MINERALOGICAL MAGAZINE, JUNE 1980, VOL. 43, PP. 727-31

Kimberlite and kimberlitic intrusives of southeastern Australia

JOHN FERGUSON

Bureau of Mineral Resources, Geology and Geophysics, PO Box 378, Canberra, Australia, 2601

SUMMARY. Fifteen widely separated occurrences of kimberlite and kimberlitic rocks are now known in southeastern Australia. Those that have been satisfactorily dated isotopically give ages ranging from Permian to Late Jurassic. One occurrence exhibits an intimate spatial association with carbonatite. The classification of these rocks as 'kimberlitic' is partly based on their mode of emplacement, and particularly on the presence of crust/mantle inclusions. Compared with African kimberlitic magmas, the southeastern Australian examples have lower incompatible-element contents. These differences are interpreted as representing slightly greater degrees of partial melting of a four-phase lherzolite assemblage at shallower depths ($\sim$ 65 km) than typical African kimberlite magma.

FIFTEEN widely separated areas of kimberlite and kimberlitic rocks are now known in southeastern Australia, in the States of South Australia, Tasmania, Victoria, and New South Wales (fig. 1). Field relationships indicate that all these intrusives in southeastern Australia postdate the Proterozoic. Isotopic dating of whole rocks and phlogopite indicates a spread of ages. The Kayrunnera occurrence is the oldest that is isotopically dated, giving an Early Permian age of $\sim$ 260 Ma (Stracke *et al.*, 1979), a date also confirmed by fission-track studies (Gleadow and Edwards, 1978). Middle and Late Jurassic ages have been obtained from Walloway, Terowie, and Meredith (Stracke *et al.*, 1979; Day *et al.*, 1979), and Delegate (Lovering and White, 1969) respectively. The tentative Cainozoic age assigned to the Jugiong occurrence (Stracke *et al.*, 1979) is still under review.

The term 'kimberlitic' has been used to describe most of these rocks (Ferguson and Sheraton, 1979) although in the rare circumstance where fresh rock is available it usually shows significant departure from kimberlite *sensu stricto*. (For a recent review of kimberlite nomenclature see Skinner and Clement, 1979). This anomalous situation arises from the fact that, throughout the world, kimberlites are characteristically highly weathered, and that their pristine mineralogy and chemistry is thereby obscured. For this reason igneous rock classification methods cannot normally be applied and these rocks are therefore usually identified by their style of emplacement, nodule-type, and heavy-mineral content. In terms of these three parameters the southeastern Australian occurrences are kimberlites. Moderately fresh rocks from the Eurelia occurrence are very similar to evolved kimberlites; elsewhere the freshest rocks have chemical similarities with olivine nephelinite, melilitite, olivine analcitite, and ankaramite (Ferguson *et al.*, 1979). The massive kimberlite dykes reported west of Eurelia may well be associated with primary carbonate-bearing lamprophyric rocks recognized in the nearby Walloway diapir (Tucker and Collerson, 1972).

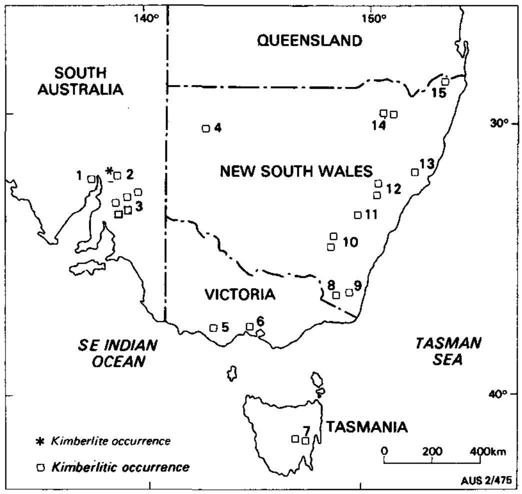


FIG. 1. Localities of kimberlitic occurrences in southeastern Australia. 1. Port Augusta. 2. Walloway/Eurelia. 3. Terowie. 4. Kayrunnera. 5. Bullenmerri. 6. Meredith. 7. Oatlands. 8. Delegate. 9. Bombala. 10. Jugiong. 11. Abercrombie. 12. Nulla Mountain. 13. Gloucester. 14. Bingara. 15. Mount Brown.

