R.O. Chalmers, Commemorative Papers (Mineralogy, Meteoritics, Geology)

Edited by

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Possible Origins and Ages for Sapphire and Diamond from the Central Queensland Gem Fields

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ABSTRACT. Mining of sapphire has been carried out for over 100 years on the central Queensland gem fields. Zircon and the occasional diamond, like the sapphires, occur as clastic grains. The Hoy Basalt (a Tertiary basalt province of plugs and restricted flow remnants) was considered to be the source of the sapphire and zircon. Age determinations on basalts of the Hoy Province indicate eruption at different times from the early Eocene to the Middle Miocene. The recognition of sapphire and zircon bearing pyroclastic deposits at Bedford's Hill, the Divide and near Sheep Station Creek in the Rubyvale area suggests that most of the sapphire and zircon in the alluvial deposits came from the pyroclastics and not from the weathering of basalt.

Evidence points to sapphire and zircon-bearing felsic parental rocks, which were crystallised around the crust-mantle boundary. The gem minerals were largely brought to the surface by pyroclastic eruptions, particularly during the Early to Middle Eocene. Two groups of alluvial zircons (smaller, pale yellow crystals and large reddish brown crystals) give separate fission track ages. These suggest eruptive thermal resettings around 58 Ma and 20 Ma respectively. The apparent absence of substantial volcanism in the southern part of the Anakie Inlier during the Jurassic and Cretaceous probably reflects a cooler regional geotherm. The occurrence of low-uranium zircon of Late Cretaceous age (66 Ma) in some of the gem field clastic deposits suggests that conditions may have been appropriate for the emplacement of diamond bearing material during this period.

The central Queensland gem fields (Fig.1) have been producing sapphire, zircon and occasional diamonds for more than 100 years (Robertson, 1980). The source of this sapphire was considered to be the Hoy Basalt by previous workers (Jack, 1892; Dunstan, 1902; Veevers

et al., 1964; Stephenson, 1976, 1990).

Jack (1892) concluded that the basalt was the source of the sapphire after observing the association of pleonaste and sapphire in the alluvial deposits. He also observed that zircon was prolific and was associated with

gold in alluvial deposits beneath basalt at the Basalt Hill diggings north-west of Anakie. Although Jack was informed of the presence of small blue sapphires in the auriferous deposits none were found during his visit.

Dunstan (1902) recorded both pleonaste and corundum in basalt at Mount Leura and Mount Hoy and was shown sapphire reportedly coming from basalt at Black Peak.
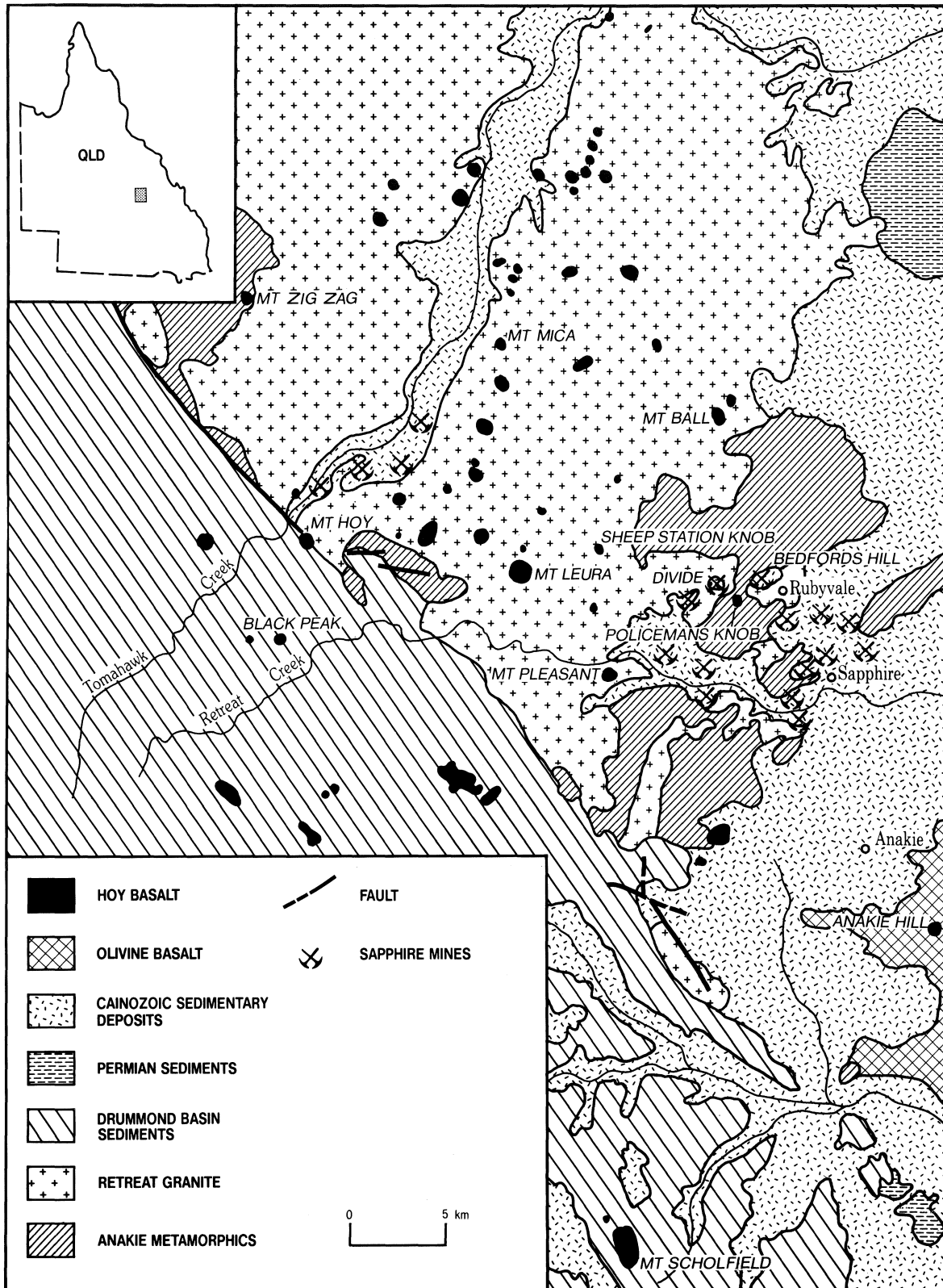

