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Gemstone Characteristics, North-East Barrington Plateau, NSW

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Abstract: Corundum and zircon concentrates from gravel deposits in two northern Barrington plateau prospects were studied for their features, to investigate potential gemstone sources within the catchment zone. The studies utilized field research, colour sorting, gemmological microscopy, EDAX and PIXE trace element analysis and zircon fission-track dating. The results showed statistical differences in corundum suites from different gravel horizons, which suggested different source areas. Anorthoclase and ilmenorutile were identified as inclusions in Barrington corundums for the first time. Zircon fission-track results showed that several episodes of volcanic eruptions were involved (66–4 Ma), reinforcing and adding to previous eruption ages. This suggests multiple corundum delivery both in space and time into drainage systems.

Keywords: Corundum, ruby, gravels, terraces, eruption, trace elements, mineral inclusions, zircon, gemstone sources.

INTRODUCTION

The Barrington volcanic plateau, 150 km north-northwest of Newcastle (Figure 1, page 117) is one of the many basalt lava fields in eastern Australia (Mason 1989, O'Reilly and Zhang 1995, Sutherland and Fanning 2001). The field is particularly noted for its association with gemstones (ruby, sapphire, zircon), brought up in multiple basaltic eruptions between 60 and 4 Ma and concentrated by erosion into adjacent alluvial deposits (Sutherland et al. 1998, Sutherland and Fanning 2001). The presence of gem quality ruby in the Barrington deposits (Webb 1997) has promoted investigations into the economic potential of the gem deposits by the Australian exploration and mining company Cluff Resources Pacific NL. Exploration and testing programs have been concentrated in the northeastern part of the province, particularly in the terraces and recent alluvial deposits of the upper Manning River at Gummi Flats. Plates 1 to 3 show examples of rubies and sapphire from the Gummi Flats deposits.

This study presents:

1. The first detailed comparison of corundums found in the Gummi Flats terraces, to assist in evaluating their origin and distance travelled from source regions.

2. Detailed fission-track dating on zircons concentrated from the northeastern Barrington field that helps to clarify the extent of gem bearing eruptive episodes in this area.

GEOLOGICAL SETTING

The general geology of the Barrington Plateau region, its economic deposits and literature are outlined in Gilligan et al. (1987) and Sutherland and Graham (2003). The general geology of the study area in the North-East Barrington Plateau is summarised below.

Basement geology consists of Late Devonian to Early Carboniferous mudstone and siltstone with minor interbedded conglomerate, lithic sandstone and limestone. Most of this material was deposited in a deep marine environment. The sheet-like deposits of greywacke within the mudstone were probably deposited by turbidity currents, while some of the conglomerates may have been deposited as submarine fans. A Permian hornblende-biotite granodiorite pluton and associated dykes intruded through the folded Devonian, Carboniferous and Early Permian sedimentary rocks at Gummi Flats. These sequences are capped mostly by Cenozoic basaltic flows.

This volcanic activity most likely extended from around 60 Ma to perhaps < 5 Ma. Alkali basaltic flows and tuffaceous and fragmented volcanics are common, and form the resistant plateau region. Underlying these massive basalt flows is a basaltic horizon containing highly altered basalt bombs. The sequence includes ankaramitic basalt that may mark an intrusive sheet.

This elevated basalt plateau has been subjected to radial drainage patterns over time, cutting into the basalts and underlying Palaeozoic sediments and granodiorites. Local stream and drainage patterns have accumulated clasts of these rocks as well as gem stones in many river flats and catchment areas. Changes in stream patterns and velocities have created river terraces in localised areas.

STUDY AREA

Two study sites were investigated in this study in the northern Barrington Plateau.

Gummi Flats Area

The main sampling sites for corundum and zircon included sections of older terraces and the present alluvial terrace deposits of the upper Manning River. These lie below the eastern edge of the basalt field both upstream and downstream of Backwater Creek junction (Figure 2, page 101). The deposits were excavated during bulk testing and sampling programs by Cluff Resources Pacific NL, during the period 2000–2003.

Suites of corundums were recovered from heavy mineral concentrates from four specific gravel horizons: The upper (A) and lower (B) horizons of the Upper Terrace deposit (Trench 11); the Middle Terrace deposit (C; Trench 4A) and Recent alluvial deposit (D; Trench 2A). The zircons were recovered from heavy mineral concentrates from the Upper Terrace deposit (Trench 11).

(A). Upper gravel horizon of the Upper Terrace (Section 18-A; Figure 3, page 102).

This grey gravel horizon ranges in thickness up to 0.5 m and overlies the lower gravel horizon for approximately 55 m strike-length in the test trench. It is moderately to well sorted and exhibits mostly rounded to sub-rounded lithic fragments with sizes from sub-mm up to 250 mm. There is an upward fining in the sequence, and a grey clay matrix makes up approximately 45% volume of this horizon. Lithic types include, igneous, metamorphic and metasedimentary rocks. Generally more granodiorite fragments are present than in the underlying gravel horizon.

(B). Lower gravel horizon of the Upper Terrace (Section 18-B; Figure 3).

This gravel contains rounded to sub-angular, igneous, metamorphic and meta-sedimentary lithic fragments, with sizes ranging from sub-mm to > 256 mm. The horizon is up to 2.6 m thick and has a reddish fine sandy clay matrix, with occasional sand and silt lenses up to 20 cm in length and 10 cm thick. There is indistinct upward fining, but generally the horizon is very poorly sorted. This horizon is overlain in part by the grey gravel horizon (Section 18-A), and a medium grey sand or a fine silty clay. Humus topsoil some 0.5 m thick caps the sequence. Weathered granodiorite forms the underlying basement.

(C). Middle Terrace horizon (Section T4A; Figure 4, page 103).

The horizon consists of sub-rounded to sub-angular, igneous, metamorphic and meta-sedimentary rocks. Rock sizes vary from sub-mm to > 256 mm. An orange clay matrix, with sporadic black clay lenses up to 20 cm thick underlies a grey gravel in some places. Some fragments show heavy manganese staining. The horizon ranges up to 2.5 m thick, is poorly sorted but shows a slight fining upwards. Basement is weathered granodiorite, and large sporadic fresh granodiorite boulders appear at the base of the gravels. A fine sandy clay of varying colour overlies the gravel horizon, and is up to 2.7 m thick. Black organic topsoil cover is variable, but averages 0.5 m.

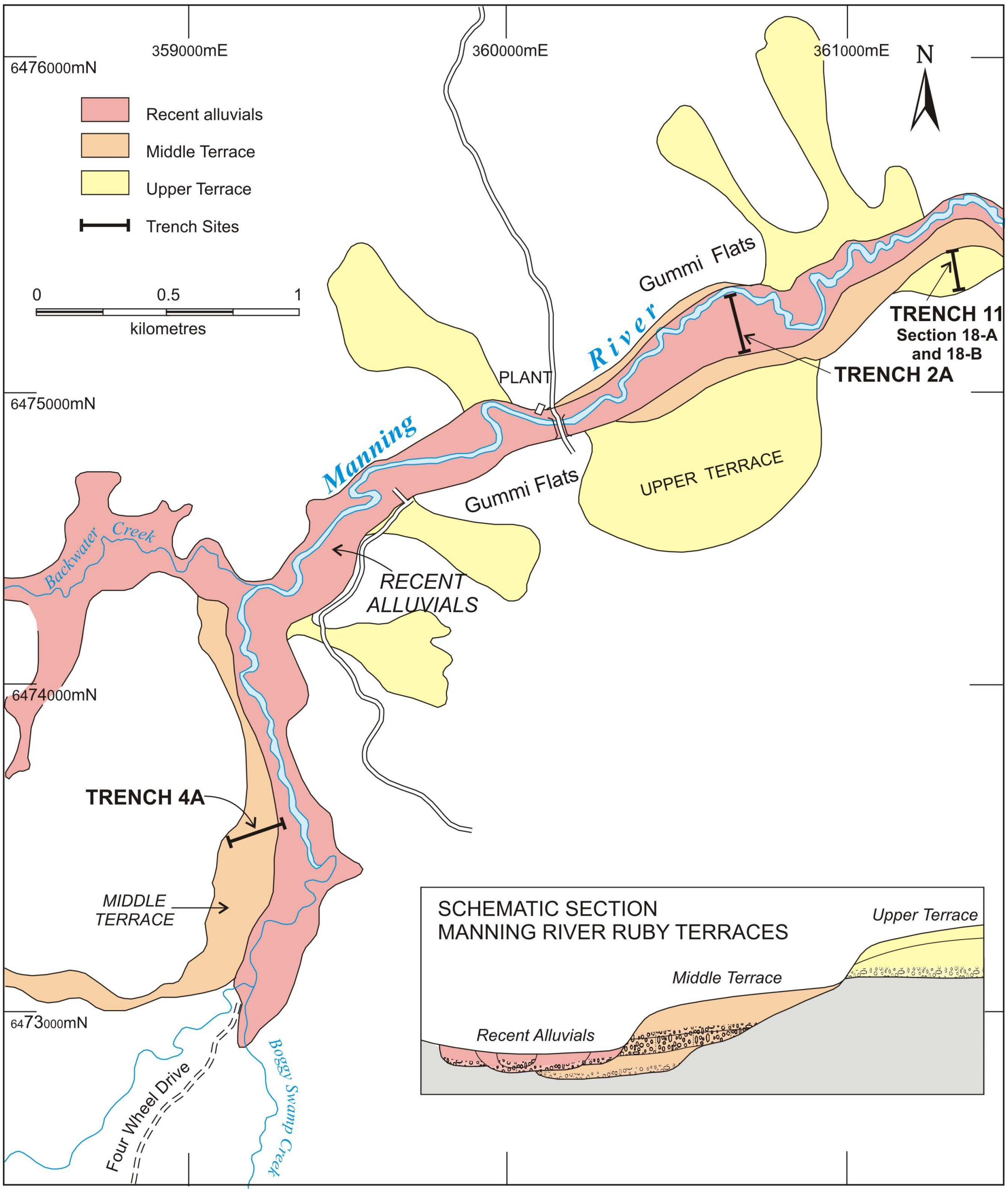

Figure 2. Sample site locations, Gummi Flats, Manning River deposits, with schematic section showing gem-bearing deposits (inset).