Petrography. Weathering of much of the material from the occurrences included in the study by Ferguson and Sheraton (1979) restricted petrographic investigations to moderately fresh samples from four kimberlitic occurrences at Eurelia, Terowie, Kayrunnera, and Jugiong.

Massive kimberlite dykes found at Eurelia, and kimberlitic dykes found at Terowie and Kayrunnera, are all rich in mica. Phenocrysts in these dykes comprise phlogopite plates, up to 2 mm in diameter, and euhedral olivine up to 1 mm in diameter pseudomorphed by carbonate, serpentine, and chlorite. The very fine-grained groundmass consists of phlogopite, magnesite, opaque minerals, and, in some cases, brown spinel and perovskite.

At Jugiong the massive kimberlitic rocks occur as major pipe-like bodies and as dykes. Euhedral olivine, or its pseudomorphs, forms phenocrysts up to 1 mm across; angular xenocrysts, up to 5 mm in diameter, comprise olivine, orthopyroxene, clinopyroxene, garnet, and spinel (i.e. a lherzolitic assemblage). The very fine-grained groundmass contains aegirine, aegirine-augite, augite, richterite, orthoclase, magnesite, and minor amounts of albite, analcime, chlorite, perovskite, and magnetite. Some of these phases are probably secondary, together with the obvious replacement minerals of serpentine, brown mica, and magnetite. A feature of the rocks is the presence of spherical or irregular light-coloured ocelli up to 5 mm across. There is a correlation between the compositions of the olivine phenocrysts, which range from Fo_{91} to Fo_{86} in different intrusions, and mineralogical differences in the groundmass and ocelli. In rocks with more magnesian olivine phenocrysts, the ocelli consist of analcime, magnesite, and only minor augite. With decreasing Fo, clinopyroxene becomes more abundant and sodic (aegirine), richterite appears, and orthoclase becomes the predominant felsic mineral. In the most evolved rocks a brown mica is present, and richterite forms mantles to xenocrystic pyroxene and olivine.

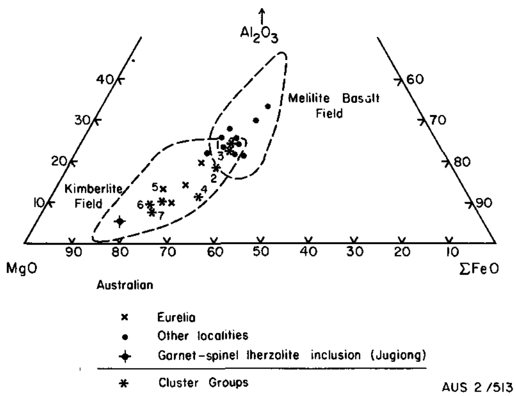


FIG. 2. Al_2O_3-MgO-total FeO diagram for kimberlitic rocks of southeastern Australia, showing kimberlite and melilite basalt fields of Cornelissen and Verwoerd (1975). Also indicated are the compositions of a garnet-spinel lherzolite nodule from Jugiong, the kimberlitic cluster groups (1-7) of McIver and Ferguson (1979).

Brecciated (diatreme-facies) kimberlitic rocks are found in two intrusions at Jugiong which have been drilled to a depth of $\leqslant$ 200 m. These rocks contain nucleated autoliths (Ferguson *et al.*, 1973) and angular to rounded fragments similar to the lapilli found in kimberlite from the Kao pipe in Lesotho (Clement, 1973). Lapilli and nucleated autoliths locally make up as much as 40 per cent, by volume, of the rock; lapilli are more abundant than autoliths. The lapilli are characterized by a range of grainsize ($<$ 1 to $\sim$ 15 mm), produced by a mixture of phenocrysts and xenocrysts, whereas the autoliths, typically 1-12 cm across, are more even-grained. The nuclei of the autoliths comprise mantle or crustal rock or mineral fragments and, rarely, kimberlitic lapilli.