Fig.1. Simplified geological map of the central Queensland sapphire fields.

This also led Dunstan to believe that the basalt in the Anakie area was the source of the sapphire. He reported the presence of clear white zircon in alluvium devoid of sapphire below the basalt at Policeman's Knob and confirmed the absence of sapphire, olivine and pleonaste in the zircon bearing auriferous deposits at the Basalt Hill diggings. He concluded that these auriferous gravels were the oldest in the district.

Veevers et al. (1964) supported Dunstan's (1902) views on the origin of the sapphire. Wilson (1974) held a different view and proposed that the sapphire was brought to the surface during the early phases of violent eruption of the Hoy Basalt that produced "...volcanic debris and occasional lava flows...". He contended that "...by the time the volcano's life was drawing to a close, its capacity to bring to the surface large quantities of material from deep in the earth was seriously reduced..." and therefore few sapphires would be found in the existing plugs. However, Stephenson (1976) tended to be less emphatic although he still considered the basalt to be the transporting medium. In his study of the origin of the sapphire in Queensland, Stephenson mentioned a corundum-anorthoclase xenolith in basalt at Mount Leura and put forward three possible origins for the corundum and zircon: i) xenocrysts derived from deep crustal metamorphic material; ii) primary crystals which grew in a basaltic melt under unknown exceptional circumstances; and iii) xenocrysts derived by disaggregation of mantle or deep crustal material.

He considered the first proposal was untenable in the presence of growth zoning textures in corundum and the second proposal unlikely in the context of the anorthoclase association. He favoured the third proposal on the basis of euhedral habit, growth zoning and rare preservation with anorthoclase. Corundum recovered from the Hoy Basalt is encased in a green pleonaste spinel reaction rim - the reaction rim indicating disequilibrium with the surrounding host basalt. Some contain fluid inclusions and Irving (1986) suggests that the 'megacryst assemblage' may have crystallised from phonolitic magma at elevated pressure.

Two possible sources of the sapphire, (a) weathering of extensive basalt flows and (b) weathering of pyroclastic deposits, have been suggested by Stephenson (1990). He considered the latter source to be limited and his preferred interpretation as to the origin of the sapphire is a "...mantle source region of limited extent which contains older, fractionated sapphire-bearing source rocks, periodically sampled on an accidental basis by mafic volcanism...".

Geology

The general geology of the gem fields has been discussed by Veevers et al. (1964) and Robertson (1983). The Hoy Basalt Province differs from other central Queensland provinces in the dominance of volcanic plugs and undersaturated alkaline volcanism.

More than 70 plug intrusions occur within an area approximately 50 km in diameter near to the present exposed eastern margin of the Drummond Basin. Nearly two thirds of the plugs fall within a north-northeast trending zone approximately 10 km wide near the centre of the volcanic province, suggesting possible deep structural control (Fig.1). Other minor alignments have also been observed (Stephenson et al., 1989). Most of the plugs intrude Retreat Granite while others intrude the Anakie Metamorphics and sediments of the Drummond Basin. Several breccia bodies have been located in the Rubyvale area and breccia has been noted at the margins of some plugs (Mount Ball). However, most plugs are composed of massive, fine grained basalt.

Basanite forms by far the greater number of the plugs followed by alkali basalt, nepheline hawaiite and hawaiite with only minor nephelinite, transitional hawaiite and basalt (Stephenson et al., 1989; Stephenson, 1990). Veevers et al. (1964) recorded olivine dolerite at Mount Ball and along the margin at Mount Scholfield, while the centre of Mount Scholfield and a small plug to the north-west of Mount Scholfield are olivine gabbro.