(D). Recent Alluvials
(Section T2A; Figure 5, page 103).
The gravel horizon here is composed of igneous, metamorphic and meta-sedimentary rocks, that are sub-angular to sub-rounded, with a colour gradation laterally from grey, black, grey-brown to light brown. Rocks range from sub-mm to > 256 mm, with most exhibiting sub-rounded to rounded shape. The horizon is up to 2.6 m thick. A sandy clay and clay overlies the horizon below a black humus topsoil. The basement is weathered granodiorite.

East Tomalla

East Tomalla is an alluvial site, within the basalt field itself (Figure 1, page 117). This site produced zircons from a ruby prospect, and is 3 km northwest of the Gummi Flats deposits (G. Jeffreys lease). The site at 1160 m asl lies at the head of a small tributary creek that drains a local basalt cap that rises to 1200 m asl. The drainage descends north into Tomalla Creek and the alluvial deposit consists of an upper 30 cm of coarse gravels with heavy minerals concentrated towards the base and overlies a 0.5 m layer of clay. The overlying basalt shows cracking and pitting which is typical of the weathering of nepheline-bearing lavas. It contains prominent megacrysts of spinel and sparse clinopyroxene (up to 5 cm), sporadic xenoliths of spinel-metaperidotite (up to 8 cm) and rare granulites (up to 6 cm). This basanite flow descends north to 1075 m asl, where it overlies 'deep lead' alluvial deposits. These contain fragments of metasediments, igneous rocks and waterworn boulders of silicified conglomerate up to a meter across from basement sources. Obvious fragments of typical Barrington basalts are not seen. Heavy mineral concentrates from the East Tomalla zircon site for fractions both above and below 2 mm size range are described in Appendix 1.

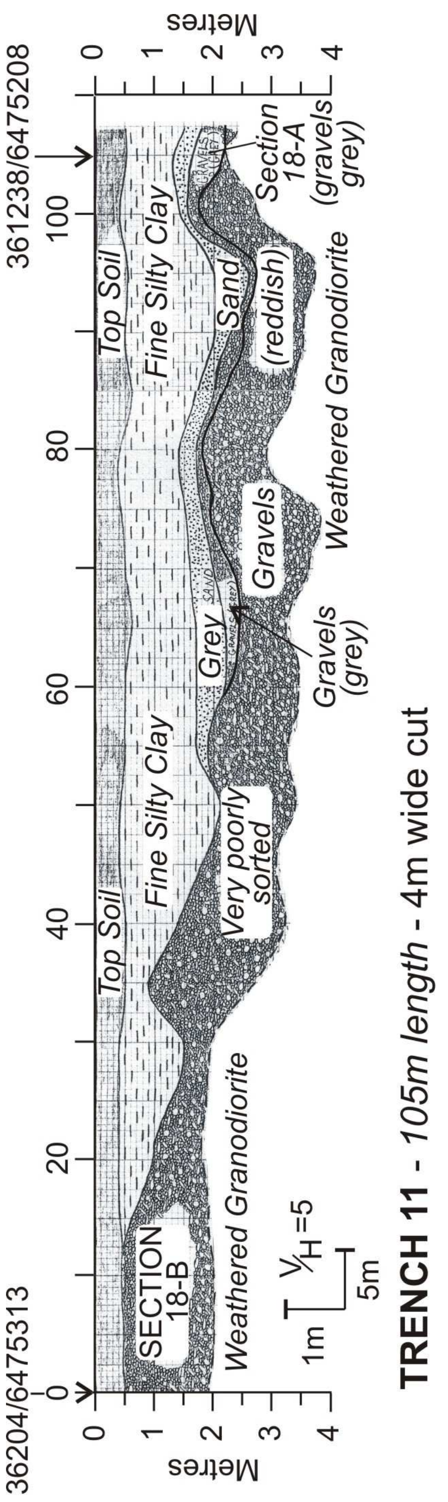

Figure 3. Cross-section, showing Section 18-A and 18-B in the Upper Terrace.

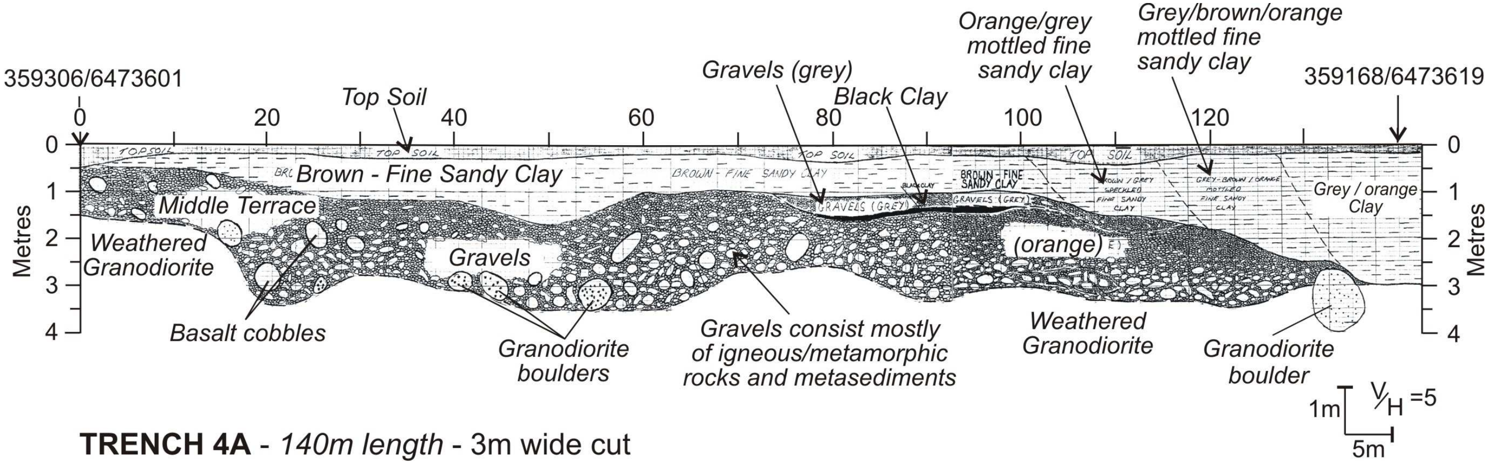

Figure 4. Cross-section, showing Section T4A in the Middle Terrace.

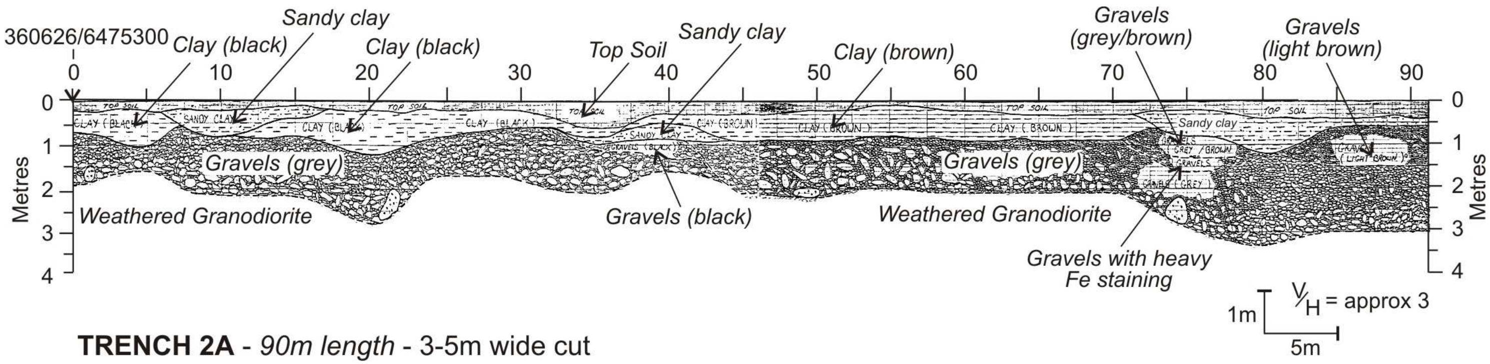

Figure 5. Cross-section, showing Section T2A in the Recent Alluvials.

METHODOLOGY

Corundum Suites

Representative suites of corundums were sampled from each of the corundum concentrates obtained from the four study horizons. The number of corundums studied from each suite was considered to represent statistical sets, based on earlier work using check monitoring of more extensive counting from one of the corundum suites. The statistical method used for this study, involved 'carat weight (ct) / sample %' analysis of corundums. The following sample weight to percentage ratios are as follows. 0–5 ct(100%), 6–10 ct(50%), 11–20 ct(30%), 21–30 ct(20%), 31–40 ct(10%), 41–60 ct(7%), 61–100 ct(5%). Note that when individual suites exceeded 100 ct, the percentage of stones analysed was calculated to conform to the above mentioned ct/% calculations, e.g. if sample weight was 200 ct then 3% of the sample would be analysed.