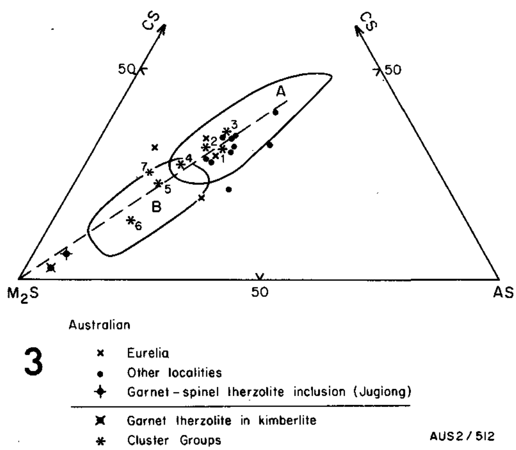
Chemistry. The kimberlitic samples from Eurelia are chemically similar to evolved kimberlitic rocks and alkaline ultramafic rocks associated with kimberlite in southern Africa (Danchin *et al.*, 1975; McIver and Ferguson, 1979). They plot within the kimberlite field of Cornelissen and Verwoerd (1975) on an Al_2O_3-MgO-FeO diagram (fig. 2), and have relatively high Niggli mg (0.77-0.84) and k (0.68-0.95) values. Si/Mg ratios are slightly higher than those suggested by Fesq *et al.* (1975) as typical of uncontaminated kimberlite ($<$ 0.9), but this probably reflects their more evolved nature, that has involved fractionation of a phase with low Si/Mg (e.g. olivine). Trace-elements mostly fall within the range of kimberlite and related rocks—high Cr, Ni, Rb, Sr, Nb, Ba, La, Ce, Pb, and Th. Nb/Y ratios are particularly high, similar to those of kimberlites from South Africa (Kable *et al.*, 1975), and comparable with those of highly alkaline mafic rocks in general (Pearce and Cann, 1973). The low Zr/Nb and K/Rb ratios are also similar to those of kimberlites from other localities (Dawson, 1971; Kable *et al.*, 1975).

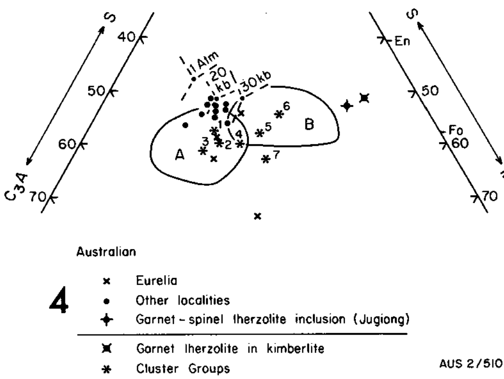
Rocks, including nucleated autoliths, from the Jugiong area have a range of compositions but differ from normal kimberlites in their relatively high SiO_2, Al_2O_3, and Na_2O, and lower MgO contents. Niggli mg values are consequently slightly lower (all except one are in the range 0.62-0.77), and k values are considerably lower (0.19-0.38) than in the kimberlites from Eurelia. Most samples plot in the region of overlap of the melilite basalt and kimberlite fields on the Al_2O_3-MgO-FeO diagram (Cornelissen and Verwoerd, 1975), although two values plot farther into the kimberlite field, and the most evolved sample plots well inside the melilite basalt field (fig. 2). Trace-element contents are similar to those of alkaline ultramafic rocks, including kimberlite, although Si/Mg and Zr/Nb ratios are higher, and Nb/Y lower, than in Eurelia kimberlite.