Some of the plugs contain abundant xenoliths and xenocrysts. Anorthosite, gabbro, pyroxenite, granulite, lherzolite, granite, and metasediments along with spinel, anorthoclase, pyroxene, sapphire, zircon and rare amphibole have been found (Veevers et al., 1964; Stephenson, 1976; Griffin et al., 1987; Stephenson et al., 1989; Robertson, unpublished data). Abundant spinel lherzolite, felsic to mafic granulite and granite accompanied by minor garnet pyroxenite and gabbro occurs at Mount Leura (Griffin et al., 1987) while xenocrysts of spinel, pyroxene and anorthoclase are common. Anorthosite xenoliths at Black Peak (Veevers et al., 1964) are accompanied by abundant black rimmed pyroxene xenocrysts. Sheep Station Knob contains abundant lherzolite, pyroxenite and metasedimentary xenoliths and some granulites (Griffin et al., 1987), accompanied by abundant anorthoclase and minor pyroxene xenocrysts. Xenocrysts of sapphire have been reported from Mount Leura, Mount Hoy, Mount Pleasant, and Black Peak (Dunstan, 1902; Stephenson, 1976). Zircon occurs as xenocrysts in the basalts at Mount Leura, Mount Pleasant and Mount Hoy (Stephenson, 1976; Robertson, unpublished data).

Age of Hoy Basalt Province

Five periods of igneous activity have been indicated by K-Ar whole rock age determinations for the Hoy Basalt so far (Table 1 [see Appendix]). Policeman's Knob (55.5-56.2 Ma) is the oldest dated basalt. Other localities gave age groupings of Early Oligocene (31.3 Ma), Late Oligocene (28.2-25.6 Ma; Sheep Station Knob; Mount Llandillo), Early Miocene (19.8 Ma; Mount Leura) and Middle Miocene (14.5 Ma; olivine nephelinite Anakie Hill).

Fission-track ages derived from zircon from alluvial deposits in the Rubyvale area (Table 2 [see Appendix]) extend the age of known volcanic episodes. Clear, white zircon similar to that recorded by Dunstan (1902) in alluvium below Policeman's Knob gives an age of 65.9 ± 5.5 Ma and has an average uranium (U) content of 21 ppm. Sherry coloured zircon (34 ppm U) gives an age of 58.0 ± 3.8 Ma comparable to the age of the Policeman's Knob basalt. A brownish-red zircon (101 ppm U) with an age of 20.3 ± 1.2 Ma lies within error of the Early Miocene eruption age of Mount Leura.

Temperature-Pressure Determinations (Xenoliths and Xenocrysts)

Griffin et al. (1987) in their study of the geothermal profile and crust-mantle transition beneath east-central Queensland derived equilibration temperatures and pressures ranging from 865 to 900°C and 7.2 to 9.8 kb from garnet granulite from Sheep Station Knob. A garnet websterite from Mount Leura gave a derived temperature of 1000°C and a pressure of 13.5 kb. These pressures represent depths of about 25 km to 33 km. From their work Griffin et al. (1987) concluded that the spinel lherzolite associated with the garnet granulite and the garnet websterite became the dominant rock type at a depth of 30 km and persisted, interlayered with pyroxenite to depths of approximately 55 km in central Queensland.

Stephenson (1976, 1990) and Stephenson et al. (1989) suggested that the CO_2 rich fluid inclusions in sapphire and sapphire-bearing anorthoclasite were formed at a minimum pressure of formation of 10 kb, indicative of an upper mantle origin. On the basis of the work of Stephenson (1976, 1990), Griffin et al. (1987) and Stephenson et al. (1989) it may be concluded that a large proportion of the magma comprising the Hoy Basalt Province was generated in the upper mantle before being extruded at the surface.

Irving (1986) found distinctive fluid inclusions in Anakie sapphire forming planar arrays transverse to the growth zoning. Heating-freezing studies revealed two main types. One which contains pure CO_2 and has similarities to such fluid inclusions in sapphire in minette from Yogo, Montana (Roedder, 1972). The other fluid inclusion type comprises multi-phase inclusions with CO_2, H_2O plus halite, sylvite and unidentified mineral phases. The multi-phase inclusions remained unhomogenised at temperatures up to 685°C. The evidence from these hydrous inclusions, together with growth zoning, CO_2-rich inclusions and the association of corundum intergrown with anorthoclase at Mount Leura (Stephenson, 1976) and with sanidine + rutile in alkali basalt from Loch Roag, Scotland (Upton et al., 1983) led Irving (1986) to suggest "...a high temperature (and pressure) magmatic origin for the corundum megacrysts...".

Pyroclastic Deposits

The early shaft mining of sapphire at the Divide (GR 670102 Rubyvale 1:100 000 Sheet) and Bedford's Hill (GR 707103 Rubyvale 1:100 000 Sheet) may have worked primary volcanic deposits. Such pyroclastic deposits were being worked for sapphire during the early to middle 1970's (Robertson, unpublished data) at depths of 15 to 20 m on Bedford's Hill, at the Divide and adjacent to Sheep Station Creek at Reward (GR 667060 Rubyvale 1:100 000 Sheet). At Bedford's Hill, pyroclastics 1 to 4 m thick (Fig.2) overlie granite and are overlain by fluviatile sediments derived partially from the pyroclastics but mainly from the Retreat Granite and the Anakie Metamorphics. Gravelly lenses up to 1.5 m thick and containing sapphire are dispersed throughout the fluviatile sediments. The sapphire and zircon bearing pyroclastics on Bedford's Hill contain both air fall and surge deposits preserved in depressions in the granitic terrain.

