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Occurrences and Origins of Gem Zircons in Eastern Australia

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ABSTRACT. In eastern Australia, zircons are common in alluvial deposits derived from Tertiary volcanic rocks. They are typically accompanied by corundum, pleonaste spinel and ilmenite ('the zircospilic association'). Although most occur in or near granite areas, fieldwork and dating confirm alkali basalts and some trachytes as their hosts; some even being found *in situ*. Most crystals show corrosion effects from their transporting magmas.

A wide range of zircon crystal habits suggests diverse but, as yet, unknown sources. Possibilities include: (a) accidental sources from syenitic intrusives, plutonic cumulates and pegmatites, and (b) cognate origins in fractionated basaltic magmas, particularly their felsic end members. Dry, peraluminous alkaline magmas may be responsible for most of the large zircons. Eight groups are described on their physical characteristics. Most are (101)-pyramid dominant forms with short prisms. Variations in the incidence of crystal types show trends that may record changes in magma composition as well as temperature profiles.

Felsic intrusions associated with Mesozoic and Cainozoic 'hot spot' trails form potential reservoirs to provide zircon xenocrysts in later basalts. The relative contribution of these to older Palaeozoic granitoid zircon sources is uncertain, pending detailed isotopic work.

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KEYWORDS: zircons, alluvial gems, eastern Australia, crystal forms, basaltic sources, alkaline origins, fission-track dates.

Alkali basalts containing megacrysts of zircon are reported from a few localities in eastern Australia (eg. Binns, 1969; Stephenson, 1976) and we report several new occurrences. They may be accompanied by corundum, pleonaste and ilmenite, comprising the 'zircospilic association' of Hollis (1984). Similar occurrences are known from the Eifel, West Germany (Dana, 1898) and Irving & Frey (1984) list other records from France, Scotland, Algeria, Madagascar, Nigeria and South-East Asia. A further record comes from Thailand (Vichit *et.al.*, 1978). Derived alluvial occurrences are widespread in eastern Australia (Fig.1) and some yield gem zircons. These can exceed fist size in the Anakie Gemfield, Queensland. Large zircons (over 2 mm) also occur in trachytes and trachytic pyroclastics at Blue Mountain, Victoria, and Elsmore Hill, New South Wales (Lishmund & Oakes, 1983). Although small zircons are often abundant in alkali granitic rocks, large zircons are very poorly represented by an unconfirmed pegmatite source near Rubyvale, Qld, and a syenite at Jingera, N.S.W.

Zircons derived from alkali volcanics generally show rounding and sometimes fine surface corrosion textures, clearly distinct from abrasion produced by subsequent alluvial transport. A few crystals are completely sharp and uncorroded. A range of origins is suggested, from cognate and in equilibrium with their host magmas to accidental, disequilibrium xenocrysts. Fission-track dating of alluvial zircons gives results consistent with local volcanic sources (Gleadow, *et.al.*, 1976; Yim, *et.al.*, 1984.)

Interest in sapphires has generally overshadowed the zircons, about which only passing references are made. This study outlines important occurrences of large ('gem') zircons and their physical groupings, especially crystallography. Some implications regarding their origins, based on crystal morphologic studies, are examined with reference to the work of Pupin (1980), Caruba (1978) and Kostov (1973).

Uranium contents of a number of the zircons described here, from the Australian Museum collections, have been reported by Mumme (1967) and are greater than those typical of kimberlitic occurrences (Davis, 1976). Further U values are given in Table 2.

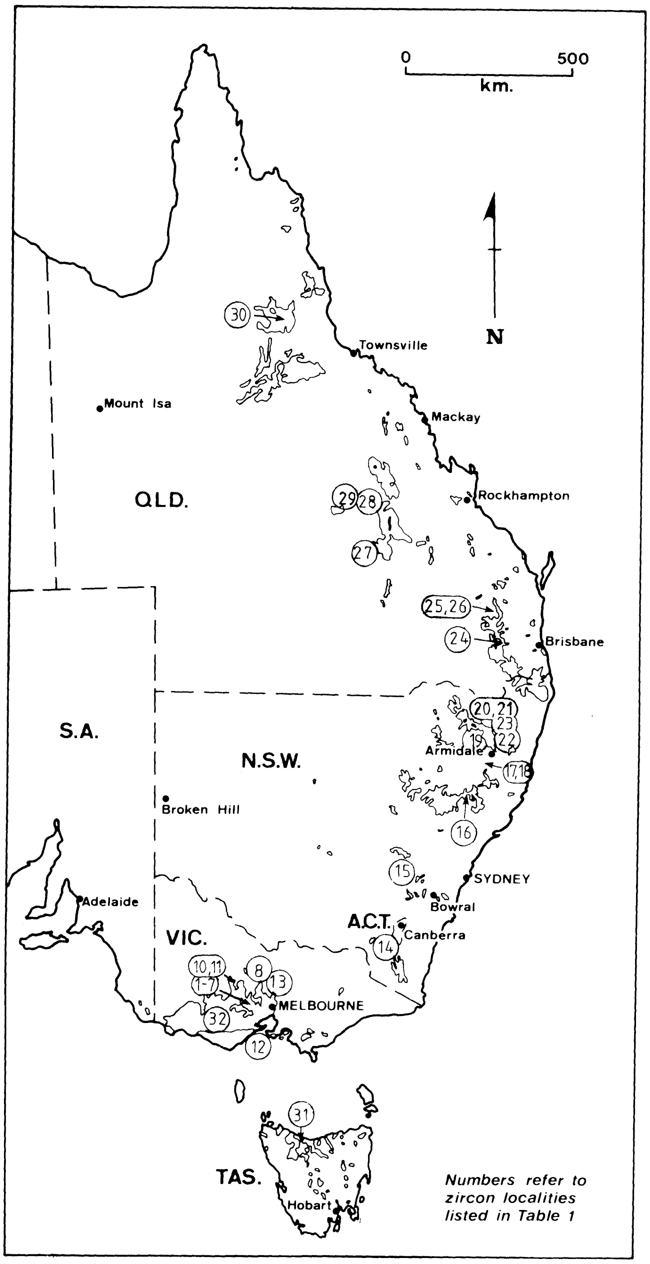
Physical Characterisation of Zircons

Morphologic classification of zircon crystals has been extensively studied by Pupin (1980) who adopted a logical crystallographic scheme based on experimental temperature and alkalinity relationships with melts. These relationships have been questioned by Caruba (1978) and it appears that other factors such as melt compositions, water content and cooling rates play important roles in determining crystal types (Kostov, 1973). Pupin delineated fields of crystal types characterising different igneous rocks, including a trend for gem zircons from alkali basalts. The gem zircon field was based on limited material and different trends have emerged from the present work. Pupin's chart proved too complex for objective crystal classification of the gem zircons, as many show differing form developments on the one crystal. The scheme adopted (Fig.2) proved ideal for trend delineation from crystal counts.

Kostov (1973) showed that melts low in U, Th, alkalis and water produced (100)-dominant crystals. Pupin & Turco (1973) regarded these forms as typifying high-temperature, peraluminous magmas. (110)-dominant crystals were conversely rich in U, Th, alkalis and water and developed at lower temperatures. Prismatic crystals result from rapid growth, whereas bipyramidal forms indicate slow development (Kostov, 1973).