The selected corundums were viewed under a gemmological binocular microscope and the visible features noted, among a range of physical parameters. These parameters included: colour, magmatic corrosion (resorption), alluvial abrasion, fusion crusts, fracture surfaces, percussion marks, mineral inclusions, hydrothermal fluid lines and growth zoning. The mineralogy of surface crusts and exposed inclusions in the corundums were investigated using an EDAX system, linked to a JEOL JXA-8600 Superprobe, in the School of Science, Food and Horticulture, BRCI campus, North Parramatta, University of Western Sydney.

The examined corundums were divided into five separate colour groups and percentages of each feature noted within them are listed in Table 1, (Upper Terrace - upper and lower horizons) and Table 2, (Middle Terrace and Recent Alluvials). Colour ranges were further subdivided for each unit/suite into a Colour-Shade grouping, (e.g. very pale, pale, medium and dark). The percentages of features counted in each colour subdivision are presented as a series of histograms and represent a more detailed analysis of colour sorting and associated corundum features. (Figures 6 and 7, pages 118 to 120).

Previous work on Gummi alluvial corundums (Sutherland and Coenraads 1996; Sutherland et al. 1998) demonstrated that the Pink - Red Group and some Blue Group corundums have mineral inclusions such as sapphirine, trace element ratios with Cr / Ga > 1 and colour absorption patterns (decreasing absorption at 600–850 nm) that typify metamorphic origins. Some Blue, Green, Yellow and related Grey - Brown - Black corundums however, have different mineral inclusions (e.g. peonaste spinel), trace element ratios with Cr / Ga < 1 and colour absorption (sustained or increasing absorption between 600–850 nm) that characterise magmatic origins.

To supplement this work, further trace element determinations were made on Gummi corundums by Proton-induced X-Ray Emmission (PIXE) methods and are presented in Table 3. The analyses were made on the PIXE analytical facility at Guelph University, Canada, using a beam current between 1 to 3 nA, a charge accumulation above 0.5 μc and approximately 5 minutes analytical time per sample (M.I. Garland, University of Toronto, analyst). A mylar filter was used to eliminate the intense Al X-rays produced by the corundum, which eliminated some light element determinations (e.g. Mg).

The overlap in characteristics for the Blue Group Gummi corundums makes precise assignment of the origin of these stones uncertain in this colour group (Tables 1 and 2 on pages 106, 107; Figures 6 and 7). However specific features, such as colour growth zoning, may indicate a magmatic origin, while specific inclusions such as sapphirine may indicate a metamorphic origin.

Zircon Suites

Zircon grains up to 2 mm in size from each of the two study sites were grouped into colour subsets prior to submission to Geotrack International P.L., for mounting, etching and irradiation at the Lucas Heights NSW reactor. The resultant fission-track counting used a Zeiss

®AXIOplan microscope. Details of the analytical methods and statistical treatments used in the analyses are outlined in Green (1981, 1983), Galbraith (1981, 1988, 1990) and Hurford and Green (1982, 1983). The fission-track results are summarised in Tables 4 and 5 on page 111.

RESULTS

EDAX Analysis

Analysis identified the following mineral phases associated with the corundums in inclusions and alteration crusts. Mineral inclusions identified were Mg-rich to Fe-rich pleonaste to hercynite spinel, sapphirine, anorthoclase feldspar, ilmenorutile and a magnesium-iron aluminosilicate. The spinels and sapphirine were previously recorded from Barrington Tops corundums, but anorthoclase and ilmenorutile are new records as inclusions in these corundums. Differences in fusion crust mineralogy were also noted, with Mg and Fe-rich spinels being the most common, although aluminosilicates (mullite) were also present. Some specimens exhibited fusion crusts combining both Mg-rich and Fe-rich spinel, but usually on different sides of the stone.

Grouped Corundum Features

The main aspects of the features found in different corundum groups (Tables 1 and 2) are summarized for each sample horizon. Three main corundum groups are considered, a Ruby Group, with colours ranging from dark red to very pale pink, a Grey-Brown-Black Group (GBB), and a Blue-Green-Yellow Group (BGY).

SECTION 18-B, lower gravel horizon (Upper Terrace)

Ruby Group Over 80% of these corundums exhibit both magmatic resorption and heavy fracturing, while another 14% show either resorption or heavy fracturing. Nearly 2% have a surface fusion crust, 3.3% include percussion marks and 0.4% contain sapphirine inclusions.

Grey-Brown-Black Group (GBB) Nearly 85% combine resorption and heavy fracturing, while a further 10.7% show resorption, and only < 2% of stones show percussion marks.

Yellowish Group (BGY) Nearly 86% exist as resorbed and fractured stones. Stones showing only resorption make up 14.2%. Nearly 5% contain spinel inclusions.

Greenish Group (BGY) Nearly 95% show resorption and heavy fracturing, 5.4% show only heavy fracturing, whilst 5.2% show a combination of resorption and heavy fracturing, along with spinel inclusions.

Blue Group (BGY) Nearly 99% show both resorption and heavy fracturing, with 2.4% containing spinel inclusions and 1.2% showing percussion marks. Some 1.5% of stones show only fracturing.

SECTION 18-A, upper gravel horizon (Upper Terrace)

Ruby Group Here 52.6% show a combination of resorption and heavy fracturing, 1.9% show a fusion crust and 0.5% have percussion marks. Some 3.5% of stones contain spinel, sapphirine or ilmenite (optical identification) as inclusions.

Grey-Brown-Black Group (GBB) Only 7.4% of stones show either resorption or heavy fracturing, 2.8% contain spinel inclusions, while 0.3% have a fusion crust and 0.3% show percussion marks.

Yellowish Group (BGY) While 19.7% of stones show only resorption, nearly 78% of stones show a combination of resorption and heavy fracturing. About 4% have spinel inclusions, 1.3% show percussion marks and 2.6% of stones show only heavy fracturing of which 1.3% have a fusion crust.

Greenish Group (BGY) About 77% show resorption and heavy fracturing, 3.8% contain spinel inclusions and 1.9% show percussion marks. About 23% show resorption as the only feature.

Blue Group (BGY) Nearly 74% have a combination of resorption and heavy fracturing and of these 0.5% are fusion crusted stones. Some 3.2% have percussion marks and 2% of these show heavy fracturing only. Another 24.8% of stones are resorbed, with only 0.6% having percussion marks.

	Corundum 'Ruby' Metamorphic	Corundum (GBB) Magmatic	Corundum 'Yellowish' (BGY) Magmatic	Corundum 'Greenish' (BGY) Magmatic	Corundum 'Blue' (BGY)
R	37.4	6.7	19.7	23.0	24.4
F	6.4	0.7	1.3		2.0
R-F	50.3	89.2	72.5	71.3	67.8
R-C	0.7				
F-C			1.3		
R-SpI	0.8	0.5			
F-SpI		0.5			
R-SapI	0.5				
F-SapI	1.6				
R-P					0.6
F-P					
R-F-C	1.2	0.3			0.5
R-F-SpI	0.4	1.8	3.9	3.8	1.7
R-F-SapI	0.1				
R-F-ILI	0.1				
R-F-P	0.5	0.3	1.3	1.9	3.2
R-C-SpI					
R-C-SapI					
F-SpI-P					
R-F-C-SpI					
R-F-C-SapI					
ZONED					11.1%
No. of stones analysed:	116	117	21	38	65

Section 18-A
Upper Terrace, Upper Horizon Gravels
Grouped percentages

	Corundum 'Ruby' Metamorphic	Corundum (GBB) Magmatic	Corundum 'Yellowish' (BGY) Magmatic	Corundum 'Greenish' (BGY) Magmatic	Corundum 'Blue' (BGY)
R	10.7	10.2	14.2	5.2	22.8
F	3.6	2.2		5.4	1.5
R-F	80.1	83.0	81.1	84.2	72.1
R-C					
F-C					
R-SpI				2.6	
F-SpI					
R-SapI					
F-SapI					
R-P					
F-P					
R-F-C	1.9				
R-F-SpI		2.8	4.7	2.6	2.4
R-F-SapI	0.4				
R-F-ILI					
R-F-P	3.3	1.8			1.2
R-C-SpI					
R-C-SapI					
F-SpI-P					
R-F-C-SpI					
R-F-C-SapI					
ZONED					2.6%
No. of stones analysed:	276	204	76	52	114

Section 18-B
Upper Terrace, Lower Horizon Gravels
Grouped percentages

Table 1. Grouped corundum percentages, from the Upper Terrace, Sections 18-A and 18-B. R Shows Resorption, F Heavily Fractured, C Fusion Crust, P Percussion Marks, SpI Spinel Inclusions, SapI Sapphirine Inclusions, Ili Ilmenite Inclusions