At the Divide, sapphire and zircon bearing pyroclastics, when present, form the basal part of the sapphire bearing strata. Erosion of the pyroclastics resulted in gullying into which coarse gravel, composed of basalt, metamorphics, granite and reworked pyroclastics, were deposited. The gravel contained both sapphire and zircon. This sequence is overlain by sandy strata derived from the Retreat Granite, Anakie Metamorphics and the Kettle Conglomerate Member of the Permian Aldebaran Sandstone and shows some similarities to the Scrub Lead type of Robertson (1983).

The pyroclastic deposits at Bedford's Hill, the Divide and Sheep Station Creek contain no recognised silcrete. However, the fluviatile sediments overlying the pyroclastics and found elsewhere on the gem fields contain boulders, cobbles and pebbles of silcrete (Robertson, 1983). The age of the silcrete is not accurately known. The basaltic plug at Mount Llandillo (26.3 Ma) intrudes silcrete developed on Permian conglomerate similar to that in the Aldebaran Formation further to the east (Robertson, 1983). Silcrete underlying basalt in the Emerald Region may be younger than the overlying mid-Tertiary basalt, having formed during the weathering of the basalt (Grimes, 1980). Grimes suggests that the main period of silcrete formation in the Fitzroy Region extended from Late Eocene to the end of the Early Oligocene.

Origin of the Sapphire, Zircon and Diamond

Evidence for the possible origins of the sapphire, zircon and diamond have been drawn from a number of sources that are discussed in the following sections.

Zircon

Hollis & Sutherland (1985) studied zircons from the

Reward-Rubyvale area. They were not aware of the pyroclastics, but considered that a basalt source would be inadequate to explain the various morphological types in the alluvials. Unpublished work by the present authors on the crystal morphology of zircons from the central Queensland gem fields supports a multi-sourced origin for the zircon.

The pyroclastic deposits at Bedford's Hill and the Divide were observed to contain large (1-4 cm diameter) clear white to sherry coloured zircon and smaller zircon (1-5 mm diameter) varying from these colours to light yellow-brown. On crystal morphology (when crystal faces are present), the smaller zircons recovered from mining operations in this vicinity correspond to Hollis & Sutherland's (1985) Boat Harbour group, occurring as xenocrysts in undersaturated alkaline lavas. A number of the zircons are highly polished while others show etch pitting. Large zircons exhibit few crystal faces, are usually well rounded and cannot normally be categorised using crystal morphology.

No brownish-red to red zircons have been recovered from the pyroclastics although brownish-red to red zircons are common in the sapphire bearing strata in the overlying fluviatile sediments. The red zircon does not match the Boat Harbour grouping but tends to fall in a scattered field (Robertson, unpublished data). Some

mauve-orange zircon related to the Elsmore Group and brown to red-brown zircon related to the Nundle Group (FT date 20Ma) is found in the Reward-Rubyvale zircon concentrates (Hollis & Sutherland, 1985). The small pale yellow crystals from here (FT date 58 Ma) are not related to the Boat Harbour group, as they commonly exhibit pyramidal faces on 211 (Hollis & Sutherland, unpublished data).

Anorthoclase

Anorthoclase xenocrysts occur with corundum and zircon and weathered xenoliths of lherzolite, pyroxenite, granulite and granite in the pyroclastic deposits. The presence of this material in both the pyroclastics and several plugs of the Hoy Basalt suggests that it may have been generated from similar source areas. The composition of anorthoclase associated with corundum in the Mount Leura xenolith is shown in Table 3 (see Appendix), along with compositions of its secondary alterations of increasingly less sodic content and an anorthoclase megacryst of comparable composition to that of the xenolith.

Irving & Frey (1984) believed that anorthoclase and

Fig.2. Sapphire bearing pyroclastic deposits at a depth of 20 m on Bedford's Hill, north of Rubyvale, central Queensland. Photo A.D. Robertson.

zircon are never in equilibrium with basaltic liquids and such megacrysts are exotic to their hosts. Anorthoclase is not produced near the liquidus of alkalic basalt compositions under most conditions and zircon may crystallise from felsic liquids but is not expected to be a liquidus phase of basaltic magmas (Watson, 1979; Watson & Harrison, 1983).

Chapman & Powell (1976) maintained that anorthoclase crystallises from the magmas no more mafic than benmoreite and the initial experiments of Chapman (1976) indicate that in a basanitic melt, anorthoclase is unstable at pressures greater than approximately 5 kb. Anorthoclase is known as a phenocryst phase and presumably a near-liquidus phase from 'evolved' liquids such as nepheline benmoreites, phonolites and trachytes (Irving & Frey, 1984). Although it may be transported by more primitive basaltic hosts in association with high pressure pyroxene and/or garnet megacrysts as well as high pressure, high temperature xenoliths, anorthoclase is considered by many to be a relatively low pressure phase. However, Guo *et al.* (1990) suggested that experimentally determined partition coefficients for Ba between typical anorthoclase megacrysts and parent magmas of evolved derivatives of basalt compositions are best approached at conditions of 10-15kb and 1000-1050°C.