Zoning is widespread in large zircons, sometimes producing colour banding parallel to the pyramid faces (Rubyvale brown crystals) and darker colouration along interfacial edges (Bullenmerri). Density of fission tracks also shows strong zoning, occasioned by differing U, Th contents.

Colour is an important distinguishing feature for some zircon assemblages. The crystal counts for the four Horse Gully groups (Fig.3) show distinct results for each colour group. Gem zircons broadly define scarlet, brown (colourless to deep brown) and mauve-orange colour groups. The latter often show irregular patchy colouration. Pale green to deep blue-green varieties are rare but occur in most of the groups noted. One Elsmore Hill crystal showed sharp zoning from deep blue-green to scarlet. Pale green zircons are fairly common at Bullenmerri.



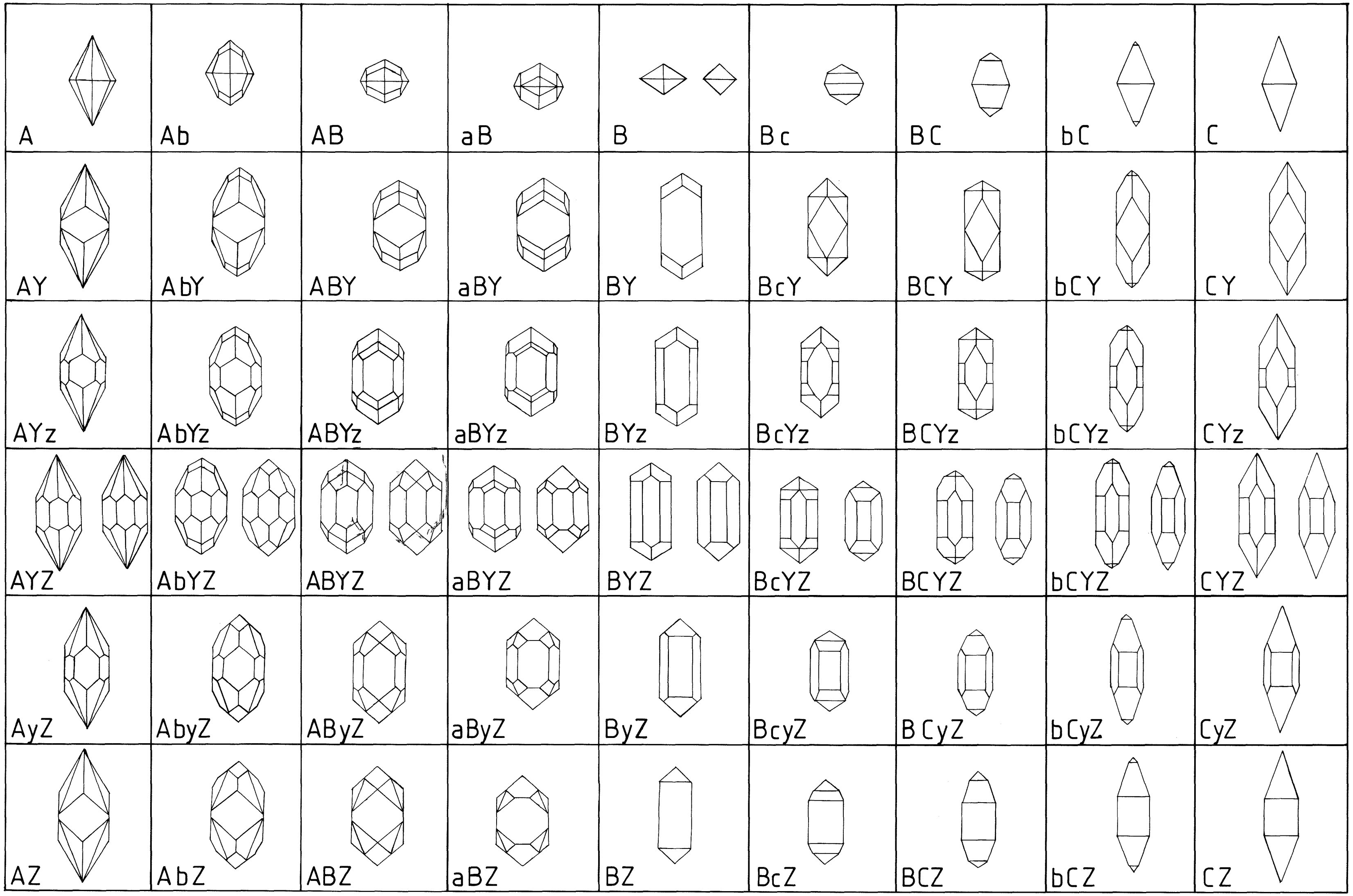
Numbers refer to zircon localities listed in Table 1

FIG. 1 DISTRIBUTION OF BASALTS, EASTERN AUSTRALIA

Colour centering in natural zircons, including New England examples, was investigated by Fielding (1970) who showed a link between U and certain trace elements, notably praesodymium and erbium. Blue-green and scarlet zircons from Blue Mountain, Victoria, showed similar fission-track densities, indicating that lattice damage does not necessarily determine colour (A.Gleadow, pers.comm.).

Randomly orientated rutile needles are widespread in the scarlet crystals. Other phases include ilmenite crystals and rods of apatite. Bullenmerri zircons show higher levels of radioactivity which cannot be accounted for by microprobe analyses of U and Th. Small opaque inclusions, yet to be identified, may include allanite and other radioactive phases.

Surfaces usually show etching features, largely produced by magmatic or gaseous corrosion. These range from glossy, rounded surfaces to finely peaked