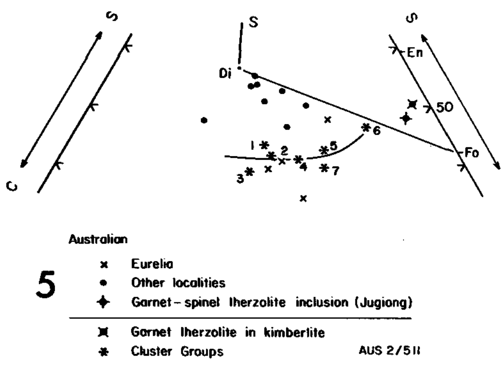
Compared with African kimberlites the Jugiong rocks have lower *RE* concentrations with a pattern similar to that of the very highly SiO_2-undersaturated Hawaiian basalts and of a Tasmanian olivine melilitite (Frey *et al.*, 1978). Compared with African kimberlites and olivine melilitites the lower incompatible-element abundances of the Jugiong kimberlitic rocks are consistent with an origin involving a greater proportion of melting at relatively shallower depths (Ferguson and Sheraton, 1979; Frey *et al.*, 1977; Frey *et al.*, 1978).

Chemical analyses of the kimberlites and kimberlitic rocks of southeastern Australia have been recalculated in terms of the four *CMAS* components (O'Hara, 1968). The results are presented graphically in figs. 3-5 which represent planes within, or forming a side of, the tetrahedron. Studies of the planar projections of these analysed rocks are compared with the experimentally determined phase boundaries as well as with seven groups of rocks representing 126 analyses of kimberlites and associated alkaline ultramafic rocks from southern Africa that have been established from statistical cluster analysis (Danchin *et al.*, 1975; Ferguson *et al.*, 1975). As pointed out by McIver and Ferguson (1979), the trend displayed by these seven cluster groups indicates that olivine and orthopyroxene were the dominant fractionating phases during the early stages of kimberlite evolution, whereas the more evolved rocks are accounted for by olivine-dominated fractionation.

Fig. 3 shows the projection of the southeastern Australian analyses from or towards S on to the plane M_2S-CS-AS; it can be seen that the analyses plot on a linear trend extending from the olivine corner which is coincident with that of the established cluster groups (McIver and Ferguson, 1979). Most of the samples plot in the field of alkaline ultramafic rocks associated with kimberlites,







FIGS. 3-5. FIG. 3 (*top*). Projections from, or towards, *S* on to the M_2S-CS-AS plane in the *CMAS* tetrahedron for kimberlitic rocks of southeastern Australia. The figure also shows the kimberlitic cluster groups (1-7) and fields of kimberlites (B) and associated kimberlitic rocks (A) of McIver and Ferguson (1979), and the average garnet lherzolite in kimberlite (Ito and Kennedy, 1967). FIG. 4 (*middle*). Projections from, or towards, diopside on to the C_3A-M-S plane in the *CMAS* tetrahedron for kimberlitic rocks of southeastern Australia. Positions of the pseudo-invariant points are from O'Hara (1968). En = enstatite, Fo = forsterite; fields as in fig. 3. FIG. 5 (*bottom*). Projections from A on to the *C-S-M* face of the *CMAS* tetrahedron for kimberlitic rocks of southeastern Australia. En = enstatite, Fo = forsterite, Di = diopside; fields as in fig. 3.