Possible Origin of the Gemstones

Few primary fluid inclusions have been found in zircon from the gem fields. Most of the fluid inclusions are secondary developed along annealed fracture planes. Robertson (1984) reported rutile inclusions in zircon similar to those found in the sapphire. Some of the zircon recovered from the pyroclastic deposits on Bedford's Hill contained rutile inclusions and the occurrence of rutile in both zircon and sapphire suggests a possible common source. Irving (1986) considered the low uranium zircons (7-30 ppm U) have trace element assemblages similar to zircons found in nepheline syenite pegmatites but have much lower trace element assemblages than zircons from granitoids. This uranium range also includes that found in zircons recovered from 'kimberlitic sources' (Davis, 1976; Sutherland *et al.*, 1986). On the basis of the experimental evidence for instability of anorthoclase in basalt and the presence of both zircon and corundum in nepheline syenite pegmatites, Irving (1986) drew the inference that the megacryst assemblage in the Hoy Basalt "...may have crystallised from a phonolitic magma at elevated (probably deep crustal) pressures...".

The fluid inclusions within the sapphire (Stephenson, 1976, 1990; Irving, 1986) suggest a pressure of formation greater than 10 kb as the CO_2 fluid inclusions are considered to be pseudo-secondary and the pressure before fracturing was possibly greater. The corundum-anorthoclase association (Stephenson, 1976) indicates that the corundum was not a primary phase in the Hoy Basalt, in accord the work of Chapman & Powell (1976),

Irving & Frey (1984) and Guo *et al.* (1990) that anorthoclase megacrysts do not crystallise from magmas more mafic than benmoreite. Therefore the corundum in both the basalt and the pyroclastics is classed as xenocrystic material.

The presence of diamond with sapphire and zircon in the fluviatile sediments raises several questions, one of which is the source of the mineral. Dunstan (1902) first recorded diamond from the sapphire wash and, since then, diamonds continue to be recovered as a byproduct of sapphire mining. However the source(s) of the low-uranium bearing zircon and the diamond have yet to be identified. Low uranium bearing zircon (0-40 ppm U) is known to be associated with kimberlitic material (Davis, 1976), possibly nepheline syenite pegmatite (Irving, 1986) and carbonatite (Faulkner & Shigley, 1989). None of these rock types are yet recorded from the sapphire fields.

Breccia pipes occur in the Rubyvale area but little is known of their materials and heavy mineral content. Several circular depressions have been recorded between Reward and the Drummond Ranges in the vicinity of Retreat Creek. A drilling program (Robertson, 1974) and a seismic survey (Searle, 1974) covered the circular depression (GR 663052 Rubyvale 1:100 000 Sheet) in the vicinity of Reward. However, no hidden diatreme was discovered and Siemon (1977) considered the area may have been part of an old stream channel. The depressions to the west of Reward have not been examined in any detail.

Sudden outgassing in some alkali volcanic diatremes may initially transport and emplace material from a deep seated origin (diamond facies) prior to the onset of alkali basaltic volcanism (Hollis *et al.*, 1983; Temby *et al.*, 1984; Sutherland *et al.*, 1985). If the early eruptive material in diatremes of this type was to be eroded prior to the onset of alkali basaltic volcanism and its accompanying pyroclastics derived from higher mantle environments, then the diamonds and any associated zircon would appear mainly in the alluvial deposits (Temby *et al.*, 1984). Such a sequence of circumstances may have occurred on the central Queensland gem fields since no basalts or pyroclastics have been recorded containing diamond.

Possible Ages of Emplacement for Sapphire and Diamond

Three distinct periods in which zircon was brought to the surface have been recorded for the central Queensland gem fields (Table 2 [see Appendix]). The oldest recorded zircon (clear white in colour; 65.9 ± 5.5 Ma) has the lowest average uranium content (21 ppm). This material is morphologically similar to that found in alluvial deposits at Policeman's Knob and the Basalt Hill Diggings and is not accompanied by sapphire.

The sherry coloured zircon (34 ppm U; 58.0 ± 3.8 Ma) is a common colour and size in pyroclastic deposits containing sapphire and is accompanied by minor amounts

of the low uranium zircon. The age of eruption given by this zircon is comparable to that of the Policeman's Knob basalt and its uranium content is comparable to zircon derived from nepheline syenite pegmatite. The high uranium-bearing red zircon (101 ppm U) unrecorded from the sapphire bearing pyroclastic deposits, but a type found in the overlying fluviatile deposits is more characteristic of syngenetic zircon inclusions in sapphire from the New England gem field (Coenraads et al., 1990).