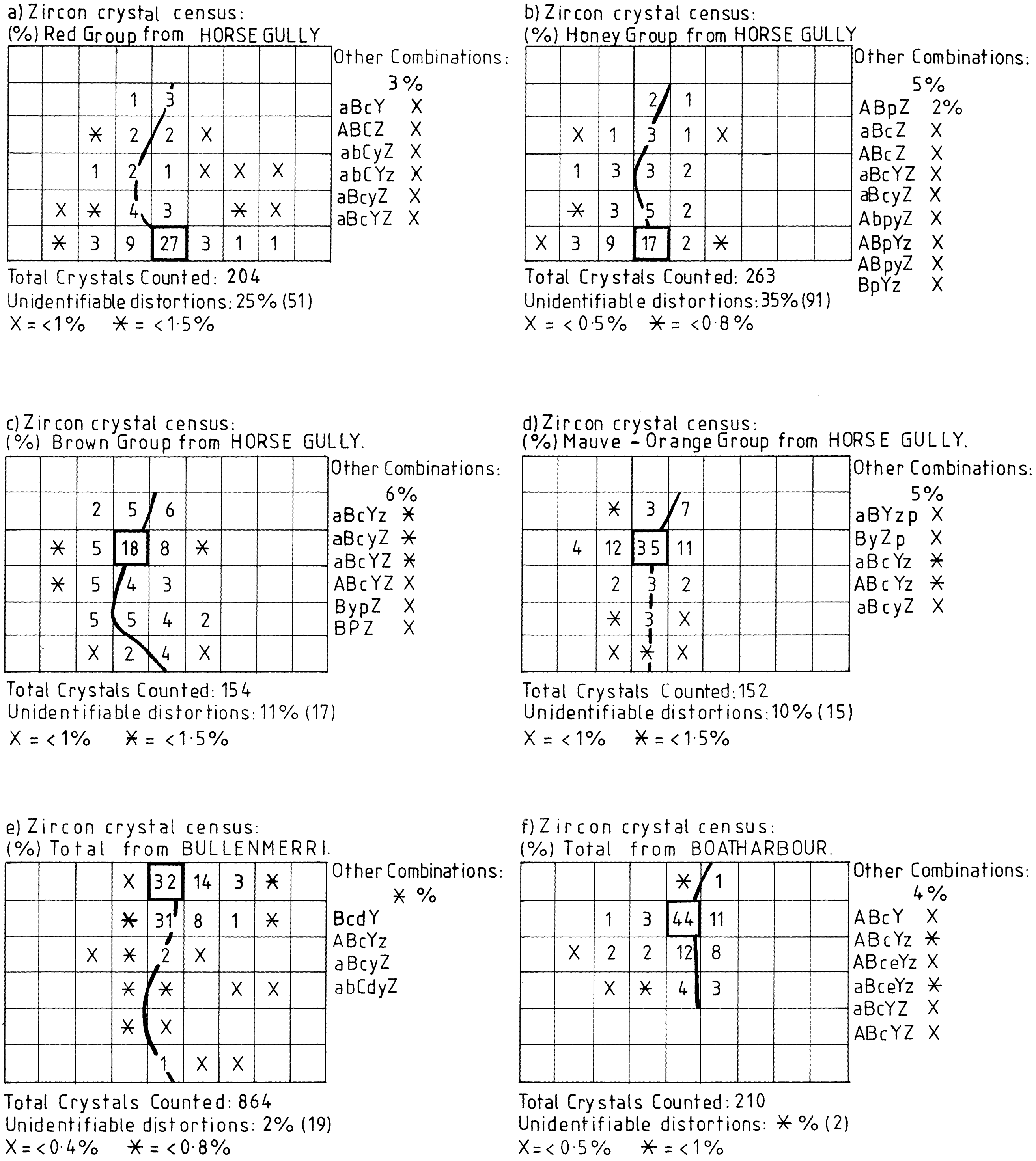
PYRAMIDS:
A = 211
B = 101
C = 301
D = 201
E = 321

PRISMS:
Y = 110
Z = 100

PINACOID:
P = 001

Lower case indicates minority form, eg. bCyZ = 301 ≫ 101, 100 ≫ 110.

Fig. 2 Crystal characterisation chart for common zircon forms. Systematic arrangement reflects an upward progression from (100) to (110) prisms, and a sequence, from left to right, from (211) through (101) to (301) pyramids. The general scheme is a simplified adaption of Pupin's scheme (1980). No rigid relationship between crystals, temperatures and alkalinity is implied, however the progression upwards may reflect decreasing temperatures and alkalinity of magams.



a) Zircon crystal census:
(%) Red Group from HORSE GULLY

			1	3				
		*	2	2	X			
		1	2	1	X	X	X	
	X	*	4	3		*	X	
	*	3	9	27	3	1	1	

Other Combinations: 3%
aBcY X
ABCZ X
abCyZ X
abCYz X
aBcyZ X
aBcYZ X

Total Crystals Counted: 204
Unidentifiable distortions: 25% (51)
X = <1% * = <1·5%

b) Zircon crystal census:
(%) Honey Group from HORSE GULLY

			2	1				
	X	1	3	1	X			
	1	3	3	2				
	*	3	5	2				
X	3	9	17	2	*			

Other Combinations: 5%
ABpZ 2%
aBcZ X
ABcZ X
aBcYZ X
aBcyZ X
AbpyZ X
ABpYz X
ABpyZ X
BpYz X

Total Crystals Counted: 263
Unidentifiable distortions: 35% (91)
X = <0·5% * = <0·8%

c) Zircon crystal census:
(%) Brown Group from HORSE GULLY.

		2	5	6				
	*	5	18	8	*			
	*	5	4	3				
		5	5	4	2			
		X	2	4	X			

Other Combinations: 6%
aBcYz *
aBcyZ *
aBcYZ *
ABcYZ X
BypZ X
BPZ X

Total Crystals Counted: 154
Unidentifiable distortions: 11% (17)
X = <1% * = <1·5%

d) Zircon crystal census:
(%) Mauve - Orange Group from HORSE GULLY.

		*	3	7				
	4	12	35	11				
		2	3	2				
		*	3	X				
		X	*	X				

Other Combinations: 5%
aBYzp X
ByZp X
aBcYz *
ABcYz *
aBcyZ X

Total Crystals Counted: 152
Unidentifiable distortions: 10% (15)
X = <1% * = <1·5%

e) Zircon crystal census:
(%) Total from BULLENMERRI.

			X	32	14	3	*	
			*	31	8	1	*	
		X	*	2	X			
			*	*		X	X	
			*	X				
				1	X	X		

Other Combinations: * %
BcdY
ABcYz
aBcyZ
abCdyZ

Total Crystals Counted: 864
Unidentifiable distortions: 2% (19)
X = <0·4% * = <0·8%

f) Zircon crystal census:
(%) Total from BOATHARBOUR.

				*	1			
		1	3	44	11			
	X	2	2	12	8			
		X	*	4	3			

Other Combinations: 4%
ABcY X
ABcYz *
ABceYz X
aBceYz *
aBcYZ X
ABcYZ X

Total Crystals Counted: 210
Unidentifiable distortions: * % (2)
X = <0·5% * = <1%

Fig. 3. Crystal census of some large zircon groups from eastern Australia: **a.** Newbury Group, Horse Gully, east of Inverell, N.S.W. **b.** Inverell Group, Horse Gully. **c.** Nundle Group, Horse Gully. **d.** Elsemore Group, Horse Gully. **e.** Boatharbour Group, Sisters Creek, Boatharbour, Tas. **f.** Bullenmerri Group, Lake Bullenmerri, near Camperdown, Vic.

or mammillated textures similar to those seen on garnets from Ballogie, Qld (Hollis *et.al.* 1983). Deep, rounded cavities probably represent dissolved, prismatic inclusions.

Groupings based on colour and crystal types may also show distinctive size ranges and degrees of prismatic development (Table 1). The Lyonville Group excepted, gem zircons show very few crystals smaller than 1 mm. Crystals below 2 mm seldom show recognisable crystal form, due to corrosional rounding. This indicates that zircons were seldom in equilibrium with their final melt environments and small crystals were dissolved. This is in direct contrast to the small prismatic zircons of acid granites (*sensu lato*) which are mostly smaller than 0.5 mm.

Classification of Zircon Assemblages

Large alluvial zircons from eastern Australia can be divided into eight morphologic groups based on crystals, colours and sizes (Table 1). These groups are named after localities where host rocks are known, and they are listed in order of major crystal development. The Newbury and Nundle Groups are proving widespread, but three others are so far only known from single localities. Present data are insufficient to determine relationships with hosts, but sharp uncorroded euhedra of the Lyonville Group appear to be cognate to their host trachytes. Others, especially the larger sizes, may be derived from rocks that are not directly related to their hosts. Predominant crystals are listed from Fig.2 which is a modification of Pupin's scheme. Decreasing temperatures appear to favour (110) prism development, although Pupin's (1980) tight relationship between crystals and temperatures ('Indice T') is questioned (eg. Caruba, 1978). Increasing alkalinity appears to shift crystal development towards (101) and (301) pyramids (Pupin's 'Indice A').