	Corundum 'Ruby' Metamorphic	Corundum (GBB) Magmatic	Corundum 'Yellowish' (BGY) Magmatic	Corundum 'Greenish' (BGY) Magmatic	Corundum 'Blue' (BGY)
R	7.8	7.1	30.8	7.7	12.2
F	8.7	1.8		15.5	
R-F	71.7	84.8	69.2	69.2	84.7
R-C					
F-C					
R-SpI	0.4				
F-SpI		0.8		7.6	
R-SapI					
F-SapI					
R-P					
F-P					
R-F-C	2.3	1.6			
R-F-SpI	3.1	1.6			
R-F-SapI	1.2				
R-F-ILI					
R-F-P	1.7	2.3			3.1
R-C-SpI	0.9				
R-C-SapI	0.7				
F-SpI-P					
R-F-C-SpI	0.8				
R-F-C-SapI	0.7				
ZONED				13.5%	
No. of stones analyzed:	105	105	13	13	76

Section T2A, Recent Alluvials, Grouped percentages

	Corundum 'Ruby' Metamorphic	Corundum (GBB) Magmatic	Corundum 'Yellowish' (BGY) Magmatic	Corundum 'Greenish' (BGY) Magmatic	Corundum 'Blue' (BGY)
R	14.4	23.1	10.0		23.6
F					1.9
R-F	28.1	69.4	60.0	78.6	64.5
R-C	12.2				
F-C					
R-SpI					
F-SpI			10.0		
R-SapI					
F-SapI					
R-P		2.5	10.0		
F-P					
R-F-C	28.1			7.2	2.3
R-F-SpI		2.5	10.0	14.2	4.0
R-F-SapI	5.1				
R-F-ILI					
R-F-P	3.5				1.8
R-C-SpI	2.5				
R-C-SapI					
F-SpI-P					1.9
R-F-C-SpI	3.1	2.5			
R-F-C-SapI	3.0				
ZONED					
No. of stones analyzed:	53	43	10	14	58

Section T4-A, Middle Terrace, Grouped percentages

Table 2. Grouped corundum percentages, from the Middle Terrace (Section T4A) and the Recent Alluvials (Section T2A). R Shows Resorption, F Heavily Fractured, C Fusion Crust, P Percussion Marks, SpI Spinel Inclusions, SapI Sapphirine Inclusions, Ili Ilmenite Inclusions

Section T4A (Middle Terrace)

Ruby Group Almost 71% of stones show resorption and heavy fracturing, 34.2% contain fusion crusts, while 8.1% contain sapphirine inclusions, 3.1% spinel inclusions and 3.5% show percussion marks. Some 14.4% show only resorption and 12.2% show resorption with fusion crusts.

Grey-Black-Brown Group (GBB) Nearly 75% of stones are resorbed and heavily fractured, with 5% containing spinel inclusions and 2.5% a fusion crust. Otherwise 23.1% are resorbed only and 2.5% are resorbed and show percussion marks.

Yellowish Group (BGY) Only 70% of stones are resorbed and heavily fractured with 10% of these containing spinel inclusions. Just 20% show resorption with 10% of these having percussion marks. Stones showing only heavy fracturing but containing spinel inclusions account for 10% of the suite.

Greenish Group (BGY) All stones show resorption and heavy fracturing, with 7.2% of these having a surface fusion crust and 14.2% spinel inclusions.

Blue Group (BGY) About 73% show resorption and heavy fracturing, with 2.3% having a fusion crust. Some 4% contain spinel inclusions and 1.8% show percussion marks, Just 23.6% of this suites stones show resorption only, nearly 2% show heavy fracturing only and just 1.9% show heavy fracturing, percussion marks and spinel inclusions.

Section T2A, Recent Alluvials

Ruby Group Nearly 82% of stones are resorbed and heavily fractured showing combinations of either spinel or sapphirine inclusions, fusion crusts and percussion marks. Only 9.8% show resorption as the main feature.

Grey-Brown-Black Group (GBB) Some 90.3% are resorbed and heavily fractured, while 3.2% contain spinel inclusions and fusion crusts and 2.3% show percussion marks. Only 1.8% are just fractured and 0.8% are fractured with spinel inclusions.

Yellowish Group (BGY) Around 69% of stones are resorbed and heavily fractured, with 30.8% showing resorption only.

Greenish Group (BGY) In this group 92.4% are resorbed or heavily fractured or a combination of both, while 7.6% are heavily fractured and contain spinel inclusions.

Blue Group (BGY) Nearly 85% show resorption and heavy fracturing, while 3.1% are resorbed, heavily fractured with percussion marks and 12.2% show resorption only. Some 13.5% of the group show growth zoning.

Colour-Shade Features

The main features in each colour shade group (Figures 6 and 7) are summarised for each shade.

Ruby Group

Very Pale The Middle Terrace (T4A) lacks very pale pinks. The other 3 terraces feature strong percentages of heavily fractured and resorbed stones. The Upper Terrace (Section 18-B), contains some small percentages ($< 2\%$) with sapphirine mineral inclusions.

Pale Resorption and heavy fracturing dominate as features throughout all four sections. The Recent Alluvials (Section T2A) and Middle Terrace (Section T4A) show the most variation between features and mineral inclusions.

Medium Section 18-B (Upper Terrace) shows stones with spinel inclusions and fusion crusts in $< 10\%$ of the suite. Middle terrace (T4A) gravels show up to 38% stones with fusion crusts and 9.5% spinel inclusions. Recent Alluvials (T2A) stones have spinel, sapphirine inclusions, plus fusion crusts in amounts $< 5\%$.

Dark Resorbed and heavily fractured stones feature heavily in the upper terrace horizons. The Recent Alluvials (T2A) and Upper Terrace gravel horizons contain stones with spinel and sapphirine inclusions plus fusion crusting in $<$ 10%. Middle Terrace gravels contain no stones with mineral inclusions. However fusion crusting is present in around 35% of the suite.

Grey-black-brown Group (GBB)

Very Pale Resorption and heavy fracturing dominate. Less than 10% of stones show spinel inclusions in both horizons of the Upper Terrace, plus approximately 2% show fusion crust and percussion marks.
Pale Over 80% of stones in the Upper Terrace horizons and Recent Alluvials (T2A) feature resorption and heavy fracturing, and $<$ 5% with spinel inclusions were noted in each of the 3 horizons. The Middle Terrace (T4A) stones show higher (10%) spinel inclusions, fusion crusts and percussion marks in the resorbed and heavily fractured stones.
Medium All 4 horizons show high percentages of resorbed and heavily fractured stones; Only the Recent Alluvials contain stones with fusion crusts and spinel inclusions in $<$ 5%.
Dark Resorbed and heavily fractured stones are predominant in all 4 horizons. Only the Recent Alluvials and Section 18-A feature stones with percussion marks.

Blue-greenish-yellowish Group (BGY)

Very Pale Resorbed and heavily fractured stones are only noted in Section 18-B and the Middle Terrace.
Pale Resorption and heavy fracturing dominate as coupled and single features in stones from both horizons of the Upper Terrace and Recent Alluvials (T2A), while $<$ 10% fusion crusting, percussion marks and spinel inclusions are seen throughout all 4 suites.
Medium High percentages of resorbed and heavily fractured stones occur in all 4 suites. The Middle Terrace shows minor (approximately 6%) percussion marks.
Dark Only resorption and heavy fracturing is seen as single or combined features in Section 18-A stones. Section 18-B stones show $>$ 10% percussion marks and the Middle Terrace (T4A) stones contain approximately 12% with fusion crusts and spinel inclusions.
Yellowish Resorbed and or heavily fractured stones feature heavily throughout the 4 suites, however small percentages ($<$ 5%) of spinel inclusions, fusion crusts and percussion marks are present in the Upper Terrace gravel horizons. The Middle Terrace (T4A) shows approximately 10% assemblages of spinel inclusions and resorbed or heavily fractured stones with percussion marks.
Greenish Resorbed and heavily fractured stones are dominant features in all suites. Only the Middle Terrace has stones with $>$ 10% spinel inclusions.

Apricot Group

Detailed examination showed that apricot coloured stones are actually light pink rubies, but the orange/apricot colouration is due to penetration by iron oxide minerals into numerous fractures and fissures within each stone.
Light Apricot Resorption and heavy fracturing dominate stones from Upper Terrace gravels (Section18-B) and contain $<$ 10% sapphirine and spinel inclusions. Section T4A, (Middle Terrace) shows $>$ 20% fusion crusting on stones. One stone showed pronounced surface resorption, with intersecting fluid inclusion trails.
Dark Apricot Less than 10% of stones have sapphirine and spinel inclusions in Section 18-B Upper Terrace, with approximately 10% fusion crusted stones present. Section 18-A Upper Terrace stones show 5% with fusion crusting. Stones from the Recent Alluvials (T2A) contain 10% spinel inclusions and 10% fusion crusting. The Middle Terrace (T4A) contains 30% resorbed, heavily fractured stones showing fusion crusts and nearly 30% resorbed, heavily fractured and fusion crusted stones with sapphirine inclusions.

Corundum Trace Element Contents

Among the chromophore elements, iron is the dominant trace element and ranges from about 2500 to 13,300 ppm. Titanium ranges from about 15 to 1200 ppm, and vanadium is relatively minor ranging from below detection to nearly 200 ppm. Gallium and chromium are the only other important trace elements in corundum trace element comparisons, with gallium ranging from below detection to nearly 300 ppm. The Cr/Ga ratios of the corundums fall into 3 main groups of element ratios and are summarised below.

