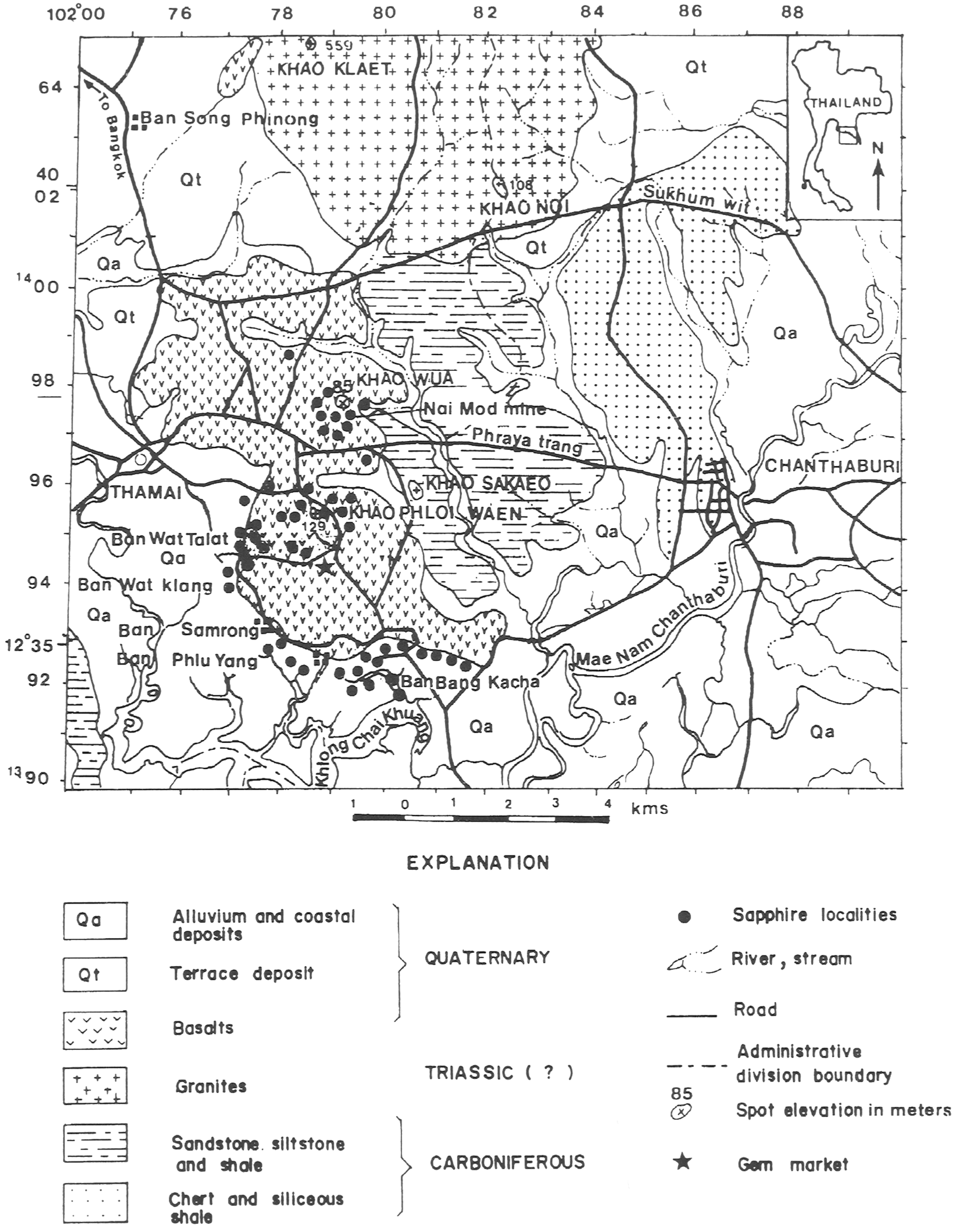

FIG. 3. Location of the Nai Mod mine in the Khao Wua area, approximately 7 km northwest of Chanthaburi in the First Zone. The sapphire–zircon–magnetite-bearing xenolith described in this paper was found here. Basalt sample localities and their chemical analyses are listed in Table 2.

of us has before seen, nor read of, such a xenolith. Its study gives a direct approach to the understanding of the origin of corundum and its related minerals in basalt. The texture, mineralogical relationships and chemical compositions in the xenolith are described here and its genesis discussed.

Geological background

The most significant ruby-sapphire concentration associated with basalts in Thailand are the famous Chanthaburi-Trat gem fields (Vichit, 1987, 1992). In this gem field, there is a variation of gem colours in three distinctive geographic zones (Fig. 2):

- Western Chanthaburi, is characterized by blue, green, yellow and star sapphires.
- The Chanthaburi and Trat provinces are characterized by blue and green sapphires and rubies.
- The Trat zone, close to the Kampuchean border, has only rubies.The first zone contains some of the oldest and best known sapphire deposits in Thailand around Khao Wua, Khao Phloi Waen and Ban Bang Kacha (Fig. 3). In 1992–3 about ten small mines and a few pit miners still worked some areas. Most of the finest yellow, green and star sapphires found in Thailand come from the first zone. For blue sapphires, good quality material is found in both the first and second zones.

The sapphire–zircon–magnetite-bearing xenolith was found in the first zone, approximately 7 km northwest of Chanthaburi (Fig. 3). It was collected by P. Vichit from discarded gravels (tailings from the jig concentrates left after hand sorting of gem corundum).