Other groups may be delineated with further work, but assemblages examined suggest that the existing groups are well defined. Large zircon assemblages are described from key localities, typifying occurrences associated with alkali volcanics in eastern Australia. More than one zircon group may be present in assemblages, particularly in Central Victoria and in the New England and Central Queensland sapphire fields, indicating multiple origins.

1. Upper Loddon River, Lyonville, Vic. Alluvium in the Loddon River, upstream from Lyonville Springs, contains abundant zircon, ilmenite, rarer black spinel, magnetite and corundum. Most of the heavy minerals are derived from the late Tertiary trachytes at Babbingtons Hill and the Quaternary basalts of the Bullarto Plateau. There are three distinct groups of zircon:

(a) Newbury Group: these constitute the largest and most abundant zircons, ranging from 0.5 to 5 mm. Although showing little abrasion, most crystals are well rounded due to magmatic corrosion. Colours are typically scarlet to orange-red; more rarely shades of grey, brown, green and blue are found, and a few are parti-coloured green and brown. Euhedra are practically all (101) pyramids with short (100) prisms, representing forms taken by Pupin (1980) to indicate hot, dry, alkaline source magmas. Zircons of identical habit come from an olivine basalt at Newbury, south of Lyonville. A similar host rock is envisaged for the Newbury Group zircons from Lyonville Springs.

(b) Lyonville Group: distinctively sharp, uncorroded euhedra between 0.2 and 1 mm; pale orange to almost colourless. (211) faces are usually developed with the (101) + (100) forms and acicular inclusions of rutile are abundant.

(c) Colourless type: small, elongate and abraded crystals range from 0.05 to 0.3 mm. Although crystal morphologies are mostly obscure, a range of medium to highly developed prismatic forms are represented. Complex (100), (110), (101) and (211) combinations occur. These are types that typify some shallow-crustal granites. As there are no outcropping granites in the area it seems likely that these small zircons have been recycled from the local Ordovician sandstones or from former Permian tillites.

2. Blue Mountain, near Trentham, Vic. A quarry on the northeastern slopes of Blue Mountain exposes deeply weathered biotite-anorthoclase trachyte overlying related ashes and agglomerates. Both yield mainly pale orange zircon euhedra that are uncorroded and up to 2 mm. Crystal forms lie in the BZ-ABZ range (Fig.3), typifying the Lyonville Group. Zircons are probably cognate microphenocrysts and are associated with abundant magnetite crystals. Similar zircons are common in soil developed from trachyphonolite at Mt Wilson, from trachyte at Babbingtons Hill and McAlister Hill, and from soda trachyte at Camels Hump, Mt Macedon, all in the same region. These trachyte centres belong to the Woodend Group, dated at around 6 Ma (Ewart et.al., 1984).

3. Leonards Hill-Sailors Creek, near Daylesford, Vic. Red soil resting on alkali basalt on the western slopes of Leonards Hill, south of Daylesford, yields abundant prismatic mauve-orange zircons, up to 9 mm long (Daylesford Group). Many are sharp euhedra although most are corroded and they often show semi-skeletal development with tubular cavities and embayments parallel to the C axes. Crystal forms show a peak occurrence between the Newbury and Lyonville Groups, to which they are probably related. Crystals in and above the (a)ByZ range are absent. Their strongly prismatic and skeletal habits make them distinctive. They occur associated with late Tertiary alkali basalts and derived alluvials in a region some 25 km across, to the south and west of Daylesford, including Hepburns Lagoon and the Newlyn ('Bullarook') area deep leads.

Sailors Creek, between Daylesford and Leonards Hill, shows an exceptional profusion of zircons. They are associated with scarce corundum, pleonaste and abundant ilmenite. Most zircons belong to the Daylesford Group, but other types include short, pyramidal scarlet and, rarely, blue-green crystals of the

Group Name	Crystals	Normal colour	Prism:Pyramid	Size,mm.	Host rock	Localities
Newbury	BZ	Scarlet	0 - 1	0.5 - 20	Alk.ol.basalt	1, 3, 4, 6, 9, 18, 19, 20, 21, 22
Lyonville	aBZ, BZ, minor ABZ	Orange	0.2 - 2	0.2 - 1	Biot-anorthocl. trachyte	2, 3, 5, 6, 7, 8
Daylesford	BZ, minor ABZ	Mauve-orange	1 - 15	1 - 9	Alk.ol.basalt	9, 10, 11
Flinders	BYZ	Scarlet	0.2 - 3	0.2 - 2.5	Alk.basalt	12
Inverell	aBZ, minor aBZ, aByZ	Pale brown	0.2 - 3	1 - 25	Alk. basalt	20, 21, 28, 29
Nundle	aBYz, minor ABYz, BYz	Brown	0.2 - 1	1 - 12	Alk.ol.basalt	13, 16, 17, 20, 21, 27, 28
Elsmore	Same as Nundle	Mauve-orange	0.2 - 1	1 - 10	Trachytic tuff	14, 15, 20, 21, 23, 24, 25, 26, 28, 30
Boatharbour	BY, minor BYz	Scarlet	0.2 - 1	0.3 - 20	Ol.melilitite	31
Bullenmerri	B, BY, minor Bc	Yellow-brown	0 - 0.5	1.5 - 17	Basanitic tuff	32

Table 1. Morphologic groups of gem zircons from alkali volcanics, eastern Australia.

Localities:

1. Newbury, nr Trentham, V.
2. Blue Mountain, nr Trentham, V.
3. Blue Creek, nr Trentham, V.
4. South Bullarto, V.
5. Babbingtons Hill, Lyonville, V.
6. Loddon R. Lyonville, V.
7. Mt. Wilson, nr Bullarto, V.
8. Camels Hump, nr Woodend, V.
9. Leonards Hill — Daylesford, V.
10. Hepburns Lagoon, nr Newlyn, V.
11. 'Bullarook', Newlyn Area? (NMV Coll).
12. Point Leo, nr Flinders, V.
13. Tea Tree Ck, nr Lancefield, V.
14. Tumbarumba Area, NSW.
15. Oberon Area, NSW.
16. Duncans Ck, nr Nundle, NSW.
17. Brickclay Ck, nr Walcha, NSW
18. Rocky River Area, nr Uralla, NSW.
19. Tingha, NSW.
20. Elsmore Hill, nr Inverell, NSW.
21. Horse Gully, nr Inverell, NSW.
22. Oban, NSW.
23. Bald Nob, NSW.
24. Murphys Ck, nr Helidon, Q.
25. Ballogie, nr Proston, Q.
26. Brigooda, nr Proston, Q.
27. Mt. Moffat Area, Q.
28. Rubyvale — Sapphire, Q.
29. Tomahawk Ck, Hoy Prov., Q.
30. Lava Plains, Q.
31. Sisters Ck, Boatharbour, T.
32. Lake Bullenmerri, V.

