ORIGIN OF GEM CORUNDUMS FROM BASALTIC FIELDS

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Summary
Favoured basalt fields yield gem corundums among their xenocrystal offerings. They are recorded in 6 continental regions, within 15 countries and involve over 40 main basalt fields. The corundums commonly include 'magmatic' blue, green to yellow, colour-zoned sapphires and less commonly 'metamorphic' various coloured sapphires and ruby. Magmatic suites (60% of basalt fields) dominate over mixed magmatic/metamorphic suites (25%) and metamorphic suites (15%).
Magmatic sapphires contain diverse, but characteristic, mineral inclusions. Co-existing zircon yields uranium-lead isotope formation ages and presumably also the sapphire crystallisation ages. These ages are usually close to host basaltic eruption ages. Rare sapphire-bearing felspathic xenoliths suggest a coarse syenitic origin. Crystallisation of magmatic sapphires has been variously ascribed to mid-crustal carbonatitic-silicic hybrid melt interactions or to lower crust/mantle felsic melts Low volume melting of hydrous mantle to produce such syenitic melts was proposed from zircon/basalt dating within Australian sapphire fields. Growth from buffered high pressure syenitic melts undergoing fugitive alkali carbonatitic volatile loss is supported by recent studies in Scotland.
Metamorphic sapphire and ruby suites incorporate mineral inclusions and trace element contents that indicate a range of metamorphic source assemblages. Rare corundum-bearing metamorphic xenoliths suggest various contact metamorphic, alumino-silicate regional metamorphic and lower crust granulitic sources.
In eastern Australia, trace element contents in corundums sampled from a 3000km long basaltic tract differentiate corundums into several separate magmatic and metamorphic fields. A few corundum suites show intermediate geochemical characteristics between those of 'magmatic' and 'metamorphic' origin and their precise origin requires further study.

Introduction
Gem corundums, both sapphire and ruby, are eroded from particular basaltic eruptives in many continental areas (Table 1). The resistant gem material becomes concentrated in alluvial deposits, providing valuable gem deposits in some areas (Australia, South East Asia; Hughes 1997). Recent studies (Sutherland *et al.* 1998a) reveal corundums of diverse type and origin were expelled with these eruptives, which represent alkali basaltic magmas. Crystals are commonly corroded by magmatic transport and indicate xenocrystal origin.
Prominent are blue, green to yellow, colour-zoned sapphires. Silk in the form of iron and titanium oxides, exsolved along crystallographic directions, is a common feature. These corundums are usually assigned to a magmatic, but non-basaltic, origin (Sutherland 1996; Guo *et al.* 1996; Sutherland *et al.* 1998b; Upton *et al.* 1999). The zoning is ascribed to magmatic growth and the mineral inclusion suites contain a wide variety of species compatible with crystallisation from evolved magmas. Co-existing zircon inclusions give Pb-U isotope ages that typically link in with basaltic magmatism ages in the area and generally lack inherited ages to link them to any local metamorphic terrains. Trace element contents are highest in Fe and Ti, slightly enriched in Ga and low in Cr. Cr_2O_3/Ga_2O_3 ratios