The region is covered with Quaternary basalt in an area approximately 3 by 7 km (Fig. 3). Khao Wua and Khao Phloi Waen are small hills, 85 m and 129 m above sea level respectively. Khao Phloi Waen is probably a volcanic plug (Taylor and Buravas, 1951). A ^{40}Ar/^{39}Ar age of 3.0±0.19 Ma(step heating technique) was reported for a Khao Wua basalt (Charusiri *et al.*, in prep.) and the Khao Phloi Waen basalt yields a K-Ar age of 0.44±0.11 Ma (Barr and Macdonald, 1981). To the east, Carboniferous sedimentary rocks consist of phyllitic shale, shale, sandstone, siltstone and chert. Triassic granites lie to the north and Quaternary alluvium to the west and the south (Sivabovorn *et al.*, 1976; Salyaphongse and Jungyusuk, 1983).

Basalts of the area are generally strongly alkalic, low in silica and high in titanium. Termed 'basanitoid' or 'nephelinite' by Vichit *et al.* (1978) and Barr and Macdonald (1978, 1981), they are generally fine-grained and olivine-bearing, and at several places contain clinopyroxene megacrysts and mantle-derived lherzolite xenoliths. New chemical analyses of basalts from Khao Phloi Waen and their localities are presented in Table 2.

At Khao Wua, basalts contain abundant round lherzolite xenoliths up to 15 cm in size, and occasional glimmerite (phlogopite) xenoliths. Aluminous augites occur as angular, ragged megacrysts up to 5 cm in size characterized by distinct striations, vitreous lustre, and sub-conchoidal fracture (Vichit, 1987, 1992).

The sapphires and associated heavy minerals are mined at relatively shallow depths in deeply weathered basaltic rocks around Khao Wua and Khao Phloi Waen and at 2 to 15 m depth in surrounding areas.

Sapphires commonly range from 0.5 to 4 cm in size with exceptional specimens up to 10–12 cm. Large stones tend to be opaque and non gem quality. Most sapphire occurs as tabular crystals with the hexagonal prism terminated at both ends by basal parting. Twin crystals are sometimes observed. The sapphires show a range of colours; pale blue to dark blue (occasionally pure, but often with green dichroism), pale green to bottle green, yellowish-green, greenish-yellow and yellow. Star- and green sapphires predominate over blue or yellow sapphires. Colour zoning is common in blue and green sapphires but is only occasionally observed in yellow stones. Yellow sapphires form 10% of the sapphires mined and are usually less than 10 carats in uncut weight.

Pyrope garnet occurs as angular to subangular anhedral grains, 0.5 to 6 cm in size, displaying subconchoidal fracture. Dark stones appear pale to dark reddish brown in the interiors or thin splinters. Some are partially to heavily weathered.

Zircon is mostly brown to pale reddish- and orange-brown subangular fragments with some crystal faces, varying in length from 0.4 to 1.5 cm.

Spinel is generally black and sometimes occurs as corroded octahedral crystals from 0.5 to 2 cm in size. Magnetite also occurs.

Dark micas are reported in sapphire deposits in the Khao Phloi Waen–Khao Wao area. The mica occurs as aggregates (glimmerites) ranging in size from less than a centimetre to 6 cm across. A sample analysed by XRD at the Australian Museum was phlogopite (R. Pogson, pers. comm.). According to the pit miners, mica in the basaltic topsoil is an indicator for sapphires.

Determination of corundum origin in the volcanic provinces

Study of inclusions in sapphire. Inclusions in sapphires associated with volcanic provinces include alkali feldspar, columbite, gahnospinel, hercynite, hornblende, ilmenite, niobium-rutile, mica, plagioclase, pyrrhotite, pyrrhotite-pentlandite intergrowth, thorite, uranium pyrochlore, zircon, iron-rich melt inclusions and two- or three-phase fluid inclusions

TABLE 2. Chemical analyses of basalts from the Khao Phloi Waen area, Chanthaburi province. Major and trace elements were determined by X-ray fluorescence and FeO by titrimetric method (analysts: S. Sripairotikool, S. Saengsila, W. Chantarawong, N. Morakot, K. Chingchit and P. Amnartsakulrit, Mineral Resources Analysis Division, Department of Mineral Resources, Bangkok, Thailand). The basalts are classified following Coombs and Wilkinson (1969) and Best and Brimhall (1974)