Sample number	Mineral Locality	Number of grains	Standard track density x10^{6}cm^{-2}	Fossil track density x10^{6}cm^{-2}	Induced track density x10^{6}cm^{-2}	Correlation coefficient	Chi square test	Age Myr	Uranium ppm
8322-54	Mt Moffat, Qld	9	1.225 (5365)	1.032 (1175)	2.006 (2285)	0.994	pass	27.6 ± 1.1	87
8322-70	Duncans Creek	10	1.225 (5365)	1.752 (1182)	1.555 (1049)	0.903	pass	60.4 ± 2.7	68
8422-52	Elsmore Hill	12	1.225 (5365)	0.838 (881)	1.218 (1280)	0.915	pass	37.0 ± 1.7	53
8422-53	Horse Gully	11	1.225 (5365)	0.950 (915)	1.418 (1367)	0.686	pass	35.9 ± 1.6	62

Table 2. Analytical results: Fission track dating of zircons from New South Wales and Queensland. Brackets show number of tracks counted. Standard and included track densities measured on external detector surfaces and fossil track densities on internal surfaces (5 = 0.5). Ages calculated using Zeta = 87.9 ± 0.64 for dosimeter glass U3. Age dating by Geotrack International, Geology Department, University of Melbourne.

Newbury Group, and occasional colourless, pale-green, yellow or pink anhedra of unknown group affinities.

4. Point Leo, near Flinders, Vic. Beach sands yield abundant concentrates of scarlet zircon, blue corundum, pleonaste and ilmenite up to 3mm. Zircons are heavily abraded and recognisable crystals are very rare. Only five were recovered from several thousand grains. These were all BYZ forms, indicating a distinct field, the Flinders Group. Zircospilic minerals appear to be eroding out of mid-Tertiary olivine basalts in the catchments of a nearby creek. Wave action has produced rich concentrates at the beach heads.

5. Horse Gully, east of Inverell, New England Sapphire Field, N.S.W.: Alluvial sapphire workings between Inverell and Glen Innes, on the New England Tablelands, yield abundant zircon, corundum, pleonaste, ilmenite and very rare diamond. Zircospilic alluvials are derived from Tertiary volcanics which have been extensively denuded. Spinel and rarely corundum occur as megacrysts in some basalts (MacNevin, 1972). Zircons near source areas are largely unabraded but show variable magmatic disequilibrium, corrosion and etching. Abrasion is more apparent in the Horse Gully occurrence where four distinct groups show little overlap of characteristics. Crystal census details are given in Fig.3.

(a) Newbury Group: rounded to euhedral crystals range up to 17 mm, but are typically around 8 mm. Most are scarlet to deep orange-red; many being of gem quality. A few are brownish-red and transluscent. The majority are (100) + (101) forms, and rare acicular crystals show elongation of (100) consistent with growth into cavities. Short-wave U.V. fluorescence is nil to weak orange, and the group shows about four times normal background radioactivity.

(b) Inverell Group: these are the largest and most abundant zircons. They range from colourless through pale yellow-brown to colours almost indistinguishable from the brown type. Many crystals are of gem quality, being typically 12 mm and up to at least 25 mm. Original complete crystals many cm. across are indicated. The fragments are often blocky, strongly etched or smoothed, often with finely pitted surfaces. Euhedra are seldom sharp, and identifiable crystals are rare with gross distortions. Crystals show a large morphologic range, the majority being in the ABZ range. A multi-source series is suggested, perhaps including some lower temperature pegmatitic sources. Some crystals are flattened along (100) and show evidence of attachment (see below). Fluorescence is a brilliant yellow, and radioactivity is the lowest of any zircons tested.

(c) Elsmore Group: these are the least abundant zircons at Horse Gully, although elsewhere in the Glen Innes-Inverell districts they may be predominant. Rounded to sharp euhedra are typically 5 mm but range up to 10 mm. A pale mauve or lilac colour is characteristic, often with patchy distribution and colourless areas. A majority of crystals are in the low-prism, high-pyramid area of the classification system (Fig.2). Fluorescence ranges from weak to medium yellow, and radioactivity is about twice the normal background.

(d) Nundle Group: although zircons of this group show a similar range of crystal forms to (c), their orange-brown colour and slightly larger size than the Elsmore Group are distinctive.

A fission track date on Horse Gully zircon gives 35.9 Ma (Table 2) suggesting that the zircon source rocks are early Oligocene or older.

6. 'Braemar', near Elsmore Hill, New England Sapphire Field. A recently exposed section shows bedded pale-grey to brown 'trachytic' pyroclastics which yield abundant corundum, pleonaste and lesser zircon (Lishmund & Oakes, 1983). Zircons are unabraded and although most crystals are corroded, some are sharply crystallised. The assemblage shows considerable overlap of types and distinct grouping was impossible. However, all the types noted from Horse Gully are present but in different proportions.

Colour	Max. Size	Frequency	Group Affinity
Colourless	10 mm	Rare	Nundle & Elsmore
Pale yellow-brown	15 mm	Approx. 30%	Nundle & Inverell
Umber	15 mm	“ 20%	Nundle
Orange-red	12 mm	“ 25%	Newbury
Mauve-orange	12 mm	“ 10%	Elsmore
Semi-opaques	Over 30 mm	“ 15%	Newbury & Nundle

The Braemar pyroclastics are an important discovery as they provide a solution to a 'zircospilic supply' problem. The supply of zircospilic megacrysts from the basalts would not account for their abundance in the alluvials. Readily eroded pyroclastics rich in zircospilics may have been widespread and would have provided prolific sources of alluvial material. Remnants of pyroclastics are only likely where overlying basalts have afforded protection, as at Braemar.

The Elsmore zircon gives a fission track date of 37 Ma (Table 2) which, like the Horse Gully result, indicates an early Oligocene or older source.

7. Headwaters of Duncans Creek, east of Nundle, N.S.W. Weathered basalt beside the Nowendoc-Hanging Rock road at Fossicking Area No. 22, 10 km east of Nundle, yields abundant zircons, pleonaste, ilmenite and scarce corundum (Sutherland, *et.al.*, 1984). Zircons are colourless, through honey to deep orange-brown, and comprise a single Nundle Group. Crystals are extensively shattered and partly rounded by corrosion. Sizes range from 1 to 15 mm with a noteworthy absence of smaller crystals. Partial solution of the zircons indicates that they were not in equilibrium with their host alkali olivine basalt. Other basalts in the area appear zircon-free. A trondjhemite pluton 10 kms to the north, and a 'stressed' granite pluton 20 km NNE (Binns, 1967) indicate that granitic cumulate sources are a possibility; alternatively, a cognate origin in Tertiary fractionated basalts should be considered.

The Nundle zircons yield a fission track age of 60.4 Ma (Table 2) so that the host basalt is a small remnant of the earliest basalts erupted in the area (60-35 Ma; F.L. Sutherland & P. Wellman, in prep.). This age closely matches that of the Square Top theralite intrusion 3 km west of Nundle (60.1 Ma recalculated minimum age; McDougall & Wilkinson, 1967). This intrusion shows differentiation to a tinguaite end member (Joplin, 1971). Thus, nepheline syenite magma belonging to this may occur at depth to contribute zircons to associated basalt eruptions.

8. Anakie Sapphire Field, Central Qld. A large area, producing sapphire and gem zircon, with workings centered around The Willows, Tomohawk Creek, Sapphire–Rubyvale and Glenalba, is associated with Tertiary alkaline volcanics (Veevers *et.al.*, 1964). Country rocks consist of Palaeozoic granites and metamorphics, some of which contain small zircons. Gem zircons occur in post mid-Tertiary, high-energy alluvial spreads and most show major abrasion. Some rounded pebbles of zircon from Reward are fist-sized.