Table 1. Corundum-bearing basaltic fields

Continent Country/State	Area	Main Age	Type
Africa			
Nigeria	Kaduna	Neogene	Mag
Kenya	Garba Tula	Neogene	Mag
	Turkana	Neogene	Mag
Rwanda	Kamemba	Neogene	Mag
Madagascar	Antsiranana	Neogene	Mag
Asia			
China	Hainan	Neogene?	Mag
	Fujian	Neogene?	Mag
	Jiangsu	Neogene	Mag
	Shandong	Neogene	Mag
Laos	Ban Huai Sai	Neogene	Mixed
Thailand	Kanchanaburi	Neogene	Mixed
	Phrae	Neogene	Mag
	Si Saket	Neogene	Met
	Chanthaburi	Neogene	Mag
	Trat	Neogene	Mixed
	BoRai	Neogene	Met
Cambodia	Pailin	Neogene	Mixed
Vietnam	Di Linh	Neogene	Mag
	Phan Thiet	Neogene	Mag
	Gia Kiem	Neogene	Mag
Australia			
Queensland	McLean	Neogene	Mag
	McBride	Neogene	Mag
	Rubyvale	Paleogene	Mag
	Anakie	Paleogene	Mag
	Boyne	Neogene	Mag
New South Wales	New England	Paleogene	Mixed
	Wellington	Mesozoic?	Mixed
	Barrington	Paleogene	Mixed
	Oberon	Neogene	Mag
	Tumbarumba	Neogene	Mixed
Victoria	Myrniong	Paleogene	Mixed
Tasmania	NE Tasmania	Paleogene	Mag
Europe			
Scotland	Outer Hebrides	Paleogene	Mag
	Midland Valley	Paleozoic	Mag
	Velay	Neogene	Mag?
France	Jizerska Louka	Cenozoic	Mag
Czech Repbl	Trebivlice	Cenozoic	Met?
N. America			
United States	Idaho	?	Met?
	Montana	Paleogene?	Met?
S. America			
Colombia	Mercaderes	Cretaceous?	Met?

Mag = Magmatic origin. Met = Metamorphic origin

Compiled from Keller *et al.* (1985); Mychaluk (1995); Guo *et al.* (1996); Sutherland (1996); Hughes (1997); Sutherland *et al.* (1998a,b); Upton *et al* (1999); Malinkova (1999).

generally fall below 1 and Fe_2O_3/TiO_2 mostly between 4-800. Colour absorption spectra show significant Fe^{2+} to Fe^{3+} charge transfer effects.

Other gem corundums are variously coloured sapphires and ruby. Colour zoning is usually subdued and the colour spectrum grades from pastel blues to fancy coloured sapphires and ruby. Mineral inclusion suites are similar to metamorphic assemblages as they include phases such as sapphirine and fassaite pyroxene. Trace element contents in these corundums trend to lower Fe and Ga and higher Cr than the magmatic sapphires. Cr_2O_3/Ga_2O_3 ratios largely exceed 1 and Fe_2O_3/TiO_2 mostly falls between 1-200. Colour absorption spectra in blues lack noticeable Fe^{2+} to Fe^{3+} charge transfer effects, while absorption peaks for Cr show up in the violet, mauve, purple, pink sapphires and are prominent in ruby.

Both corundum types appear in comparable proportions in some basalt fields. Metamorphic corundums in the Barrington, Australia and Pailin, Cambodia fields are remarkably similar in trace element and mineral inclusions, suggesting similar metamorphic sources in widely separated gemfields (Sutherland *et al.* 1998a). Minor metamorphic components are now identified in an increasing number of magmatic-dominant sapphire suites.

Origin of magmatic sapphires

These sapphires have somewhat controversial origin, although most workers agree they represent xenocrysts from felsic rather than basaltic melts. This is supported by rare sapphire-bearing syenitic xenoliths (Sutherland 1996; Upton *et al.* 1999) and sapphire-bearing xenoliths that contain zircon with Pb-U ages related to basalts (Coenraads *et al.* 1995).

A study based on mineral inclusions proposed the corundum crystallised from hybrid interaction of carbonatitic and silicic magmas at mid-crustal levels (Guo *et al.* 1996). This was questioned as a major mechanism after re-appraisal of sapphire inclusions (Sutherland *et al.* 1998b) and a deeper origin related to low volume melting of hydrous (amphibole/biotite) mantle was proposed. Corundum crystallisation was considered to take place as mantle plumes approached and faded. A further study (Upton *et al.* 1999) included oxygen isotope data. This supported corundum crystallisation in syenitic melts within metasomatised mantle. Preferential alkali loss during fugitive carbonatitic escape was invoked to achieve aluminous conditions for corundum crystallisation

The generation of aluminous alkali melts within mantle lithologies has been a controversial subject (Yaxley and Kamenetsky 1999), but may be compatible within mantle regimes under certain conditions (Draper and Green 1999).