Colour	Fe(ppm)	Ti(ppm)	Cr(ppm)	Ga(ppm)	V(ppm)	Ca(ppm)	Cr/Ga
Colourless	3027-3045±4	15.16±2	BD-6±1	19-20±1	BD	0-49±3	<0.02-0.34
Pale blue-green	5780-6160±6	212-245±2	BD	64-65±1	45-69±2	BD	<0.02
Light blue-green	9925_10065±8	51-62±2	BD	259-261±1	7-9±2	0-69±3	<0.02
Green-blue	6105-7610±6	62-183±2	BD	128-142±2	BD	BD	<0.02
Yellow-blue	12308-13325±9	481-1242±4	BD	109-110±2	24-31±4	BD	<0.02
Dark blue	8462-9536±8	75-361±3	BD	220-299±2	12-14±2	BD	<0.02
Pale lavender	5383-5607±6	175-193±2	180-195±2	29-30±1	53-59±2	0-12±3	6.13-6.63
Lavender	4990-5063±6	207-214±2	315-322±2	44-47±1	95-97±2	BD	7.07-718
Grey-lavender	5570-5607±6	84-89±2	355-363±2	23-25±1	27-29±2	BD	14.16-15.90
Violet	5660-5811±6	365-385±3	499-501±2	48-49±1	194-195±3	BD	10.26-10.48
Purple	3765-3827±5	42-46±2	165-480±2	22-25±1	12-14±2	BD	7.60-19.20
Light purple	5610-5660±6	292-326±2	490-500±2	45-46±1	154-162±2	BD	10.83-10.90
Browny pink	3720-3838±5	64-65±2	248-258±2	26-27±1	25-26±2	BD	9.07-9.90
Pink	2565-2607±4	30-41±2	688-730±2	29-37±1	15±2	BD	31.42-32.31
Purple pink	4416-4426±5	256-258±2	946-961±3	33-34±1	18±2	BD	27.63-27.65
Pink	2859-3104±4	29-37±2	688-730±2	22-23±1	15±2	BD	31.42-32.28
Bright pink	3074-3125±4	43-44±2	722-763±2	20-21±1	13-14±2	BD	36.66-37.59
Bright pink	2607-3190±4	30-41±2	907-957±3	15-18±1	16-17±2	BD	36.97-52.12
Bright pink	7542-7576±7	338-346±2	1444-1683±3	46-52±1	93-2	BD	27.80-36.41
Red	2986-3190±5	41-45±2	2191-2253±4	16-18±1	12-14±2	BD-22±3	122.40-138.38
Bright red	2529-2556±4	57-60±2	1575-1629±3	22-25±1	15-16±2	BD	63.52-74.71

Table 3. Trace element contents related to a range of colours in Gummi corundums, PIXE probe results, M. Garland, analyst, range of 2 analyses each corundum.

Grns	Ns	Ni	Na	ρ s(10^6)	ρ i(10^6)	U(ppm)	Age($\pm 1\sigma$)
Latest Cretaceous (1 grain)							
1	18	15	100	0.2860	0.2384	10.0	66.5±23.2
Eocene group 1 (av.) Yellow to Orange							
8	138	142	100	2.187	2.260	37-138 (Av. 93)	53.7±6.9
Eocene group 2 (av.) Yellow							
3	130	146	83	3.013	3.352	8-260 (Av. 140)	48.5±10.0
Eocene group 3 (av.) Red							
3	219	275	93	3.769	4.742	148-233 (Av. 200)	43.7±4.1
Oligocene group (av.) Orange to Red							
2	266	349	100	3.591	5.554	105-363 (Av. 234)	35.6±3.6
Pliocene group (av.) Red							
2	34	443	100	0.540	7.039	252-345 (Av. 298)	4.2±0.7

Table 4. Zircon fission-track results, Gummi Flats. $\rho_D = 1.257–1.284 \times 10^6\,\mathrm{cm}^{-2}$ ND = 1966. Ages calculated using a zeta of 87.7 ± 0.8 for U3 glass. Analyst P.F. Green.

Grns	Ns	Ni	Na	ρ s(10^6)	ρ i(10^6)	U(ppm)	Age($\pm 1\sigma$)
Eocene group (av.)							
7	207	179	100	3.290	2.842	101-237 (Av. 153)	49.7±5.3
						Pooled age	50.2±2.2
Oligocene group (av.)							
6	177	207	100	2.805	3.477	57-417 (Av. 187)	36.8±4.2
						Pooled age	35.1±1.5
Early Miocene group (av.)							
2	136	243	200	1.743	2.958	48-317 (Av. 108)	23.5±2.7
						Pooled age	24.3±1.8
Late Miocene (?)							
1	59	277	300	0.313	1.467	79	9.2±1.3
Pliocene Group							
2	27	332	350	0.223	2.781	46-289 (Av. 168)	3.5±0.7
						Pooled age	3.5±0.5

Table 5. Zircon fission-track results, East Tomalla suite. $\rho_D = 9.906 \times 10^5\,\mathrm{cm}^{-2}$ ND = 1468. Ages calculated using a zeta of 87.7 ± 0.8 for U3 glass. Analyst P.F. Green.

Low Cr/Ga Group (< 1)

Colourless, blue-green, yellow-blue and dark-blue. These characteristically have low Cr (up to 6 ppm) and high Ga (19 to 299 ppm) giving very low Cr/Ga ratios (< 0.02–0.34).

Mid Cr/Ga Group (6–20)

Lavender, grey lavender, violet, purple and browny pink. These have greater Cr contents (165 to 501 ppm) and relatively low Ga (22 to 49 ppm), giving Cr/Ga ratios of 6.13–19.20.

High Cr/Ga Group (> 20)

Pink, purple pink and red. These contain the highest Cr contents (688–2253 ppm) and relatively low Ga (15–52 ppm), giving Cr/Ga ratios of 27–138.

Zircon Fission-Track Results

Gummi Flats

Fission-track results have delineated 6 distinctive zircon groups based on uranium contents and age results.
Group 1. (Latest Cretaceous) Yellow colour. 1 grain (U 10.0 ppm) and age of 66.5 ± 23.2 Ma.
Group 2. (Early Eocene) Yellow and orange colours, 8 grains (av. U 93 ppm) and central age of 53.7 ± 6.9 Ma.
Group 3. (Mid Eocene) Yellow colour, 3 grains (av. U 140 ppm) and central age of 48.5 ± 10.0 Ma.
Group 4. (Late Eocene) Red colour, 3 grains (av. U 200 ppm) and central age of 43.7 ± 4.1 Ma.
Group 5. (Oligocene) Orange and red colours, 2 grains (av. U 234 ppm) and central age of 35.6 ± 3.6 Ma.
Group 6. (Pliocene) Red colours, 2 grains (av. U 298 ppm) and central age of 4.2 ± 0.7 Ma.

East Tomalla

Fission-track dating delineated five separate zircon groups. The colours and uranium contents do not vary greatly within the separate age groups.
Group 1. (Eocene) 7 grains (av. U 187 ppm) and central age of 49.7 ± 5.3 Ma.
Group 2. (Oligocene) 6 grains (av. U 187 ppm) and central age of 36.8 ± 4.2 Ma.
Group 3. (Early Miocene) 2 grains (av. U 108 ppm) and central age of 23.5 ± 2.7 Ma.
Group 4. (Late Miocene) 1 grain (U 79 ppm) and central age of 9.2 ±1.3 Ma.
Group 5. (Pliocene) 2 grains (av. U 168 ppm) and central age of 3.5 ± 0.7 Ma.

DISCUSSION

Depositional Relationships, Terraces and Corundums

Deposits from the three terraces, which yielded the corundum suites, show both differences and similarities. The lower gravel horizon of the Upper Terrace, Section 18-B, lacks obvious alluvial characteristics. The horizon is very poorly sorted in size and shape of its lithic fragments, and has a heavy clay matrix; it displays some characteristics of a mass debris flow (Cas and Wright, 1987). The two upper terrace gravel horizons occur intermittently over the Gummi Flats area. The upper gravel (Section 18-A) has a different colour and shows slight fining upwards. It contains more sub-rounded lithic fragments, so could possibly have some alluvialy derived component, or mark the end of a debris flow.

The Middle Terrace (Section T4A) displays a clearer fining upwards, compared to Section18-B. The Middle Terrace has a slightly larger percentage of rounded and sub-rounded stones, but sub-angular and sub-rounded lithic fragments still dominate. Overall it is poorly sorted.

The Recent Alluvial terrace (Section T2A) shows stronger alluvial characteristics than the Middle and Upper terraces. Upward fining sequences are present, lithic fragment sizes are smaller and there is a larger percentage of rounded and sub-rounded lithic fragments. The Recent Alluvial gravels are intermittently overlain by sandy-clays and clays, with sequence patterns more typical of alluvially derived deposits.

The features noted in each corundum suite help to indicate distances travelled from their sources. Heavy fracturing dominates corundums from Recent Alluvials and the lower gravel in the Upper Terrace (Section 18-B). Preservation of fusion crusts probably indicates a lesser distance travelled by corundums. The Middle Terrace has a greater percentage of such crusted stones. Larger average sizes, poorer gem quality and more prominent surface inclusions also suggest these stones have undergone less transportation. The corundum traits from the terraces suggest the following order of increasing transport effects: Middle Terrace, Section 18-A and Recent Alluvials, Section 18-B.

Overall, sapphirine, and Mg to Fe-rich spinels (pleonaste to hercynite) dominate as inclusions in the corundums. Rubies in all four gravel horizons contain sapphirine inclusions, indicating a metamorphic origin. The Middle Terrace rubies contained the largest percentage of sapphirine inclusions, over 8%, while Section 18-B and the Recent Alluvials contain some 2–2.5% and Section 18-B under 0.5%. These differences are most likely due to varied transport processes within the gravels, including distances from the sources.