Crystals from the upper reaches of Policemans Creek, N.W. of Rubyvale are much less abraded, suggesting source regions westward towards the Drummond Range. Similar zircons have been recorded very rarely in basalts of the Anakie Field (Stephenson, 1976); sources that would appear inadequate to explain the abundant alluvial zircons. Zircons comprise three colour groupings:

(a) Pale yellow-brown, angular to rounded fragments, seldom showing crystal faces but closely resembling Inverell Group zircons.

(b) Brown to red-brown, mostly rounded crystals of Nundle Group, sometimes showing sharp crystals.

(c) Mauve-orange, mostly rounded crystals and fragments of the Elsmore Group; generally much less common than (a) or (b). In ordinary light, some crystals appear scarlet, but no orange-red (Newbury Group) zircons were noted in Reward-Rubyvale samples. Some of the yellow-brown zircons show strong colour zoning. Zircons appear to be about five times as common as corundum at Rubyvale, but pleonaste is distinctly rare.

9. Sisters Creek, near Boatharbour, Tas. Zircons are abundant in gravels associated with Tertiary basalts, with rarer spinel and blue corundum, in the Sisters Creek-Boatharbour area near Wynyard (Matthews 1973). They are mostly transparent, scarlet to orange-mauve; some showing patchy colouration, grading to colourless. Crystals show a strong predominance of (101) + (110) forms, some with minor (100) (See Fig.3). There is a large range of complex combinations with second- and third-order pyramids. Crystals show evidence of considerable magmatic corrosion, and abrasion is negligible. They are being shed into the local creeks from an olivine melilitite flow which is dated at 26 Ma (authors' unpublished data). They are associated with 'anorthoclase' derived from an underlying basalt flow. The range of crystals probably represents a low-temperature, dry, alkaline-plutonic source rock. The overlap of minor crystal types with the Elsmore, Nundle and Bullenmerri Groups is noteworthy, although the majority comprise a distinct assemblage.

10. Lake Bullenmerri, Western Vic. The recent maars at Lakes Bullenmerri and Gnotuk, southwest of Camperdown, are surrounded by basanitic tuffs and agglomerates. These contain large blocks of alkali gabbro (Grayson & Mahony 1910), basalt, Tertiary sediments and ultramafic nodules of upper mantle origin (Ellis, 1976; Hollis, 1981). Concentrated heavy mineral sand along a limited section of the eastern shore at Lake Bullenmerri contains abundant zircons (McMahon & Hollis, 1983) up to 17 mm in diameter. Elsewhere around the lakes, there are only a few small zircons. Colours are mainly pale orange-brown but range to straw yellow, pale greenish-yellow, white, colourless and dark brown. Colouring is sometimes patchy, perhaps due in part to localized minute inclusions. The zircons are non-fluorescent with radioactivity about 14 times that of the background. This may be due to inclusions of a radioactive mineral; some crystals do have conspicuous opaque black inclusions that resemble allanite. Crazing and fracturing are widespread, resulting in many broken crystals. This crazing may have occurred due to rapid cooling and depressurisation during transport in eruptions, or it may reflect metamictisation.

Many of the zircons occur as well developed crystals that show minimal corrosion or abrasion. The majority show only (101) forms and the remainder have variable development of (110) and (301) (Figure 3). According to the scheme proposed by Pupin (1980), crystals of these types, having high pyramid and low prism indices, formed in dry, alkaline plutonic source rocks at low temperatures.

The associated minerals in the beach sand appear to be of entirely deep-seated or volcanic origin and comprise black spinels, pyroxenes, olivine, amphiboles, garnets, ilmenite, biotite and anorthoclase. Corundum, normally associated with the zircon, was not found.

The Bullenmerri zircons appear to have been samples from a shallow-crustal alkaline body, of small dimensions, that was intercepted by one of the volcanic pipes. The zircons apparently come from the tuffs that accumulated around the eruption centre. The general lack of abrasion supports this local origin.

Zircon Host Rocks

Zircon megacrysts occur in many Tertiary to Cainozoic alkali basalts, trachytes, alkali breccias and intrusives. The chance of seeing a zircon *in situ* is low, as concentrations seldom exceed five crystals per cubic metre. Zircons in fresh basalts are known from the Anakie–Rubyvale, Cheviot Hills and Cooktown areas in Qld (Stephenson, 1976), east of Inverell (this study), northern N.S.W., near Armidale (Binns, 1969) and at Lake Learmonth, Vic. (National Museum of Victoria collection). Zircon is found with attached basalt near Mt Moffatt, Buckland Province, Qld (Australian Museum collection). A fission track date of 27.6 Ma (Appendix) suggests that the zircon was erupted during the main shield-forming stage of this volcano. Abundant zircon can be panned directly from weathered *in situ* basalt at Nundle and Boatharbour. Red euhedral zircons are common in late Tertiary to Quaternary alkali basalts and trachytes in the Trentham and Daylesford areas, central Vic. Zircons are about eight times as common in basalt at Newbury than in the nearby trachyte at Blue Mountain. Those occurring in basalts show considerable magmatic corrosion, but the trachytic zircons have sharp crystals which may be cognate. Crystals from different basalts of various ages (6–2.5 Ma) are physically identical, suggesting xenocrysts from a common source (J.D. Hollis, A. Gleadow, & D. Sewell in prep.).

A zircon-bearing xenolith in basalt is described from Rileys Peak near Bowral, N.S.W. (Wass & Irving 1976). A scarlet zircon crystal occurs in coarse anorthoclase of a type characterising alkaline rocks. It shows short