Origin of metamorphic sapphire-ruby

Two suites which contain abundant metamorphic corundum (Barrington, Pailin basaltic fields) characterise a ruby-sapphire-sapphirine-spinel assemblage (Sutherland and Coenraads 1996; Sutherland *et al.* 1998a). They show similar formation temperatures (770-940 °C) based on sapphirine-spinel thermometry may represent contact metamorphic/ metasomatic sources.

A corundum-sillimanite xenolith from Bo Phloi basalt field, Thailand, suggests a high grade metamorphic origin for a common grey corundum that heat treats to blue among Bo Phloi sapphires(Pisutha-Arnold *et al.* 1998). This corundum shows a strong colour growth zoning and a spread in Cr/Ga ratios, giving it somewhat unusual characteristics among the metamorphic suites.

A unique xenolith from Lava Plains, Australia, that contains a sapphire-kyanite-ilmenorutile-zircon assemblage, also denotes a high grade metamorphic origin (R.R. Coenraads, F.L. Sutherland, C.M. Fanning and P.O.W. Hoskin, unpublished data). U-Pb isotope dating suggests a Late Paleozoic age for this metamorphic sapphire association, although late-stage Neogene metasomatic zircon formation has overprinted the assemblage shortly before eruption of the host late Neogene basalts.

A pink sapphire suite from Wellington, Australia, contains fassaite and rutile inclusions (R..R. Coenraads and F.L. Sutherland, data). The fassaite appears the most aluminous yet recorded, with over 20wt% Al_2O_3 (Table 2). These corundums may originate from corundum-bearing, sapphirine-fassaite-garnet granulites, found as high pressure xenoliths within Mesozoic basaltic breccia pipes (B.J. Barron, F.L. Sutherland and L.R. Raynor, data).

Table 2 Fassaite in sapphire, Wellington, Australia

Oxide	Wt %	Cation/6O
SiO_2	43.81	Si 1.600
TiO_2	0.07	Ti 0.002
Al_2O_3	20.29	Al 0.873
Cr_2O_3	0.12	Cr 0.003
FeO (total)	2.54	Fe 0.078
MnO	0.10	Mn 0.003
MgO	9.19	Mg 0.500
CaO	22.11	Ca 0.865
Na_2O	1.02	Na 0.072
NiO	0.08	Ni 0.002
Total	99.33	3.998

Electron microprobe analysis, F.L. Sutherland

Australian case study

Eastern Australia provides a 3000km long tract of basalt-derived gem corundum deposits, which include both magmatic and metamorphic corundums for detailed investigation (Figure 1).

A geochemical discrimination diagram, based on Cr_2O_3/Ga_2O_3 and Fe_2O_3/TiO_2 ratios of the corundums divides them into several discrete, or partly overlapping, fields (Figure 2). Magmatic 'basaltic' sapphires sampled along the tract fall into a relatively restricted field (b), with most variation within Fe_2O_3/TiO_2 ratios. Related 'trapeche-like' sapphires (showing crystallographic exsolution of iron and titanium oxides, rather than a true trapeche growth structure) are offset towards higher Cr_2O_3/Ga_2O_3 and lower Fe_2O_3/TiO_2 ratios (t). This may reflect exsolution removal of Fe and Ti effects. Metamorphic corundum suites with high Cr_2O_3/Ga_2O_3 ratios fall into distinctive fields (Barrington, Wellington, Tumbarumba) suggesting diverse local metamorphic sources, compatible with observed differences in mineral inclusions. Two suites (Swanbrook and Myrniong) include fancy coloured sapphire and ruby that show transitional trace element characteristics between those of well-defined magmatic and metamorphic suites. Further study is needed to clarify whether these are Cr-enriched members of the magmatic suites or Ga-enriched members of metamorphic/metasomatic suites (e.g. skarn corundums).