Sample no.	CT-1	CT-2	CT-3	CT-4	CT-5	CT-6	CT-11
wt. % oxide							
SiO_2	40.49	43.54	40.99	42.10	41.21	41.08	40.75
TiO_2	3.15	3.05	3.03	3.18	3.33	3.27	3.20
Al_2O_3	11.42	12.29	11.16	11.93	11.75	11.63	11.74
Fe_2O_3	5.75	5.41	6.12	5.75	6.88	5.84	7.24
FeO	7.04	6.29	6.70	7.02	7.04	7.28	6.04
MnO	0.20	0.20	0.19	0.22	0.21	0.21	0.21
MgO	11.24	9.73	11.32	10.69	9.96	10.65	10.49
CaO	9.85	10.50	10.54	10.12	10.28	9.93	9.49
Na_2O	3.40	2.52	2.05	2.75	2.96	3.14	4.06
K_2O	1.48	1.51	1.55	1.49	0.96	1.34	2.67
H_2O^+	4.00	2.62	4.53	2.26	2.73	2.35	0.88
H_2O^-	0.41	0.42	0.42	0.47	0.47	0.58	0.28
P_2O_5	1.20	1.26	1.16	1.22	1.28	1.25	1.29
C	0.05	0.09	0.05	0.13	0.04	0.07	0.05
CO_2	0.07	0.26	0.07	0.37	0.07	0.07	0.15
S	0.03	0.10	0.02	0.04	0.04	0.00	0.01
Total	99.78	99.79	99.90	99.74	99.21	98.69	98.55
Norm minerals							
quartz	0.00	0.00	0.00	0.00	0.00	0.00	0.00
orthoclase	8.75	8.92	9.16	8.81	5.67	7.92	15.78
albite	10.25	20.68	12.90	16.83	18.54	14.12	4.22
anorthite	11.53	17.77	16.67	15.81	15.94	13.69	5.93
nepheline	10.03	0.35	2.41	3.49	3.53	6.74	16.32
diopside	22.89	19.23	21.69	18.99	20.62	21.28	24.76
hypersthene	0.00	0.00	0.00	0.00	0.00	0.00	0.00
olivine	14.58	12.47	14.58	14.88	12.21	14.21	10.41
magnetite	8.34	7.84	8.87	8.34	9.97	8.47	10.50
hematite	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ilmenite	5.98	5.79	5.75	6.04	6.32	6.21	6.08
apatite	2.84	2.98	2.75	2.89	3.03	2.96	3.06
calcite	0.16	0.59	0.16	0.84	0.16	0.16	0.34
Total	95.35	96.62	94.94	96.92	95.99	95.76	97.40
Different. index	30.45	30.99	25.77	30.06	28.90	30.05	37.29
100An/(An+Ab)	52.94	46.21	56.37	48.44	46.23	49.23	58.42
Trace elements							
Ba ppm	975	1064	889	1418	1142	1203	709
Ce	143	170	136	151	157	139	140
Co	81	85	70	89	75	107	103
Cr	275	321	320	308	232	293	276
Cu	67	71	64	69	64	68	66
Ga	13	18	14	16	17	15	14
Ni	233	263	254	283	171	254	187
Pb	5	6	6	6	6	7	8
Rb	29	32	41	45	43	69	67
Sr	1082	1225	1066	1387	1222	1145	1068
V	302	324	292	304	307	309	315
Y	23	23	22	26	23	21	22
Zn	143	159	143	147	164	141	156
Zr	298	321	294	304	338	296	126
Rock name	basanite	hawaiite	alkali olivine basalt	hawaiite	hawaiite	ne-hawaiite	basanite
Location	Ban Bang Kacha	Ban Bang Kacha	Ban Phlu Yang	Ban Phlu Yang	Ban Wat Khlang	Ban Si Phraya	Khao Phloi Waen
Grid ref. Fig. 2	790E 926N	794E 926N	784E 929N	780E 931N	772E 941N	787E 930N	782E 956N

(Coenraads, 1992*a*). These indicate sapphire growth in an environment rich in Fe, Al and incompatible elements (e.g. U, Th, Nb, Ta, Zr), alkalis (Na, K) and volatiles (CO_2). The abundant, iron-rich melt inclusions and crystal inclusions of iron-spinel and iron-sulphides indicate a parent melt rich in iron and poor in silica and magnesium.

Uranium-lead (U-Pb) dating of zircon inclusions in sapphire. Ion microprobe ages of zircon inclusions in sapphires from east Australian gem fields link the time of formation of sapphire and zircon with Cainozoic alkali volcanism in each area (Coenraads *et al.*, 1990; Guo, 1993).

Surface features observed on rubies and sapphires. Surface features on corundums largely suggest dissolution in corrosive carrier magmas whilst en route to the surface (Coenraads, 1992*b*).

Sapphire-bearing xenoliths. Uneven chemical resorption and negative crystal impressions in corundums indicate their inclusion in, or coarse-grained intergrowth with, other minerals (Coenraads, 1992*a,b*). However actual coarse aggregates with sapphire in equilibrium growth with other minerals are rare. Known examples include:

1. A sapphire intergrown with spinel (pleonaste?) from Reddestone Creek, New England Gem Fields, Australia. (New South Wales Geological Survey collection; missing).
2. A sapphire intergrown with anorthoclase (5 cm across), Anakie Gem Fields, Queensland, Australia (Stephenson, 1990; Coenraads *et al.* 1990; Robertson and Sutherland, 1992; Australian Museum specimen No. D44379).
3. An anorthoclasite xenolith containing corundum from Ruddons Point, U.K. (Upton *et al.*, 1983).
4. Aggregates (1–3 mm in size) of intergrown ruby, sapphire, sapphirine and spinel, Gloucester Tops, New South Wales, Australia (Sutherland and Coenraads, in prep; Australian Museum specimen No. D49689).
5. Sapphires and zircons intergrown with Al-Ti magnetite from Khao Wua, Thailand, (this paper; Australian Museum specimen No. D49690).

The xenolith from Khao Wua, Thailand

The specimen is primarily a dark reddish-brown, magnetic, octahedral Al-Ti magnetite crystal 1.5cm in size (Figs. 4 and 5). Several sapphire crystals are intergrown with the magnetite, the largest being a greenish-blue prismatic crystal measuring 1.0 cm along the *c*-axis and 0.4 cm across it (Fig. 5*a* and *b*). Another green sapphire is visible adjacent to the large crystal in Fig. 5*b*. It has a different orientation, and a furrow marks the line of contact between the two crystals. A third, silky, opaque, cream-coloured corundum crystal is visible in the bottom right hand side of Fig. 5*b*. A reddish rounded zircon crystal (0.2 cm) lies immediately left of the sapphire crystals (Fig. 5*a* and *b*). The surface of the sapphires and zircon show etch features identical to those described as due to dissolution in carrier magmas (Coenraads, 1992*b*). The sapphire shows classic triangular etch pits (Fig. 5*c*) and the zircon, rectangular pits with central pyramids (Fig. 5*d*) reflecting their internal crystal structure.