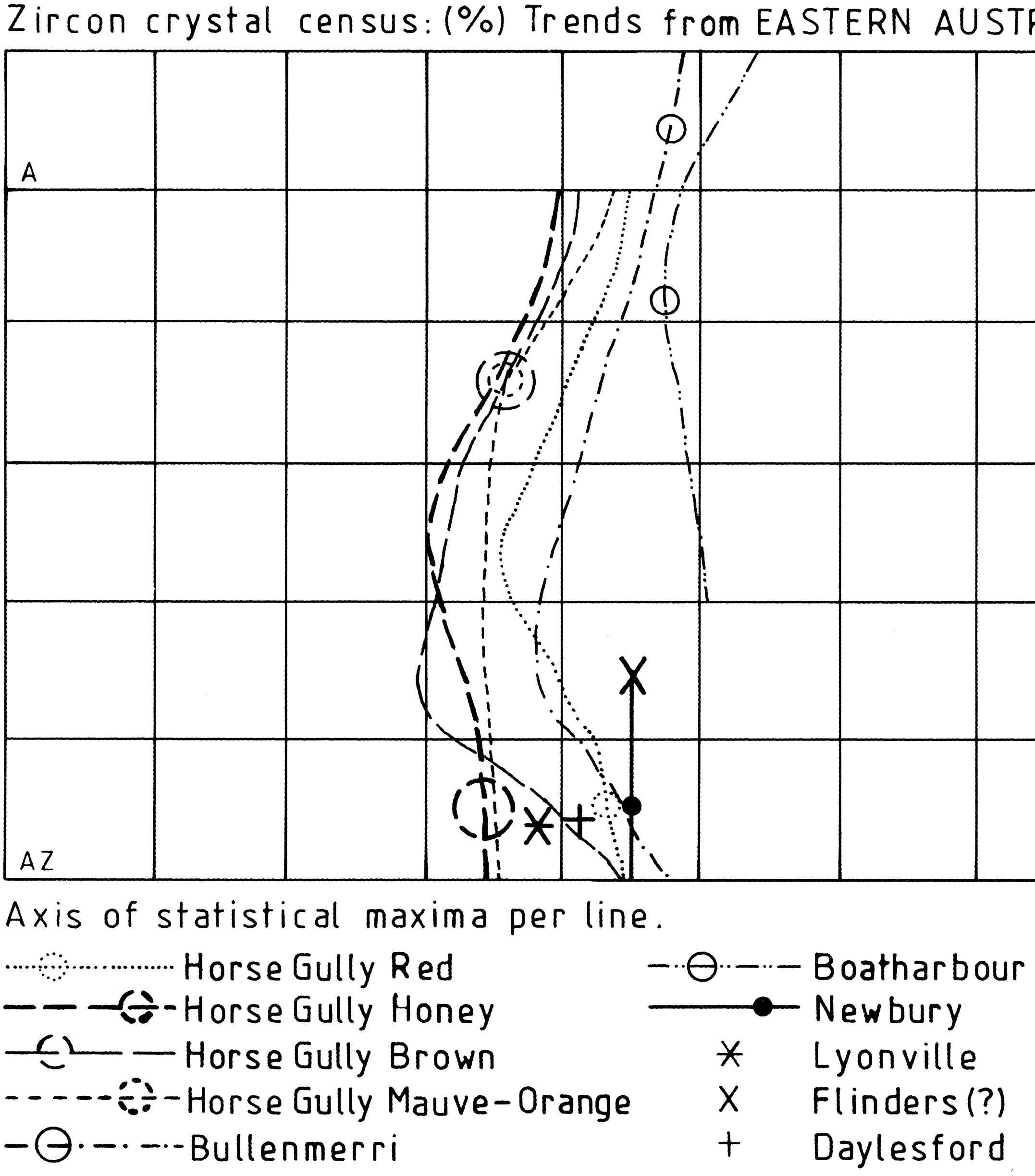


Fig. 4. Some crystallisation trends for large zircon groups in eastern Australia. Trend lines link statistical peaks of crystal type occurrence across each line. Circles show the maximum abundance stage for each group.

(110) prism development.

The zircon-bearing olivine melilitite flow at Boatharbour also contains rare xenoliths of a cumulate, olivine-bearing, nepheline syenite. No granitic or syenitic rocks are known to outcrop in the region. The nepheline syenite is probably related to Tertiary intrusions at depth. It may represent nepheline benmoreite magma associated with fractionated anorthoclase-bearing alkaline lava which outcrops below the melilitite flow.

Crystallisation Trends in Gem Zircons

Figure 4 shows a remarkably consistent set of crystallisation trends for gem zircons from eastern Australia. All groups counted, except Boatharbour, show commencement of crystallisation at the upper temperature extreme, developing (a)BZ crystal forms. The trend for the Flinders Group is poorly known and not discussed further. Gem zircons from Horse Gully and the Bullenmerri Group all show comparable trends with a right swing in the trend curve at the (a)ByZ or (a)BYZ stages. Crystallisation continued to the B or BY, low temperature forms. Peak crystallisation counts vary markedly between groups, with peaks independent of the trend curve swing. The Boatharbour trend is considerably to the right and commences with BYZ forms. The trend curve swing is at the BY crystal stage, much later than the other groups, and well to the right, suggesting more alkaline environments. Daylesford and Lyonville Group zircons are restricted to (a)BZ forms, and the Newbury Group barely proceeds past ByZ. These trend lines may give evidence of magma fractionation histories, and changes in alkalinity, although lack of proven source rocks for the zircons makes it difficult to examine individual cases.

Causes and the significance of these trends are unknown and work on experimental melts will be necessary to solve the problems. However, a hypothetical model can be suggested to explain certain aspects of the trends.

At its maximum temperature (900–1100 °C), a slightly metaluminous, Zr-rich (over 1000 ppm), Zr-saturated magma may have most of its Zr held by alkali zirconosilicate counter-ions. The slight excess of free Zr will precipitate as BZ-type zircon crystals. As the magma cools, fractionation removes alkalis by the settling out of alkaline mineral phases that are less rich in alumina; the melt becomes peraluminous, counter-ions are removed and Zr far exceeds saturation capacity. Zircon precipitation increases to a peak before decreasing as low Zr concentrations are reached. At lowest temperatures BY crystals develop.

If a magma chamber's contents remain as a closed system, a complete succession of crystal forms will develop with a peak representing a peralumious stage, as recorded for the Horse Gully and Bullenmerri Groups. Where the magma erupts before significant cooling, as in the Lyonville, Daylesford and Newbury Groups in Victoria, none of the lower temperature crystal types will be present in the assemblage. A melt that is peralkaline may fail to crystallise any zircons until fractionation can render the melt peraluminous. Such a case may be illustrated by the Boatharbour Group.

Origins of Zircons

The zircons found in alkali volcanic rocks include possible cognate types in trachyte (Lyonville Group) and magacrysts of unknown provenance in basalts (other groups). Preliminary analyses of the zircons show differences in compositions that probably reflect diverse sources (D. Sewell, pers.comm.). The only definite trend so far detected in the zircon compositions is an increase of Hf content with increasing (110) prism development. This probably indicates a temperature control as magmas fractionate to lower-temperature, less mafic compositions. The absence of (110) prism development in the Newbury, Lyonville and Daylesford Groups probably indicates eruptive cutoff of crystal development before the lower temperature forms could be expressed.

Role of fractionating basalt magmas. Most basalts are peraluminous ($Na_2O + K_2O/Al_2O_3<1$). As Australian basaltic magmas fractionated to less mafic compositions, Zr increased in concentration as an incompatible element (Sutherland, 1980; Ewart *et.al.*, unpubl.ms.). This may eventually lead to zircon crystallisation. Experimental work (Watson, 1979) suggests that felsic, non-peralkaline magmas are likely to contain zircon crystals because of the low saturation level of zircon in such compositions. Irving & Frey (1984) considered that zircon megacrysts found in lineages are only likely to be phenocrystic in the extreme fractionation end members (trachytes, benmoreites and undersaturated associates).

The east Australian evidence suggests that zircons may develop from compositions as mafic as nepheline mugearite, based on the occurrence of euhedra up to 8 mm in a dyke at Brickclay Creek, N.S.W. This rock shows Zr abundances of 325–450 ppm (Stolz, 1984; authors' unpublished data). The rock is mantle-derived and almost exclusively contains mantle xenoliths, but the relationship of the zircon to mantle sources is uncertain. Zircons also occur in alkali basalts and 'trachytes' devoid of mantle inclusions and derived from likely fractionation at crustal levels (eg. Nundle, Elsmore Hill; Sutherland, *et.al.*, 1984).