The absence of sapphire in the alluvial deposits below Policeman's Knob indicates that sapphire had not been erupted, or was not yet accessible to erosion before the Late Palaeocene. Sapphire accompanies zircon similar in colour to that of Late Palaeocene age (58.0 ± 3.8 Ma) in pyroclastic deposits on Bedford's Hill and zircon similar to the high-uranium zircon of Early Miocene age (20.3 ± 1.2 Ma) in the overlying fluviatile sediments. Thus, sapphire eruption is older than Early Miocene and possibly no older than latest Palaeocene. As no silcrete was seen in the pyroclastic beds, this may constrain the time span over which this sapphire-bearing material was emplaced. Grimes (1980) considered that the silcrete in the western part of the Fitzroy Region may have developed between the Late Eocene and end of the Early Oligocene. If this is correct then many of the sapphires on the central Queensland gem fields were emplaced by the very Early Eocene or before the Middle Oligocene. However, ion probe U/Th isotopic ages on the Rubyvale zircons give variable ages of formation compared to the fission track dates (Sutherland & Kinny, 1990 and unpublished). These ages of up to 234Ma (yellow crystals), 70Ma (larger pale low U grains) and 30Ma (red brown high U grains) open up the possibilities of multiple periods of sapphire formation and subsequent eruption.

Sutherland (1985) considered that the exact nature and origin of eastern Australian palaeogeotherms are critical to the likely sampling of any diamond window. Nickel & Green (1985) considered such a window lies between 120 to 160 km depth. O'Reilly & Griffin (1985) considered their xenolith-derived geotherm of south-eastern Australia defined a typical thermal state of the lithosphere beneath eastern Australia for the last 200 Ma. Griffin et al. (1987) showed that this geotherm described the thermal state for central-south east Queensland for the last 30 Ma. Beeston (1986) has shown that the heat flow within the Bowen Basin, to the east of the Anakie High, was far greater in the Permo-Triassic orogeny than that which affected the basin in post orogenic times.

The absence of volcanism in the region of the southern end of the Anakie Inlier from the Late Triassic until Late Cretaceous and the work of Beeston (1986) suggest that the geothermal gradient may have been less than that proposed by O'Reilly & Griffin (1985) in this part of eastern Australia. With the presence of exposed crystalline basement (possibly as old as Late Proterozoic) in the southern part of the Anakie Inlier and a lower geothermal gradient than in other periods for the area, diamonds could be potentially tapped and transported during the Late Jurassic and the Cretaceous. Transport of deep seated material at the end of the Late Cretaceous is indicated by the presence of low-uranium bearing zircon before the geothermal gradient again steepened initiating basaltic eruptions.

Conclusions

On the basis of available evidence, the sapphire found in the central Queensland gem fields was derived from around the crust-mantle boundary from source rocks more felsic than a mafic benmoreite and possibly nepheline syenite in character. The main bulk of the sapphire was transported during the pyroclastic phase of eruptions between late Palaeocene to early Oligocene time. It is not known if sapphire accompanied the younger eruptions (Early Miocene) that delivered the high-uranium zircon as no primary deposits have been found containing both the brownish-red to red zircons and sapphires.

Diamonds were most likely to have been emplaced between Late Jurassic and earliest Tertiary time when the geothermal gradient in the southern part of the Anakie High was at its lowest, thus allowing sampling through the 'diamond window'. The presence of Cretaceous-Tertiary boundary low-uranium zircon may be linked to at least some of the emplacements providing diamonds in the central Queensland sapphire fields.

References

Beeston, J.W., 1986. Coal rank variation in the Bowen Basin, Queensland. International Journal of Coal Geology 6: 163-179.

Chapman, N.A., 1976. Inclusions and megacrysts from undersaturated tuffs and basanites, east Fife, Scotland. Journal of Petrology 17: 472-498.

Chapman, N.A. & R. Powell, 1976. Origin of anorthoclase megacrysts in alkali basalts. Contributions to Mineralogy and Petrology 58: 29-35.

Coenraads, R.R., F.L. Sutherland & P.D. Kinny, 1990. The origin of sapphires: U-Pb dating of zircon sheds new light. Mineralogical Magazine 54: 113-122.

Davis, G.L., 1976. The ages and uranium contents of zircon from kimberlites and associated rocks. Carnegie Institute, Washington Year Book 62: 223-227.

Dunstan, B., 1902. The sapphire fields of Anakie. Publication of the Geological Survey of Queensland 172.

Faulkner, M.J. & J.E. Shigley, 1989. Zircon from the Harts

Range, Northern Territory, Australia. Gems & Gemology 25 (4): 207-215.

Green, P.F., 1986. Zeta calibration baselines in zircon, sphene and apatite. Chemical Geology (Isotope Geoscience Section) 58: 273-276.

Griffin, W.L., F.L. Sutherland & J.D. Hollis, 1987. Geothermal profile and crust-mantle transition beneath east-central Queensland: volcanology, xenolith petrology and seismic data. Journal of Volcanological and Geothermal Research 31: 177-203.

Grimes, K.G., 1980. The Tertiary geology of north Queensland. Pp. 329-347. In R.A. Henderson & P.J. Stephenson (eds). The Geology and Geophysics of Northeastern Australia. Geological Society of Australia Incorporated, Queensland Division.