The other side of the octahedral crystal, a partially broken surface, shows three euhedral orange-red zircons, with crystal length twice the width. Figure 5*e* shows square cross sections of two zircon crystals (bright areas) within the magnetite. Numerous small oriented elongate corundum laths are present where the octahedral crystal shows a stepped appearance (Fig. 5*f* and *g*). The tops of the steps parallel the {111} face of the octahedron and the long axes of the corundum laths parallel the edges of the steps (Fig. 5*g* and *h*). Figure 5*h* shows sharp interfaces between the corundum (showing conchoidal fracture) and enclosing octahedral crystal. The crystallographic relations between the octahedral crystal and sapphire laths suggest either a controlled intergrowth or exsolution relationship.

Mineralogy. The xenolith was sawn through the centre of the octahedral crystal parallel to {100}. The exposed faces were polished and examined using reflected light microscopy. The phases present in the octahedral crystal were analysed using a Cameca Camebax SX50 electron microprobe. Their compositional ranges are listed in Table 3. An obvious feature of the octahedral crystal is its division into irregular subgrains distinguished by a series of sub-parallel dark lamellae. The orientation of the lamellae changes from subgrain to subgrain and the dominant directions indicate crystallographic control. These dark lamellae are hydrated iron oxides possibly formed by alteration of an exsolved phase. The light (higher reflectivity) areas are Al-Ti magnetite (pinkish grey), magnetite (grey), hercynite (dark grey) and hematite (cream).

Euhedral zircon crystals and a sapphire are also exposed on the polished surfaces (Fig. 6). Minor alteration is evident around these crystals and on the surfaces of the octahedral crystal.

Phases identified in the octahedral crystal. A point count of the phases visible under reflected light (Table 3) was used to calculate the original homogeneous composition of the octahedral magnetite.

The Al-Ti magnetite (Fig. 6*a*) forms 5% of the original crystal as pinkish, irregular shaped patches. They show ragged edges not intergrown with the surrounding phases, and a homogeneous interior, slightly altered but with no distinct exsolution phases which suggest remnants of the originally homogeneous Al-Ti magnetite octahedron.

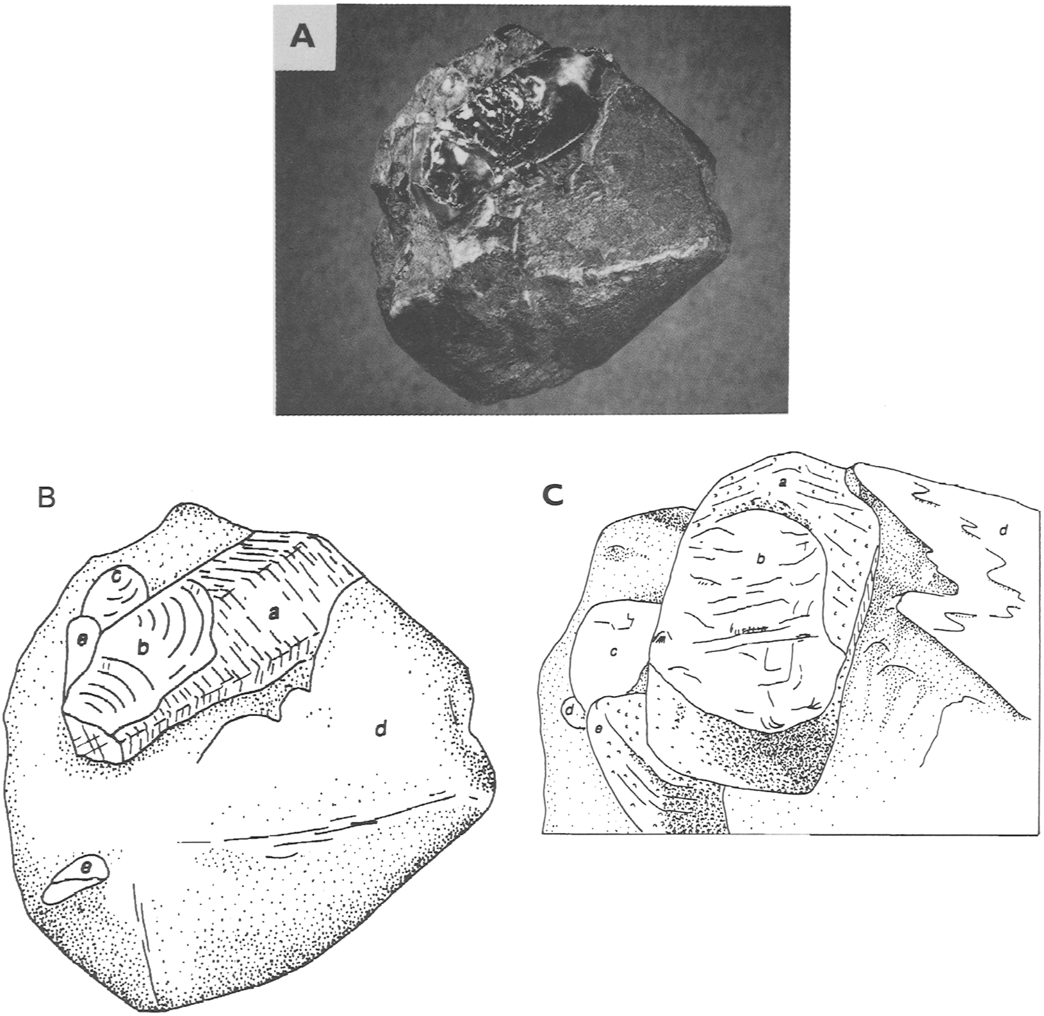

FIG. 4. Xenolith from the Nai Mod mine. *A*. Whole specimen approximately 1.5 cm in size; photograph by R. Oldfield. *B* and *C*. Line drawings of photographs 4*A* and 5*A* respectively, showing a euhedral greenish blue sapphire crystal (a), chipped and displaying conchoidal fracture (b), and a reddish zircon crystal (c) intergrown with a dark reddish-brown octahedral magnetite crystal (d). Other sapphires growing with different orientations are visible (e).