If the fractionating magmas become peralkaline, extremely high concentrations of Zr can be held by counter-ions as alkali zirconosilicate complexes (Bowden, 1966; Linthout, 1984). The counter-ion effect may be broken down by crystallisation of alkali amphiboles and pyroxenes (Watson, 1979), which result in peraluminous conditions and consequently decreased solubility of Zr in the melts (Carmichael & McDonald, 1961; Watson, 1979). This leads to greatly increased precipitation of zircon crystals, possibly as cumulates, and depletion of Zr in the host rocks (Ewart, 1982). Lesser concentrations of cumulate zircon can be expected in melts that have had lower Zr concentrations than melts that have been peraluminous throughout their crystallisation history.

Distribution of fractionated basalt end members. The east Australian Tertiary and possibly the Mesozoic volcanic/intrusive provinces include migratory 'hot spot' trails in which volcanoes develop felsic fractionates such as trachytes, rhyolites and leucitites (Wellman, 1983; Sutherland, 1983). Cognate zircons are known in these rocks in the Lyonville trachytes (Tertiary) and the Jingera syenite (Jurassic). We consider that the trachytes around Lyonville (5.9–6.1 Ma: Ewart *et.al.*, unpublished ms) probably evolved from K-rich understaturated magmas introduced into Victoria by that time (K-rich nepheline mugearites and olivine leucitites, 6.7 Ma: Irving & Green, 1976; Birch, 1976), increasing their Zr contents and opportunities for changing to peraluminous precipitation conditions. The Jingera syenite includes both quartz and nepheline normative rocks developed from a transitional basalt source rock at about the crust-mantle boundary. It shows high Zr/Nb contents and large zircon crystals (in conference talk given by Beams *et.al.*, 1983).

A large number of intrusive bodies of these fractionated felsic rocks probably exists under the main 'hot spot' volcanoes and possibly also under the migration lines where volcanic activity had not resulted. Many of these will provide potential reservoirs of zircon crystals/cumulates which may be brought up as xenocrysts during subsequent basaltic eruptions.

If zircon is also crystallised from nepheline mugearite, 'tinguaite' and mafic nepheline benmoreite magmas (Walcha, Nundle, N.S.W.; Boatharbour, Tas.) this would increase the number of potential reservoirs that could yield xenocrysts in later eruptions. Thus the widespread occurrence of zircon is the suspected function of extreme fractionation processes operating over some 220 million years.

Older zircon sources. Some of the megacryst zircons from the volcanic rocks are noteworthy for their large size and strong zoning, but confirmed reports of zircon in Palaeozoic pegmatites are generally absent. Many of these may be coming from peraluminous and mostly dry Palaeozoic granitoids (A Type of E. Australia, Collins *et.al.*, 1982). The largest and most diverse zircons come from the Inverell Group which occurs within the Permian New England batholith, a composite of four major magmatic episodes (312–232 Ma) ranging in composition from nepheline normative to highly felsic 'granites' (Hensel *et.al.*, 1982). The Inverell Group shows crystallisation over a considerable temperature range. Pegmatitic bodies in granitoids at depth could provide some of these.

Crystal Growth Sites

Cored zircons are frequent in granitoids derived from crustal anatexis (eg. Gulson & Krogh, 1975). Cores are zircons derived from pre-existing rocks that provided nucleii for the magmatic zircons. None of these cores have yet been found in the large crystals examined.

Many crystals are completely developed and appear to have grown freely in parent magmas. However, most larger crystals from the New England and central Queensland sapphire fields, belonging particularly to the Inverell and Nundle Groups, show features suggesting attachment during growth. These are:

(i) a virtual absence of complete euhedra;

(ii) a high frequency of flattened to tabular-elongate crystals;

(iii) the presence of stepped, convex faces (Fig.5);

(iv) the common development of straight, angular-profiled channels across one face, suggesting former attachment to another mineral. Apatite and rutile are possibilities as these occur as inclusions;

(v) the large size and strong zoning of crystals.

One of several possible models involves zircon growth on magma chamber or conduit walls, perhaps on suitable nucleii exposed on the magma-wall rock interface. Gradual melting of wall rocks would release attached zircons and expose fresh growth nucleii. The crystals may then settle through the magma to form cumulates. The enhancement of zircon crystallisation on magma chamber walls may result from increased fractionation of alkali-rich minerals in slightly cooler regions near contacts, rendering the magma peraluminous in their vicinity. The main body of the magma being less aluminous may show little or no free zircon development.

Subsequent violent outgassing via the magma chamber with its content of zircons would produce the zircon-rich pyroclastics seen at Elsmore Hill. Zircons stripped directly from the walls would show negligible corrosion; whereas those from the cumulates that were surrounded by less aluminous magma are likely to be partly dissolved and hence corroded. Both types of crystal preservation are widespread in the sapphire fields.

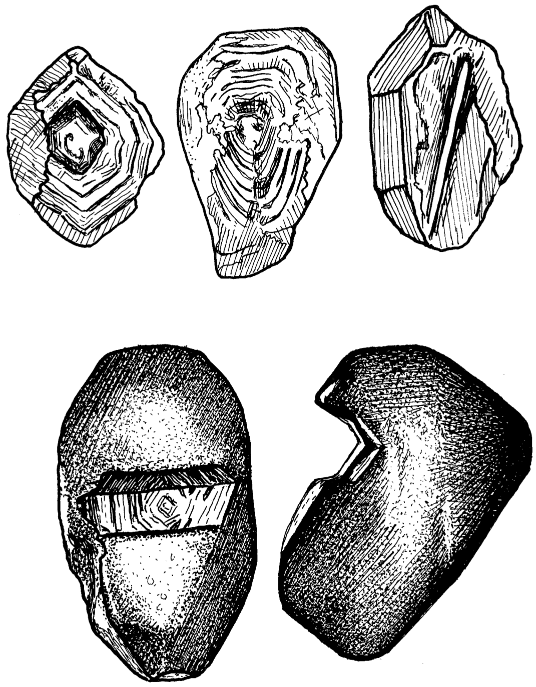


Fig. 5. Upper row: deformed zircon crystals from 'Braemar', Elsmore Hill, N.S.W., suggesting former attachment: **Left:** stepped-convex side of crystal, parallel to C axis, X2. **Centre:** similar crystal, with stepped-convex side at right angles to C axis, X3. **Right:** angular-profiled, straight trough of former acicular crystal phase, X20. **Lower row:** abraded Elsmore Group crystal from Reward, near Rubyvale, Qld., showing negative of former attached crystal, perhaps apatite, X20. Drawings: K.A. Hollis.

Conclusions

Large zircons from eastern Australia have diverse origins, few of which have been positively identified. Host rocks are generally alkali basalts, trachytes and their related pyroclastics. Most zircons from basalts are corroded, indicating disequilibrium with their host magmas. Their large sizes, strong zoning and morphologic diversity favours plutonic sources, mostly unrelated to their host rocks. Origins could include:

1. Crystallisations from peraluminous trachytes, for example the Lyonville Group in the Woodend Tertiary trachytes.

2. Syenitic magma chambers connected with the widespread Mesozoic-Cainozoic volcanism. Some zircon-bearing basalts have not been erupted through granitic country rocks, suggesting that these zircons may have crystallised in strongly fractionated magma chambers. Many crystals may have developed attached to the walls of these chambers, subsequently being carried to the surface in basaltic eruptions.

3. Cumulates in peraluminous alkali granitoid plutons, associated intrusives and metamorphics, related to the widespread crustal melting events of the Palaeozoic. The large Inverell Group zircons are candidates for such sources.

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