Guo, J.F., T.H. Green & S.Y. O'Reilly, 1990. Ba partitioning and anorthoclase megacryst genesis. Geological Society of Australia Abstracts Number 25: 239.

Hollis, J.D. & F.L. Sutherland, 1985. Occurrence and origin of gem zircons in eastern Australia. Records of the Australian Museum 36: 299-311.

Hollis, J.D., F.L. Sutherland & R.E. Pogson, 1983. High pressure minerals and the origin of the Tertiary breccia pipe, Ballogie gem mine, near Proston, Queensland. Records of the Australian Museum 35: 181-194.

Hurford, A.J. & P.F. Green, 1983. The Zeta calibration of fission - track dating. Chemical Geology (Isotope Geoscience Section) 58: 1-22.

Irving, A.J., 1986. Polybaric magma mixing in alkaline basalts and kimberlites: evidence from corumdum, zircon and ilmenite megacrysts. Geological Society of Australia Abstracts Number 16: 263-264.

Irving, A.J. & F.A. Frey, 1984. Trace element abundances in megacrysts and their host basalts: constraints on partition coefficients and megacryst genesis. Geochemica et Cosmochemica Acta 48: 1201-1221.

Jack, R.L., 1892. Sapphire, gold and silver mines near Withersfield. Publication of the Geological Survey of Queensland 81.

Nickel, K.G. & D.H. Green, 1985. Empirical geothermobarometry for garnet peridotites and implications for the nature of the lithosphere, kimberlites and diamonds. Earth and Planetary Science Letters 73: 158-170.

O'Reilly, S.Y. & W.L. Griffin, 1985. A xenolith-derived geotherm for southeastern Australia and its geographical implications. Tectonophysics 111: 41-63.

Robertson, A.D., 1974. Preliminary geological report on the Anakie Mining Field. Report of the Geological Survey of Queensland 1974/18.

Robertson, A.D., 1980. Review of the sapphire industry of central Queensland. Record of the Geological Survey of Queensland 1980 (confidential).

Robertson, A.D., 1983. Notes on the geology of the central Queensland sapphire fields. Record of the Geological Survey of Queensland 1983/51.

Robertson, A.D., 1984. Negative inclusions in zircon from Anakie. The Australian Gemmologist 15(5): 164-166.

Roedder, E., 1972. Composition of fluid inclusions. United States Geological Survey Professional Paper 44JJ, 164 pp.

Searle, D.E., 1974. Anakie seismic survey - 1973. Record of the Geological Survey of Queensland 1974/3.

Siemon, J.E., 1977. Drilling programme. Departmental Area 82D. Anakie Mining Field. Record of the Geological Survey of Queensland 1977/1.

Stephenson, P.J., 1976. Sapphire and zircon in some basaltic rocks from Queensland, Australia. Abstracts of the 25th International Geological Congress Sydney: 602-603.

Stephenson, P.J., 1990. The geological context of the sapphire occurrence in the Anakie region, central Queensland. Geological Society of Australia Abstracts Number 25: 232-233.

Stephenson, P.J., F.L. Sutherland, A.D. Robertson & J.D. Hollis, 1989. Chapter 3.3.6. Pp. 101-103. In R.W. Johnson (ed.). Intraplate Volcanism in Eastern Australia and New Zealand, Cambridge University Press, Melbourne.

Sutherland, F.L., 1985. Regional controls in eastern Australian volcanism. Publication of the Geological Society of Australia, New South Wales Division 1: 13-32.

Sutherland, F.L. & P.D. Kinny, 1990. Ion probe U/Pb isotopic ages of gemmy zircons from eastern Australia, including Tasmania. Geological Society of Australia Abstracts Number 25: 241-242.

Sutherland, F.L., J.D. Hollis & L.R. Raynor, 1985. Diamonds from nepheline mugearite? A discussion of Garnet websterite and associated ultramafic inclusions from a nepheline mugearite in the Walcha area, New South Wales, Australia. Mineralogical Magazine 49: 748-751.

Sutherland, F.L., L.R. Raynor, J.D. Hollis & P.A. Temby, 1986. Prospective relationships between diamonds, volcanism and tectonism in Australia. Fourth International Kimberlite Conference Extended Abstracts. Geological Society of Australia Abstracts Number 16: 484-486.

Temby, P.A., F.L. Sutherland & J.D. Hollis, 1984. Distribution and possible origin of diamond in eastern Australia. Geological Society of Australia Abstracts Number 12: 515-517.

Upton, B.G.J., P. Aspen & N.A. Chapman, 1983. The upper mantle and deep crust beneath the British Isles: Evidence from inclusions in volcanic rocks. Journal of the Geological Society of London 140: 105-121.

Veevers, J.J., R.G. Mollan, F. Olgers & A.G. Kirkegaard, 1964. The geology of the Emerald 1:250 000 Sheet area, Queensland. Report of Bureau of Mineral Resources, Geology and Geophysics 68.

Watson, E.B., 1979. Zircon saturation in felsic liquids. Experimental results and applications to trace element geochemistry. Contributions to Mineralogy and Petrology 70: 407-419.