The hercynite is present within all the phases except the Al–Ti magnetite. Oriented, anhedral, exsolution rods appear elongate or circular in outline, depending on their orientation with respect to the polished surface (Fig. 6*b*). If the hereynite now carries all the aluminium present in the original homogeneous crystal and occupies 19% of its volume, then the Al_2O_3 content of the original crystal must have been 10%. This is consistent with the percentage of Al_2O_3 analysed in the Al-Ti magnetite phase (7.6–12.3%) and, with the textural features described above, suggests that the Al-Ti magnetite phase is a remnant of the original homogeneous crystal.

Hematite occupies 40% of the original crystal as a bright, cream-coloured phase with straight-edged contacts against light grey magnetite. The magnetite (occupying 3% of the original crystal) is easily distinguished from the remnant Al-Ti magnetite, being less pink, fresher in appearance and containing exsolved hercynite. In places exsolved hercynite crosses magnetite–hematite boundaries without

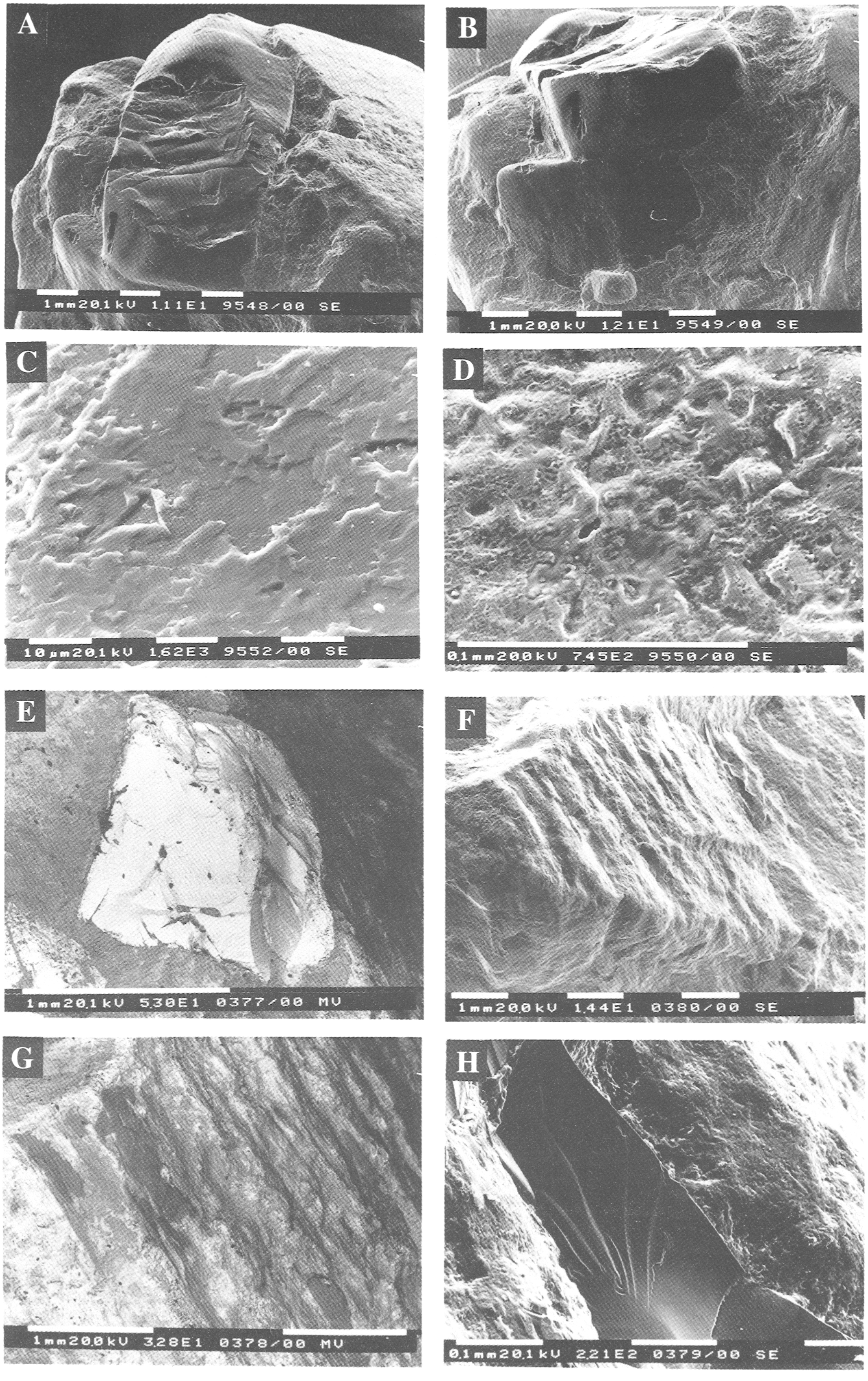
A
1mm20.1kV 1.11E1 9548/00 SE
B
1mm20.0kV 1.21E1 9549/00 SE
C
10µm20.1kV 1.62E3 9552/00 SE
D
0.1mm20.0kV 7.45E2 9550/00 SE
E
1mm20.1kV 5.30E1 0377/00 MV
F
1mm20.0kV 1.44E1 0380/00 SE
G
1mm20.0kV 3.28E1 0378/00 MV
H
0.1mm20.1kV 2.21E2 0379/00 SE