Spinel inclusions are present in all colour groups from the terraces. The Middle Terrace shows the largest percentages of spinel inclusions, while both the Upper Terrace horizons contain similar spinel inclusion percentages and the Recent Alluvials the least. These results also complicate any linking of the upper horizon gravels (Section 18-A) to the other horizons as a continuous depositional sequence. It could mark a separately derived deposit.

The Middle Terrace shows higher percentages of stones with percussion marks, which may indicate more complex transport processes than straightforward alluvial transport. Percussion marks need not entirely indicate fluvial transportation, as they can occur during eruptive processes.

Magmatic Relationships

The great majority of corundums (50–95%) show magmatic resorption indicating a hot igneous source for their provenance. The most likely hosts are the basalts which elsewhere in eastern Australia are known to carry corundum as xenocrysts (Coenraads 1992), and the corundums show fusion crusts that indicate reaction temperatures around 1000°C (Sutherland and Coenraads 1996). The ruby group in particular shows more extensive resorption and indicates more than one stage of resorption has occurred, (up to 80% secondary resorption in some colour suites). This secondary resorption is seen on fractured surfaces, suggesting some fracturing took place during igneous explosion events, which exposed further surfaces to the corrosive attack.

This magmatic scenario is reinforced by the fusion crust mineralogy, where spinels (pleonaste to hercynite) dominate the main phases. Sapphirine appears mainly in fusion crusts in the ruby suites, but is rarely seen on blue, green and yellowish corundums. Two stones were analysed which showed a dominance of pleonaste on one side and hercynite on the other side of the same crust, indicating variation in crystallization of the spinels during magmatic reactions.

Colour-Shade Relationships

The colour-shade histograms clarify relationships within colour groups from each terrace. Section 18-B contains less features throughout its colour groups than the other sections. It also exhibits heavily fractured and resorbed stones. Fusion crusts along with sapphirine and spinel inclusions exist only in small percentages.

When looking at the ruby groups, colour does not control all the features present within these corundums. Section 18-B shows the biggest range of features to occur in the dark pink colours, whereas in Section 18-A the very pale pinks and dark pinks contain the most features, (including an ilmenite inclusion in a dark pink ruby). The Recent Alluvials show only resorption and heavy fracturing in very pale pinks, whereas other pink shades show more varied features. The Middle Terrace shows most variation in corundum features in the pale pink rubys. These ruby histograms clearly show the much higher percentages of fusion crusted stones in the Middle Terrace, with pale, medium and dark colour groups all containing over 30% of such stones.

The blue, greenish and yellowish coloured corundums lack sapphirine inclusions, suggesting their predominant non-metamorphic origin. Spinel inclusions are found in $< 10\%$ amounts throughout these corundums. Only greenish corundums from Section T4A (Middle Terrace) show $> 10\%$ spinel inclusions. Resorption and heavy fracturing dominate throughout the blue, greenish and yellowish colour suites, and none have $> 10\%$ fusion crusts. In comparison to the Middle Terrace rubies, which show $> 30\%$ fusion crusts in three colour shades the blue, greenish and yellowish corundums may have undergone greater erosive transport prior to their deposition with the rubies. This suggests separate origins (i.e. magmatic vs metamorphic), eruptive mechanisms and initial transportational processes were involved.

Apricot coloured corundums resemble the rubies, in having $> 10\%$ fusion crusted stones and sapphirine inclusions. As mentioned earlier the apricot colour results from iron penetrating through fractures and fissures, changing them from pale pink to apricot. Thus, these apricot coloured stones were most likely derived from the same source as the rubies. When compared to the blue, greenish and yellowish corundums, the rubies and apricot stones show a larger range of features. To elucidate the exact mechanisms that helped accumulate all these different coloured stones together will need further detailed investigation.

Inclusion Relationships

EDAX analysis identified anorthoclase, ilmenorutile and a magnesium, iron aluminosilicate in addition to previously recorded inclusions in Barrington Tops corundums. The ilmenorutile within a green corundum from the Recent Alluvials (section T2A), suggests a magmatic origin which agrees with other blue, greenish and yellowish corundums in this horizon. The magnesium, iron aluminosilicate appears in a corundum from the Middle Terrace (T4A) and anorthoclase was found included in a blue corundum from section 18-A.

The analysis suggest a range of spinel compositions from pleonaste to hercynite. Only $< 1\%$ of rubies analysed (section T4A) contained hercynite inclusions, which is more common in corundums of magmatic origins (Sutherland and Coenraads 1996).

Analyses indicate a clear link between the mineral inclusions and their host corundum origins, either as metamorphic (ruby and apricot corundums), or magmatic (some blue, greenish and yellowish) types. This correlates well with trace element Cr/Ga ratios in these corundums. For colourless, greens, yellow and blue corundums the Cr/Ga ratios are typical of magmatic origin (< 1), while lavender, violet, purple, brown pink, pink and red corundums show Cr/Ga ratios typical of metamorphic origin (> 1).

Zircon Relationships

The zircon fission-track analyses from the Gummi Flats and East Tomalla suites suggest several eruptive episodes were involved in their magmatic transport. Correlation between the two sites show at least three main age groups, at around 50 Ma, 35 Ma and 4 Ma, as consistent eruptive events. The East Tomalla suite also indicates possible eruption of zircon at around 23 Ma and 10 Ma. Some earlier eruptive episodes for zircon are possible from the Gummi Flats zircon data at around 66 Ma and 54 Ma, particularly as these zircons show substantially lower uranium contents (10–93) than in the other groups.

The new zircon age data from northern Barrington areas can be amalgamated with previous results for the general Barrington volcanic plateau (Sutherland and Fanning 2001). The new results not only indicate an extra eruptive episode at ~ 50 Ma, but also help to confirm some previously recorded eruptive episodes at both the older (over 65 Ma) and younger (3–5 Ma) ends of the eruptive history. The young eruptive-age zircons are now known at three sites in the Barrington plateau, each one showing distinctive U contents and colours. This suggests several geographically separate eruption sites were involved. The complex history of zircon-eruptive episodes would provide multiple opportunities for associated corundum release into the Barrington drainage systems.

CONCLUSIONS

1. The terrace deposits in the northern Barrington area, show some differences in corundum features within the separate horizons.
2. The ruby suite from the Upper Terrace (Section 18-B), generally lacks fusion crusts, inclusions and are heavily fractured. This suggests greater transport processes for these corundums. This contrasts with the deposit in which the corundums occur, as it shows mass deposit features with no prolonged transportation.
3. The Middle Terrace corundums, particularly the ruby suite show the most fusion crusts and inclusions, suggesting a more proximal origin.
4. The Recent Alluvial corundums show some features that characterise both the Upper and Middle Terrace horizons. This suggests it may contain some corundums derived from these horizons. These corundums, however, also show features that suggest sourcing from additional areas.
5. As the rubies generally show a difference in transport-derived features, it is possible that the other colour groups have undergone separate transportation before amalgamation with the rubies in each terrace.
6. Colour Shade histograms and EDAX analyses of corundum inclusions and fusion crusts emphasise the distinct differences between the ruby and other corundum groups.
7. The trace element data further distinguish the ruby suites from the other corundums, with Cr/Ga ratios indicating metamorphic origins for the ruby group and magmatic origins for most other corundums.
8. Zircons that accompany the corundums yield zircon fission-track ages that range between 66 Ma to ~ 4 Ma, and augment the previously known multiple eruptive history of the Barrington province.
9. Although the precise corundum sources remain to be located, the terrace study has narrowed down potential source targets, with the Middle Terrace indicating a possible nearby source.

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Six pages consisting of color figures and an Appendix for this article follow.