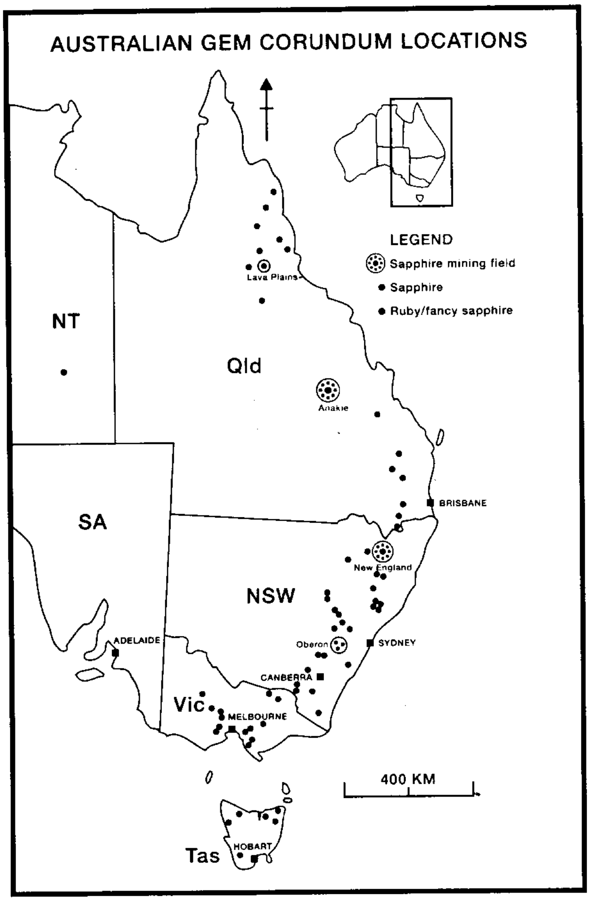

Fig 1 Gem corundum distribution, E. Australia

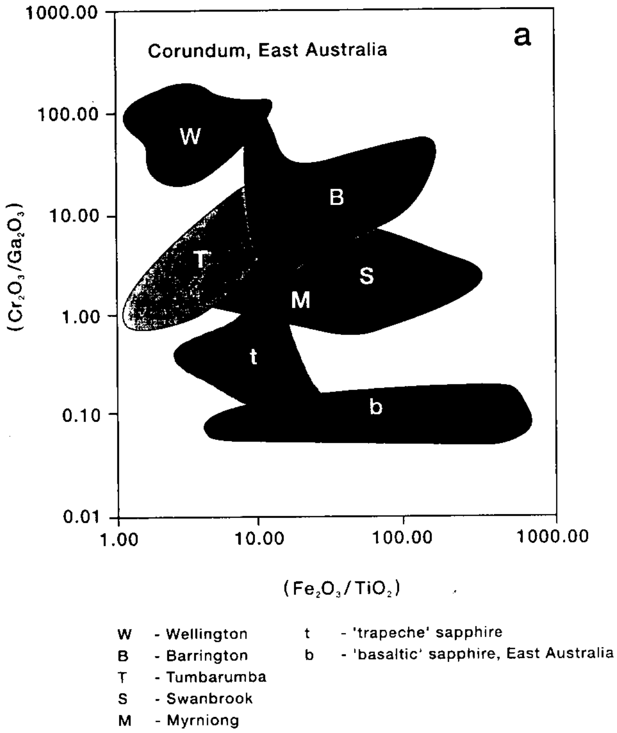

Fig 2 Trace element fields, gem corundums, E. Australia

Conclusions

Basaltic fields discharge both magmatic and metamorphic origin corundums from underlying sources. Several fields with bimodal origins are now known. Magmatic sapphire suites exhibit more consistent trace element variations than metamorphic sapphire-ruby suites, which encompass a diversity of metamorphic origins.

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