TABLE 3. Compositional ranges and modes for phases comprising the octahedral crystal in the Khao Wua xenolith (individual analyses available on request from the authors).

wt.% oxide	Hercynite	Al-Ti-magnetite	Magnetite	Hematite	Hydr. Fe-oxide	Jarosite/alunite
TiO_2	0.78–0.92	6.52–9.39	0.14–0.24	0.11–0.12	0.02–0.12	0.25
Al_2O_3	45.61–47.75	7.59–12.31	0.39–0.47	0.35–0.62	1.23–2.33	16.11
FeO	42.89–45.69	66.43–77.54	90.84–92.57	86.64–87.82	76.77–78.26	25.89
MnO	3.16–3.36	0.76–3.74	0.27–0.68	0.32–0.35	0.18–0.53	0.18
MgO	2.31–3.83	0.0–0.59	0.0–0.07	0.04–0.05	–	0.08
SiO_2	0.0–0.04	0.0–0.05	0.0–0.05	0.25–0.67	–	0.03
K_2O	–	0.10–0.14	–	0.04	–	8.59
SO_2	0.0–0.02	0.03–0.11	0.01	0.02	–	22.36
P_2O_5	0.0–0.06	0.0–0.03	–	–	0.68–0.81	–
Total	98.0–101.9	92.3–94.4	92.2–93.5	88.2–89.4	77.0–81.3	73.49
No. analyses	5	6	2	2	4	1
modal%	19	5	3	40	29	3

change, implying its exsolution in a once homogeneous magnetite that later partially oxidized to hematite (Fig. 6*b*).

Later veins of magnetite and hematite criss-cross the crystal. The veins are lined with anhedral hercynite and contain magnetite and hematite in straight-edged contact (Fig. 6*c*).

An irregular shaped, dull grey inclusion near the centre of the crystal is a jarosite $KFe_3(SO_4)_2(OH)_6$–alunite $KAl_3(SO_4)_2(OH)_6$ solid solution. It has a mosaic pattern of exsolution lamellae of Al-Ti-magnetite (Fig. 6*d*). This inclusion may have originally separated as an iron sulphide immiscible liquid in an oxide-rich melt before suffering oxidation and hydration.

U-Pb age of zircon from the Khao Wua Xenolith

Fragments from a 2 mm zircon crystal were chipped for U-Pb age analysis. Zircons contain trace uranium. Knowing the decay rate and the amount of daughter lead isotopes present, the zircons can be used for age determination and hence provide an age of the associated sapphire formation. The U-Pb analyses were made with the Sensitive High Mass Resolution Ion Microprobe (SHRIMP) at the Australian National University, Canberra, as outlined in Coenraads *et al.* (1990). Young Cainozoic zircons require special treatment of the data. The ^{207}Pb provides an effective means of monitoring the contribution of "common" Pb. In this case the ^{206}Pb/^{238}U, normalised to a standard (SL13^{206}Pb/^{238}U = 0.0928), provides an initial age estimate. From this the expected radiogenic ^{207}Pb/^{206}Pb can be calculated. This value, using a modelled common Pb composition, then yields an accurate proportion of non-radiogenic ^{206}Pb in the total ^{206}Pb. It provides a revised estimate for radiogenic ^{206}Pb/^{238}U and hence a corresponding age. The analytical results and calculated ages on four fragments from a single zircon grain are presented in Table 4.

The results give an age of zircon formation of 1–2 Ma (±<1 Ma), assuming that the measured ^{206}Pb/^{238}U ratio represents a concordant and

FIG. 5. Xenolith from the Nai Mod mine. *A*. Sapphire and zircon crystals intergrown with magnetite; a planar (111) face of the magnetite is visible to the right and a rounded zircon to the left of the sapphire crystal (see drawing 4C). *B*. Different view shows a second sapphire below the first, a line marking the contact between the two crystals; a rounded zircon crystal lies immediately to the left of the sapphires and a third, silky, opaque cream coloured corundum crystal is visible in the bottom right of the photograph; the small protrusions are magnetite. *C*. Sapphire resorbed crystal face with triangular etch pits. *D*. Zircon surface showing rectangular pits with central pyramids. *E*. Square cross sections of zircon crystals (bright areas) in magnetite, backscatter photograph. *F*. Portion of the octahedral crystal showing a stair-step appearance with steps parallel to the {111} face of the octahedron. *G*. Detail of *F*, backscatter photograph showing numerous <1 mm oriented elongate corundum (dark areas) with their long axes parallel to the edges of the steps. *H*. Detail of *F*, showing the sharp interface between the corundum (with conchoidal fracture) and the enclosing magnetite.