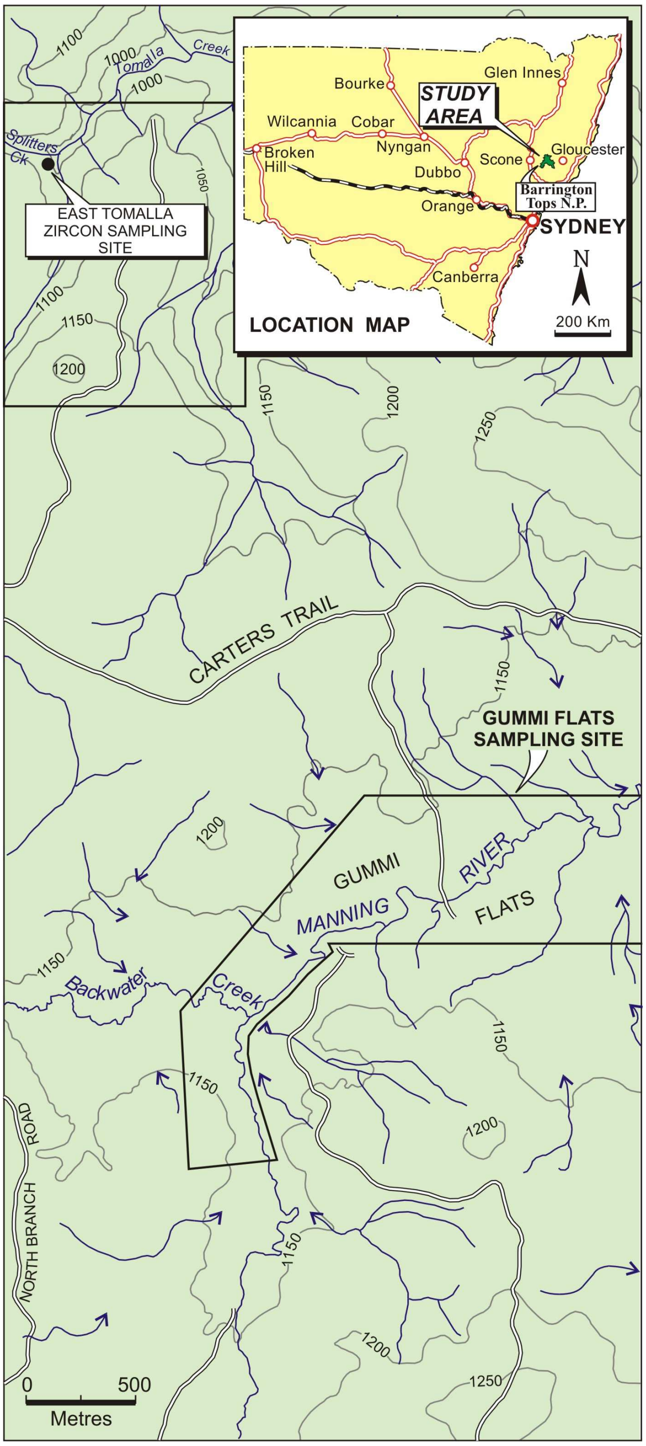

Figure 1. Locality map, study areas, showing Gummi Flats and East Tomalla sampling sites (boxes), general topography, drainage and access trails and location within New South Wales (inset).

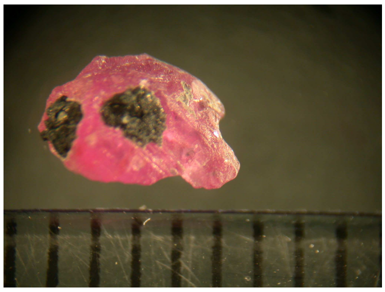

Plate 1. Resorbed ruby with preserved spinel fusion crust. (scale is in mm).

Plate 2. Resorbed ruby with sapphirine inclusion. (scale is in mm).

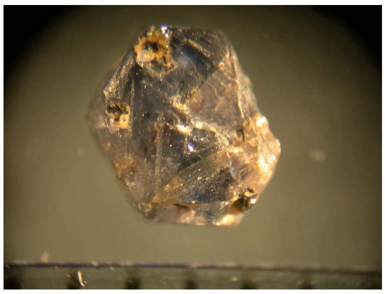

Plate 3. Pale to medium blue sapphire with several spinel inclusions. (scale is in mm).

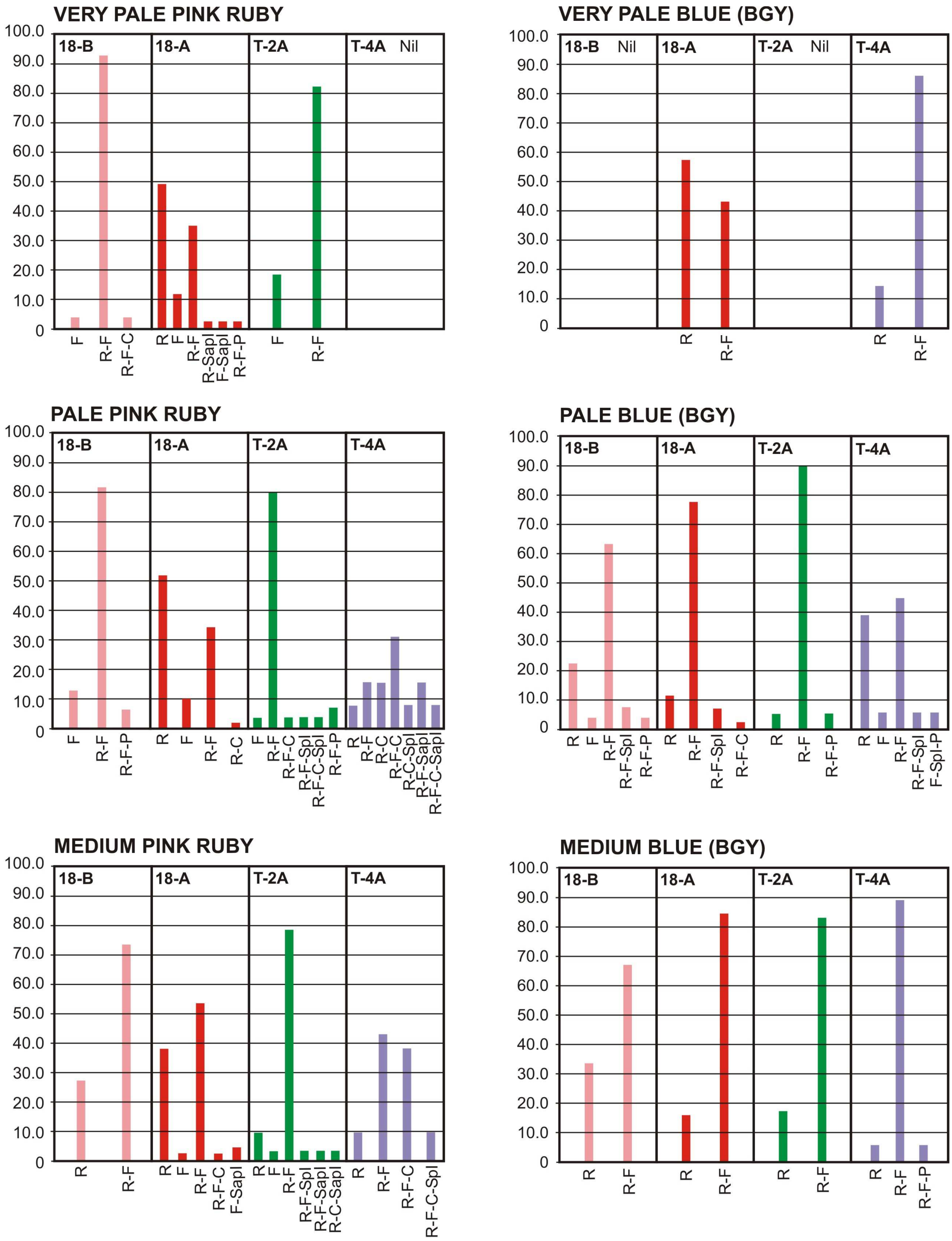

Figure 6. Colour-Shade histograms of Ruby, Blue Group corundums.

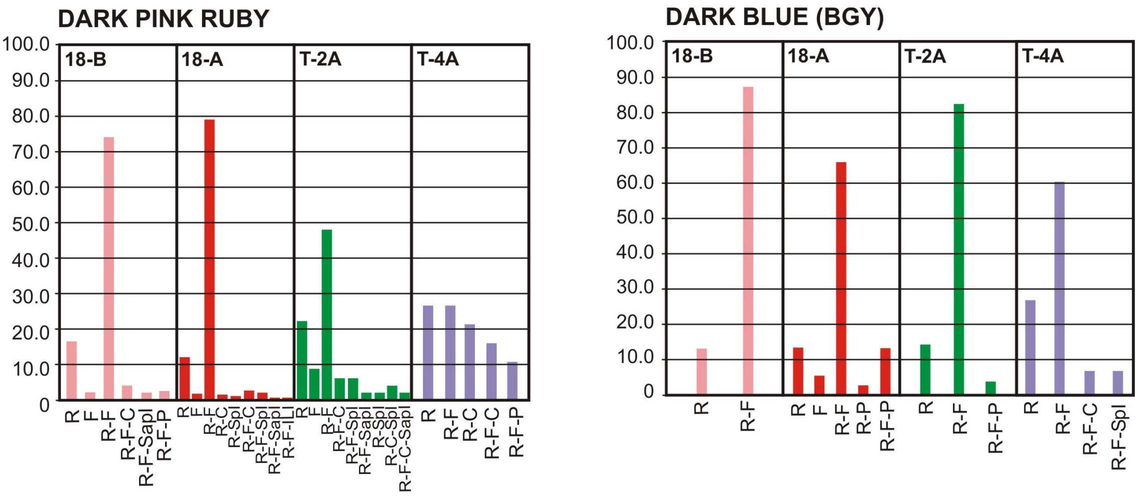

Figure 6 (continued). Colour-Shade histograms of Ruby, Blue Group corundums.