although one of the Eurelia rocks plots in the kimberlite field (Danchin *et al.*, 1975). The linear trend away from the olivine corner defined by the southeastern Australian rocks indicates that olivine, orthopyroxene, or both, were significant fractionating phases, whereas garnet and clinopyroxene were not. In fig. 4 the analyses are projected from or towards diopside on to the C_3A–M–S plane; here two distinct groups are apparent. The Eurelia rocks lie on the evolved end of the established trend defined by the seven cluster groups of kimberlites and associated rocks. As can be seen, this control line appears to be unrelated to the pseudo-invariant points applicable to 30 kb or less (from O'Hara, 1968). The remaining Australian samples group around the 20 kb pseudo-invariant point—an indication that this was the last pressure of equilibration. This pressure is also consistent with the estimate of $\sim$ 22 kb calculated from the lherzolite and eclogite nodules found in the Jugiong intrusives (Ferguson *et al.*, 1977). The presence of amphibole megacrysts in the Jugiong rocks suggests eruption from depths applicable to basaltic magma generation (Boyd, 1971; McGetchin, 1970). If this is the case, the amphiboles probably equilibrated at pressures of 20–25 kb, thus offering further confirmation of the depth of origin of these rocks. Plotting of stereographic pairs of the *CMAS* tetrahedron indicates that most samples plot near the *CMS* side, and fall closest to a plane roughly parallel to it. Consequently, in keeping with McIver and Ferguson (1979), the southeastern Australian rocks are projected from the *A* apex on to the *CMS* face of the tetrahedron, which gives mineral distortion. From this plot the two divergent trends seen in fig. 5 are better defined. The Eurelia compositions fall on the established kimberlite and associated alkaline ultramafic rock trend which initially lies at a high angle to the Di–Fo join. The remaining southeastern Australian rocks define a trend more enriched in the *S* component, and sub-parallel to the Di–Fo join (fig. 5). The two trends shown in this projection are consistent with the model of derivation by partial melting of an upper-mantle source rock of composition similar to the garnet lherzolite inclusions found in kimberlitic rocks, including those from Jugiong (fig. 5). The melting event giving rise to the 'normal' kimberlite trend, as shown by the southern African and Eurelia rocks, very likely took place at depths exceeding 125 km, whereas the upper mantle event giving rise to the Jugiong-Delegate trend probably took place at depths of about 70 km. Alternatively, the latter trend could have originated by melting at greater depths followed by equilibration at $\sim$ 70 km before rapid emplacement near the surface. In this regard it is worth emphasizing that the calculated geothermal gradient in the Jugiong area is in excess of the mean oceanic geotherm (Ferguson *et al.*, 1977), with predicted temperatures of about 1300° at a depth of 70 km. Bultitude and Green (1968) and Green (1970) have demonstrated that under hydrous conditions a small degree of melting of rocks of upper mantle composition takes place at around 27 km and 1250 °C. Therefore at the postulated temperature of about 1300 °C at 70 km depth it would seem likely that partial melting of garnet lherzolite could have taken place and, coupled with relatively minor fractionation involving olivine and possibly orthopyroxene, produce the observed trend.

Thus, from a consideration of the planar projections within the *CMAS* tetrahedron, both trend lines can be attributed to a small degree of melting within the upper mantle, but at different temperatures and pressures, followed by olivine and orthopyroxene fractionation. The composition of the garnet-spinel lherzolite nodule found in the Jugiong intrusive compares very well with that of the upper mantle, as suggested by the world-wide occurrence of garnet lherzolite inclusions in kimberlite (Ito and Kennedy, 1967), as well as with the theoretical pyrolite composition (Ringwood, 1966).

Conclusions. Most of the fresh kimberlitic rocks found in southeastern Australia show significant chemical departures from African kimberlites; relative depletion in the incompatible elements suggests greater degrees of partial melting of parent peridotite at shallower levels in the Australian situation other than the Eurelia kimberlites. The minerals found in concentrates and lherzolite nodules usually have identical compositions to those occurring in kimberlites elsewhere in the world.

In all cases, P–T estimates for the nodular assemblages from southeastern Australia indicate high temperatures of equilibration, producing steep palaeogeotherms actually exceeding the mean oceanic geotherm. The abnormally high geothermal gradients implied by these data, taken with the postulated shallow levels of kimberlite generation (60–70 km), make it unlikely that diamondiferous kimberlites of Permian or younger age will be found in southeastern Australia—except at the Eurelia locality in South Australia where magma compositions are suggestive of greater depths of formation (> 125 km).

Acknowledgements. This paper is published with the permission of the Director, Bureau of Mineral Resources, Geology and Geophysics, Canberra.

REFERENCES

Boyd (F. R.), 1971. *Carnegie Institute, Washington, Yearbook*, **70**, 138-42.

Bultitude (R. J.) and Green (D. H.), 1968. *Earth and Planet. Sci. Lett.* **3**, 325-37.

Clement (C. R.), 1973. *In* Nixon, P. H. (Editor). *Lesotho kimberlites, Lesotho National Development Corporation, Maseru*, 110-21.

Cornelissen (A. K.) and Verwoerd (W. J.), 1975. *Phys. Chem. Earth*, **9**, 71-80.

Danchin (R. V.), Ferguson (J.), McIver (J. R.), and Nixon, (P. H.), 1975. Ibid. **8**, 235-45.

Dawson (J. B.), 1971. *Earth Sci. Rev.* **7**, 187-214.