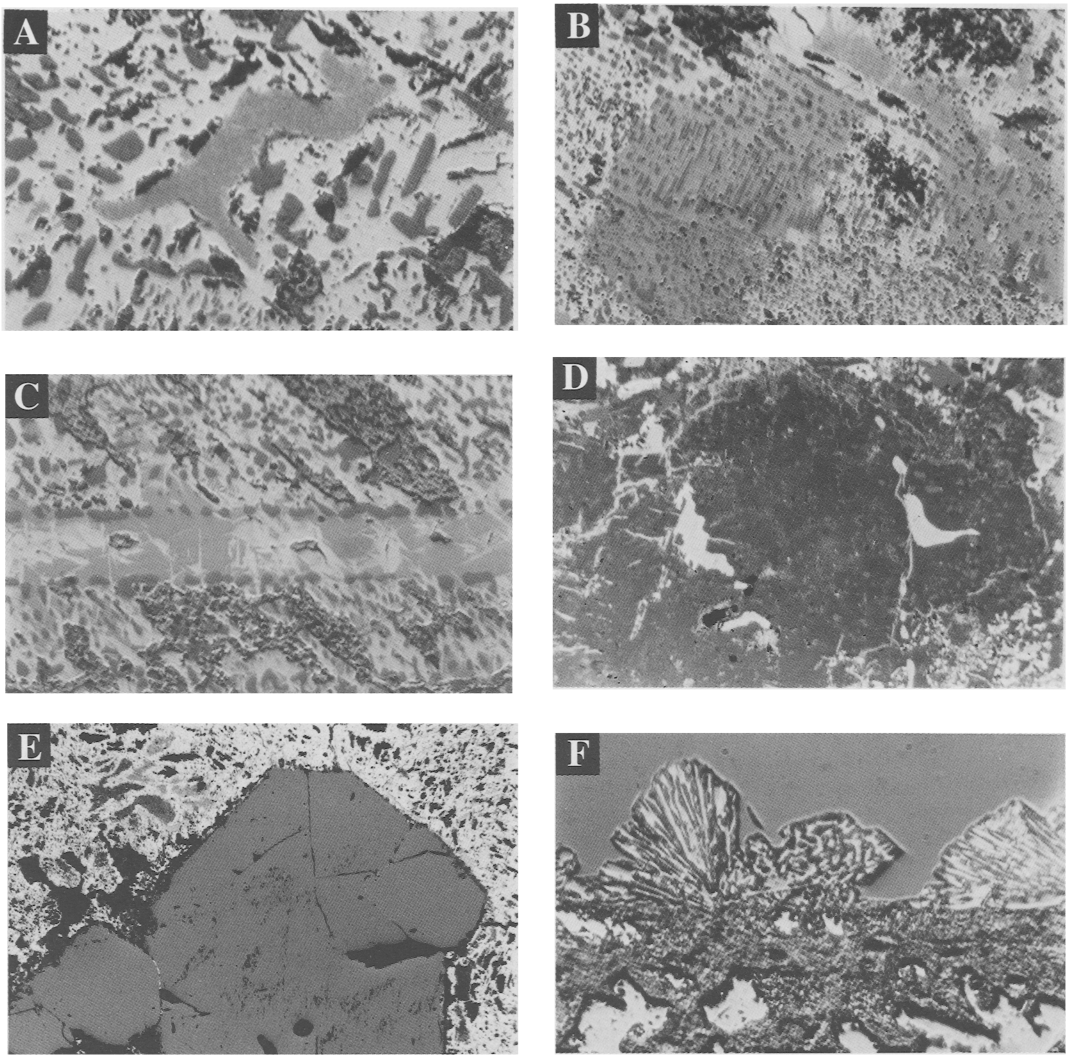

FIG. 6. Polished surface of the octahedral magnetite crystal cut parallel to the {100} direction. *A*. Homogeneous Al-Ti magnetite remnant (kangaroo-shaped) with altered surface and irregular grain boundaries surrounded by hematite (white) and hercynite (dark grey). Base of photo 0.1 mm. *B*. Oriented hercynite exsolution (dark grey) in magnetite (light grey) and hematite (white). Note hercynite exsolution crosses contacts between magnetite and hematite. Base of photo 0.1 mm. *C*. Magnetite (light grey) and hematite (white) in vein crossing octahedral crystal, with hercynite (dark grey) lining the edges of the vein. Base of photo 0.1 mm. *D*. Jarosite - alunite inclusion (dull grey) displaying a mosaic pattern of exsolution lamellae of Al-Ti-magnetite (white). Base of photo 0.18 mm. *E*. Euhedral zircon crystals (dark grey) intergrown with octahedral crystal. Al–Ti magnetite remnants are visible (light grey). Base of photo 0.92 mm. *F*. Detail of the contact between the zircon (homogenous grey) and octahedral crystal showing an alteration zone. Base of photo 0.1 mm.

undisturbed U/Pb isotopic system. The arguments against lead loss are discussed by Coenraads *et al.* (1990). This zircon shows moderately high U (194–519 ppm) and Th (216–519 ppm) with a U/Th ratio of <1 (0.69–0.94). This zircon differs from the zircon inclusions in sapphire dated from Australia, where U is higher and U/Th exceeds 1 (Coenraads *et al.*, 1990).

TABLE 4. U-Pb age of Khao Wua zircon based on four fragments from the same grain

Fragment	^{206}Pb/^{238}U $\pm\sigma$	Age $\pm\sigma$	U	Th	Pb*	Th/U	^{204}Pb/^{206}Pb
1	0.00021 ± 0.00004	1 ± <1	256	310	<1	1.21	–
2	0.00026 ± 0.00004	2–<1	361	519	<1	1.44	0.071854
3	0.00017 ± 0.00005	1 ± <1	202	216	<1	1.07	0.121955
4	0.00027 ± 0.00005	2 ± <1	194	282	<1	1.45	–

^{206}Pb/^{238}U refers to radiogenic ^{206}Pb. Pb* refers to total radiogenic Pb. Values for U, Tb and Pb are in parts per million. – denotes no detectable ^{204}Pb.