Watson, E.B. & T.M. Harrison, 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. Earth and Planetary Science Letters 64: 295-304.

Wilson, A.F., 1974. Mineral treasures of lava: Part 2. Australian Gem and Mineral Fossicker 1(3): 117-119.

APPENDIX

Table 1. Summary of K-Ar ages for Hoy Basalt

Location	Age (Ma)	Epoch	References
Policeman's Knob	56.2±1	Early Eocene	Robertson, 1983
Policeman's Knob	55.5	Early Eocene	Stephenson *et al.*, 1989
One unnamed plug	31.3	Early Eocene	Stephenson *et al.*, 1989
Three unnamed plugs	26-28	Late Oligocene	Stephenson *et al.*, 1989
Sheep Station Knob	26.5±0.7	Late Oligocene	Robertson, 1983
Mount Llandillo	26.3±0.5	Late Oligocene	K. Grimes unpubl. data
Mount Leura	19.8	Early Miocene	Stephenson *et al.*, 1989
Mount Scholfield	19.0	Early Miocene	Stephenson *et al.*, 1989
Three unnamed plugs	18-19	Early Miocene	Stephenson *et al.*, 1989
Anakie Hill	14.5	Middle Miocene	Stephenson *et al.*, 1989

Table 2. Fission track dating of zircons from Reward-Rubyvale alluvials, central Queensland.   Brackets show number of tracks counted. Standard and induced track densities measured on mica external detectors (g=0.5), and fossil track densities on internal mineral surfaces. Ages calculated using Zeta = 87.9 (8522 - 112 & 116) and 87.7 (GC114-2) for dosimeter glass U3 (Hurford & Green, 1983; Green, 1986). Analyses by P.F. Green & I. Duddy, Geotrack International, University of Melbourne, Victoria.

Sample no.and colour	No. of Grains dated	Standard of track density $\times10^6cm^{-2}$	Fossil track density $\times10^6cm^{-2}$	Induced track density $\times10^6cm^{-2}$	Correlation co-efficient	Chi square probability	Age ±1 Myr	Uranium content (av.ppm)
8522-112 fluorescent, pale grains	4	1.119 (2451)	0.582 (357)	0.432 (265)	0.964	30%	65.9±5.5	21
8522-116 brown-red crystals	6	1.119 (2451)	0.880 (462)	2.127 (1118)	0.904	40%	20.3±1.2	101
GC114-2 pale yellow crystals	10	6.182 (2726)	0.861 (801)	4.008 (373)	0.970	80%	58.0±3.8	34

Table 3. Analyses of corundum-anorthoclase composite from Mount Leura, central Queensland gem fields (D44379). The primary anorthoclase composition is compared with those of secondary polygonal recrystallisation and crystallisation from reaction with the host basalt. Analyses by B.J. Barron, using an automated ETEC electron microprobe at Macquarie University, Sydney. An anorthoclase megacryst analysis for comparison with the primary anorthoclase in the composite comes from nepheline mugearite host in the adjacent Nebo province (Analysis 3, Hollis *et al.*, 1983).

Mineral Analysis	Corundum (primary)	Anorthoclase (primary)	Anorthoclase (secondary)	Anorthoclase (host reaction)	Anorthoclase (megacryst)
SiO_2	0.00	64.27	62.03	65.12	64.74
Al_2O_3	98.53	21.45	22.66	19.63	21.87
FeO^{Total}	1.31	0.24	0.00	0.71	<0.02
MgO	0.32	0.00	0.00	0.00	0.00
Ca_2O	0.00	2.56	4.06	0.65	2.33
Na_2O	0.00	8.05	7.66	6.21	8.87
K_2O	0.00	2.43	1.77	6.98	2.01
Total	100.16	99.00	98.18	99.31	99.42
Ca		12.8	20.3	3.2	11.2
Na		72.8	69.2	55.6	77.1
K		14.4	10.3	41.2	11.5

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http://dx.doi.org/10.3853/j.0812-7387.15.1992.81

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Robertson and Sutherland, 1992, *Rec. Aust. Mus., Suppl.* 15: 45–54
http://dx.doi.org/10.3853/j.0812-7387.15.1992.83

England, 1992, *Rec. Aust. Mus., Suppl.* 15: 55–72
http://dx.doi.org/10.3853/j.0812-7387.15.1992.84

Rodgers and Hudson, 1992, *Rec. Aust. Mus., Suppl.* 15: 73–81
http://dx.doi.org/10.3853/j.0812-7387.15.1992.85

Torrence et al., 1992, *Rec. Aust. Mus., Suppl.* 15: 83–98
http://dx.doi.org/10.3853/j.0812-7387.15.1992.86

Branagan, 1992, *Rec. Aust. Mus., Suppl.* 15: 99–110
http://dx.doi.org/10.3853/j.0812-7387.15.1992.87

Chalmers, 1992, *Rec. Aust. Mus., Suppl.* 15: 111–128
http://dx.doi.org/10.3853/j.0812-7387.15.1992.88

Barron, 1992, *Rec. Aust. Mus., Suppl.* 15: 129–135
http://dx.doi.org/10.3853/j.0812-7387.15.1992.89