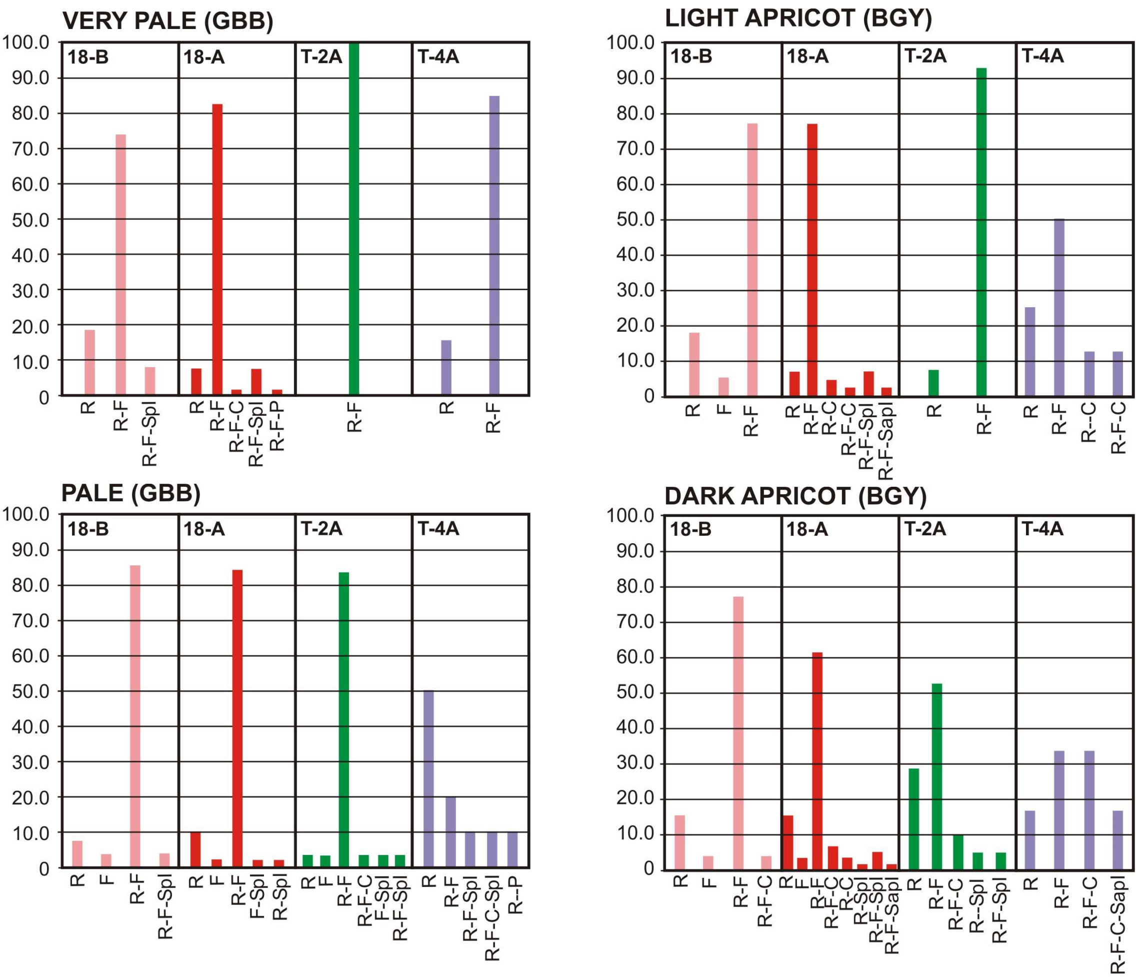

Figure 7. Colour-Shade histograms of Grey-Brown-Black (GBB), Apricot, Greenish and Yellowish Group corundums.

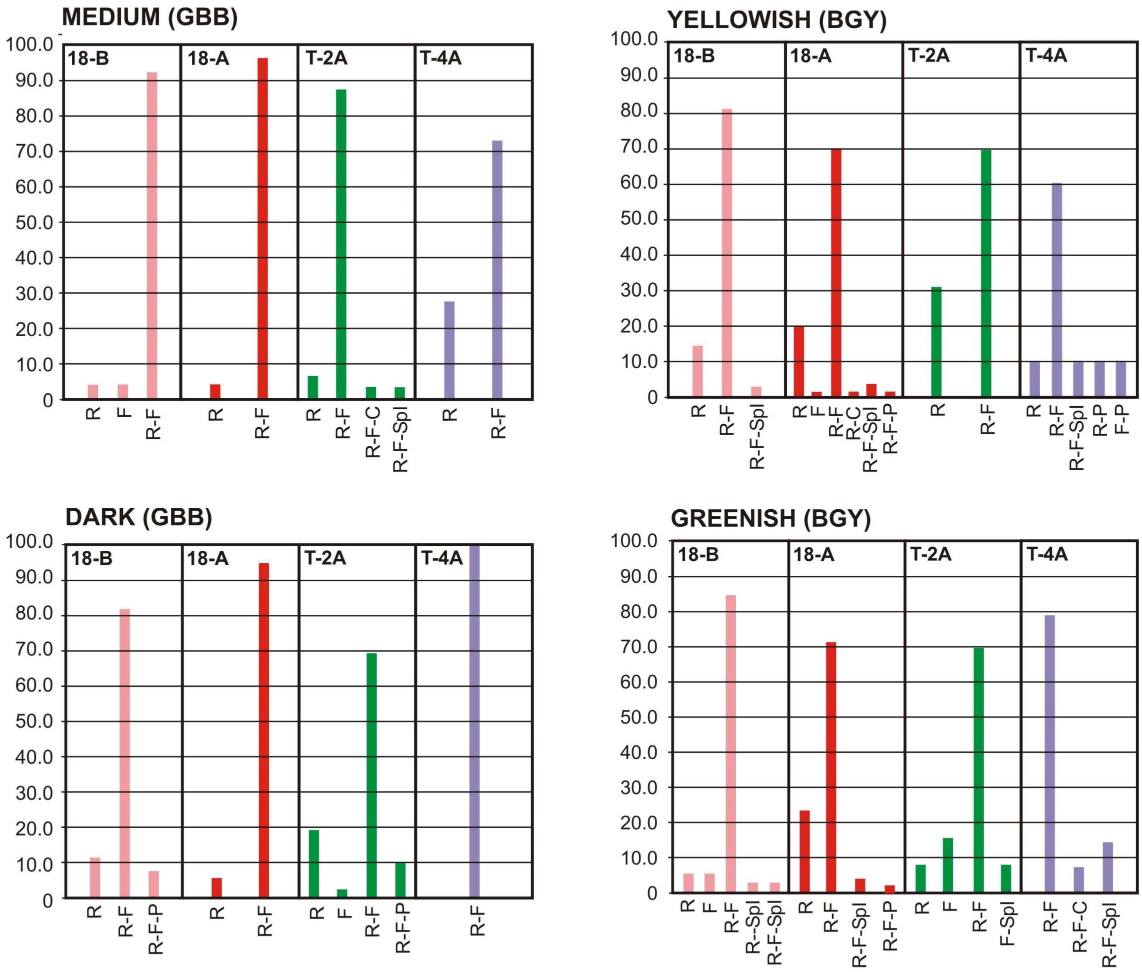

Figure 7 (continued). Colour-Shade histograms of Grey-Brown-Black (GBB), Apricot, Greenish and Yellowish Group corundums.

APPENDIX 1

Heavy Mineral Sample Description, East Tomalla
31° 49.88´S 151 ° 30.31´E 1200 m asl

> **2mm size fraction**

Magnetic	Vol%	Description
	10	Weathered ferruginous fine-grained olivine basalt with spinel and clinopyroxene xenocrysts, and rare feldspar xenocrysts.
Non-magnetic	**Vol%**	**Description**
Spinels	65	Abundant (> 85 Vol % of sample) anhedral to subhedral, equant to subprismatic, magmatically corroded, etched and polished spinel xenocrysts (some with thin basalt rinds) up to 10 mm. Rare crystal faces present on some grains.
Glassy volcaniclastics	1	Uncommon dark brown to black, finely banded, scoriaceous, vesicular vitric tuff.
Other rock and mineral fragments	24	Moderately common muscovite aplite, muscovite granite, fine-stained quartz fragments, gibbsite and lateritic ironstone. Uncommon dark brown to black anhedral prismatic magmatically corroded and polished clinopyroxene xenocrysts and well rounded milky quartz grains. Rare massive monazite.

continued on next page…

< 2mm size fraction

Magnetic	Vol%	Description
	$< 0.01 - 10$	Well rounded spherical to ovoid fragments of weathered ferruginous olivine basalt and ironstone (> 1 mm) and well rounded, equant, spherical to ovoid highly pitted spinels, some with adhering basaltic crust (< 1 mm).
Non-magnetic	**Vol%**	**Description**
Spinels	50–90	Grey to black, angular to well rounded, equant to subprismatic, anhedral to subhedral, smooth to highly pitted, commonly partially resorbed and magmatically corroded grains with rare crystal faces.
Lherzolitic detritus	∼1–5	Olivine-common, olivine-green to yellow-green anhedral, equant to subprismatic, generally glassy angular grains with pronounced conchoidal fracture. Orthopyroxene-uncommon, brown-bronze glassy, partially to highly resorbed, finely etched and striated, anhedral to subhedral, short prismatic to prismatic, angular to subrounded grains.Clinopyroxene-uncommon, lime-green to emerald green (Cr-diopside), partially resorbed, finely etched and striated, subhedral subprismatic, angular to subrounded grains.
Rock and mineral fragments	9–40	Quartz, abundant and two distinct types: 1. Well-rounded spherical to ovoid opaque white and Fe-stained grains. 2. Angular to sorted, glassy colourless (some Fe-stained) equant to prismatic grains. Muscovite aplite - common as fine grained fragments. Ironstone and gibbsite - moderately common as well-rounded grains. Gorceixite-goyazite - uncommon yellow-brown resinous concentrically zoned rounded grains. Zircon - uncommon, generally as well rounded equant, anhedral to subhedral colourless to pink (rare yellow-brown) grains. Feldspar - rare, partially resorbed glassy colourless angular subprismatic grains. Corundum - extremely rare (6 grains), generally pale pink to pink-purple (very rare blue-green) highly resorbed grain fragments.