Analyst C.M. Fanning, SHRIMP Facility, Geochronology Laboratoy, Australian National University, Canberra.

Discussion

The 1–2(±<1) Ma U-Pb age of the Khao Wua xenolith is consistent with the mean fission track age of 2.57 ± 0.20 Ma for zircons from gem deposits in the Chanthaburi district (Carbonnel *et al.*, 1973) and K-Ar ages of 0.44–3.0 Ma for alkali basaltic volcanism of the Chanthaburi province.

The results imply crystallisation of the xenolith from a melt associated with Pleistocene or late Pliocene basaltic activity. Guo (1993) suggested U-Pb dating of zircon inclusions in corundum megacrysts only reflects the age of host basaltic eruption and not a zircon formation age. He considered lead would diffuse from the zircon under high temperature and calculated that a zircon of about 0.1 mm diameter held at 1400°C at depth would require only few days for all the lead to migrate. This model makes assumptions on temperatures and periods of thermal entrainment. However, there is evidence that zircon megacrysts from basalts and kimberlites do retain their formation age characteristics (Sutherland and Kinny, 1990; Kinny, 1993) and centimetre-sized zircon megacrysts from the New England gem fields with similar U and Th contents to those of zircon inclusions in sapphires from that area gave comparable ion probe ages. Furthermore, lead loss through diffusion is less significant in the Khao Wua xenolith as the zircon is several millimetres across.

The xenolith assemblage (excluding the zircon) and the exsolved phases of the Al-Ti magnetite: corundum, hercynite, magnetite and hematite, can be considered on diagrams for the system Fe–Al–O (Turnock and Eugster, 1962). Some interpretation of the exsolution history can be made in terms of temperature and oxygen fugacity (acknowledging that the presence of Ti, Mn, Mg and Zr and higher pressures may have an effect). It is likely that crystallization of corundum, zircon and homogeneous Al-Ti magnetite took place in an Fe and Al oxide-rich melt, enriched in incompatible elements. The Al-Ti magnetite has a hercynite content (wt.% Hc) of 13 to 21% in solid solution (calculated from its Al_2O_3 of 7.6 to 12.3 wt.%, Table 3). This magnetite–hercynite solid solution composition was probably in equilibrium with the corundum at temperatures above 900°C (Turnock and Eugster, 1962; Fig. 6). The oriented corundum laths in the octahedral magnetite suggest that excess aluminium exsolved during cooling. As cooling continued to temperatures between 740° and 620°C (based on 13–21 wt.% Hc in solid solution; Turnock and Eugster, 1962: Fig. 5), the homogeneous Al-Ti magnetite appears to have exsolved into purer magnetite (Al_2O_3 0.39–0.47 wt.%) with the excess aluminium going into hercynite. The low Al (wt.% Hc < 1%) in the exsolved magnetite indicates that equilibrium was reached at temperatures below 500°C (Turnock and Eugster 1962: Fig. 5). This possibly occurred while the xenolith was in transit to, and cooling at, the surface. Extensive magnetite alteration to hematite also may have occurred at this time. Late-stage veins show hematite and magnetite in rectilinear contact, interpreted as equilibrium growth.

This study indicates that the origin of the sapphire, zircon and Al-Ti magnetite xenolith is similar to that of the New England sapphires and zircons, as proposed by Coenraads *et al.* (1990). Ti-Al magnetite is an abundant associate in the placer deposits of the New England gem fields, although a genetic link between it and the gem minerals is yet to be established. Compared to the crystal in the Khao Wua xenolith, the New England magnetite (Coenraads, 1990, Table 3) is higher in TiO_2 (9.8–22.0%) and MgO (0.6–5.7%), similar in Al_2O_3 (3.6–11.3%) and lower in MnO (0.18–0.54%).

The surface etch features observed on the xenolith compare with those observed on Thai sapphires and rubies, and Australian sapphires (Coenraads, 1992*b*), suggesting similar carrier mechanisms in both cases.

Growth conditions of xenolith—possible host melts. The precise relationships of sapphire growth from original host melts remains uncertain. However the Khao Wua xenolith shows that sapphire crystals of different colours can form together. Australian and Thai sapphires probably formed from phonolitic (nepheline syenite) magmas (Irving, 1986) at pressures roughly equivalent to the crust-mantle boundary (based on CO_2 inclusion studies; Stephenson, 1990). The range of inclusions found in such sapphires (Coenraads, 1992*a*) typically contain incompatible elements which commonly concentrate in felsic magmas. Based on these inclusions and a cobalt spinel found in a Thai blue sapphire, Guo *et al.* (1994) have interpreted the corundum to result from 'complex magma mixing processes' involving felsic and carbonitite melts. Considering the very common association of corundum with alkali basaltic terrains and the consistency of their age relationship in Australia, Thailand and China, we suggest a simpler process — the heating events that generate the magmas from which the gems crystallize are intrinsic to the processes of alkali basaltic magma generation and eruption.

Economic implications. Insufficient data exist to confirm whether all the sapphires in the Chanthaburi–Trat gem fields come from basalts in the 1–2 Ma range or whether some have older origin. However, accurate mapping of alkali basalts in that age range in the region would certainly highlight drainage systems of potential economic interest. Magnetite and zircon are definite associates of sapphire and their discovery in a basalt, soil or drainage system would be a positive indicator for possible sapphire.

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