Day (R. A.), Nicholls (I. A.), and Hunt (F. L.), 1979. *In* Denham, D. (compiler). Crust and Upper Mantle of southeast Australia. *Bureau of Mineral Resources, Australia, Record 1979/2* (unpublished), Abstract.

Ferguson (J.), Arculus (R. J.), and Joyce (J.), 1979. *BMR J. Austr. Geol. Geophys.* **4**, 227-42.

—— Danchin (R. V.), and Nixon (P. H.), 1973. *In* Nixon, P. H. (Editor). *Lesotho kimberlites, Lesotho National Development Corporation, Maseru*, 285-93.

—— Ellis (D. J.), and England (R. N.), 1977. *Geol.* **5**, 278-80.

—— Martin (H.), Nicolaysen (L. O.), and Danchin (R. V.), 1975. *Phys. Chem. Earth*, **9**, 219-34.

—— and Sheraton (J. S.), 1979. *In* Boyd, F. R. and Meyer, H. O. A. (Editors). Kimberlites, Diatremes, and Diamonds: their geology, petrology, and geochemistry. *Proceedings of the 2nd International Kimberlite Conference*, **1**, 140-60. American Geophysical Union, Washington.

Fesq (H. W.), Kable (E. J. D.), and Gurney (J. J.), 1975. *Phys. Chem. Earth*, **9**, 687-707.

Frey (F. A.), Ferguson (J.), and Chappell (B. W.), 1977. *In* Extended Abstracts of the Second International Kimberlite Conference, Santa Fe, 1977.

—— Green (D. H.), and Roy (S. D.), 1978. *J. Petrol.* **19**, 463-513.

Gleadow (A. J. W.) and Edwards (A. C.), 1978. *J. Geol. Soc. Austr.* **25**, 359-60.

Green (D. H.), 1970. *Trans. Leicester Lit. Phil. Soc.* **LXIV**, 26-54.

Ito (K.) and Kennedy (G. C.), 1967. *Am. J. Sci.* **265**, 519-38.

Kable (E. J. D.), Fesq (H. W.), and Gurney (J. J.), 1975. *Phys. Chem. Earth*, **9**, 709-34.

Lovering (J. F.) and White (A. J. R.), 1969. *Contrib. Mineral. Petrol.* **21**, 9-52.

McIver (J. R.) and Ferguson (J.), 1979. *In* Boyd, F. R. and Meyer, H. O. A. (Editors). Kimberlites, Diatremes, and Diamonds: their geology, petrology, and geochemistry. *Proceedings of the 2nd International Kimberlite Conference*, **1**, 111-28. American Geophysical Union, Washington.

McGetchin (T. R.), 1970. Program and Abstracts, International Symposium on Mechanical Properties and Processes in the Mantle, Flagstaff, Arizona, 7-8.

O'Hara (M. J.), 1968. *Earth Sci. Rev.* **4**, 69-133.

Pearce (J. A.) and Cann (J. R.), 1973. *Earth and Planet. Sci. Lett.* **19**, 290-300.

Ringwood (A. E.), 1966. *In* Hurley, P. M. (Editor). Advances in earth science. M. I. T. Press, Cambridge, Mass., 287-356.

Skinner (E. M. W.) and Clement (C. R.), 1979. *In* Boyd, F. R. and Meyer, H. O. A. (Editors). Kimberlites, Diatremes, and Diamonds: their geology, petrology, and geochemistry. *Proceedings of the 2nd International Kimberlite Conference*, **1**, 129-39. American Geophysical Union, Washington.

Stracke (K. J.), Ferguson (J.), and Black (L. P.), 1979. *In* Boyd, F. R. and Meyer, H. O. A. (Editors). Kimberlites, Diatremes, and Diamonds: their geology, petrology, and geochemistry. *Proceedings of the 2nd International Kimberlite Conference*, **1**, 71-91. American Geophysical Union, Washington.

Tucker (D. H.) and Collerson (K. D.), 1972. *J. Geol. Soc. Austr.* **19**, 387-91.

[*Manuscript received 10 January 1980*]