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High Pressure Minerals and the Origin of the Tertiary Breccia Pipe, Ballogie Gem Mine, near Proston, Queensland

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ABSTRACT. High pressure minerals found in Miocene basaltic volcanics at Ballogie include large garnets, aluminous clinopyroxenes and orthopyroxenes, olivine, kaersutitic amphibole, anorthoclase and opaque oxides; they occur together with minor amounts of biotite, corundum and zircon. The garnet, some pyroxenes and anorthoclase can be of gem quality. The minerals accompany abundant lherzolite xenoliths in the volcanics and resemble some other occurrences in SE Queensland.

A magnetic survey of the site suggests a diatreme composed largely of breccia intruded by small basaltic bodies. The garnet (Mg_{62-66} Fe_{21-24} Ca_{12-14}), clinopyroxenes (Mg_{49-56} Ca_{34-39} Fe_{10-13}, with 6.7–8.5% Al_2O_3) and orthopyroxenes (Mg_{81-84} Fe_{12-15} Ca_{3-4}, with 4.8–5.8% Al_2O_3) probably represent xenocrysts derived from garnet pyroxenites and pegmatitic garnetites interlayered with spinel lherzolite mantle. The compositions suggest that these minerals crystallized under pressure-temperature conditions around 14–15 kb and 1000–1100°C. The Ti content of the kaersutites, using a new geobarometer, gives approximate pressures of crystallization mostly between 12 kb and 14 kb.

The bulk of the Ballogie minerals were sampled from a volatile-bearing upper mantle, relatively rich in Ti, but poor in Cr. The model invoked for the emplacement of a composite diatreme such as the Ballogie pipe involves sudden outgassing above a rising diapir by crack propagation. The resultant updrag also provides the potential to transport very deep material from the diamond stability zone.

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In 1981 Mr E.A. Thomson of Boondooma, Queensland asked the Department of Mineralogy and Petrology at the Australian Museum to investigate his gemstone lease at Coverty Creek, 17 km SSW of Proston (151°31.5′ E, 26°18.0′ S). The Ballogie Gem Mine, on the east side of the creek, yields gem-quality red garnet, comparable with the Garnet Gully prospect 10 km west at Brigooda (Queensland Geological Survey, 1981). The fragments come from a small alkali basalt exposure within granite country rock. (Fig. 1.) An anorthoclase megacryst from the basalt gave a K-Ar age of 16.0 ± 0.2 Myr, interpreted as the age of eruption (Sutherland & Wellman, in prep.). Other prominent minerals brought up by the basalt include olivine, pyroxenes and oxides, typical of high pressure megacryst suites found in eastern Australia (Wass & Irving, 1976).

The Ballogie basalt is not mapped, but lies amongst the northern Main Range Volcanics of south-eastern Queensland (Murphy *et al.,* 1976). It belongs to a younger episode than the bulk of these basalts and is not lateritized.

The site has potential for gem production and possible diamond exploration (Queensland Geological Survey, 1981) and was visited by the Museum in November 1981 and May 1982. Extensive collections were made of the volcanic inclusions by Hollis and Sutherland and a magnetometer survey was made over the basaltic body by Pogson. This paper deals with the form of the basalt and the mineral inclusions. A more detailed study of the Ballogie basalt will be given in a wider petrogenetic study involving the other basalt bodies and their inclusions from the Brigooda region, under study by the Australian Museum in association with A.D. Robertson, Geological Survey of Queensland. The geophysical survey carried out by the Museum in May 1982 was the first in the institution's history.

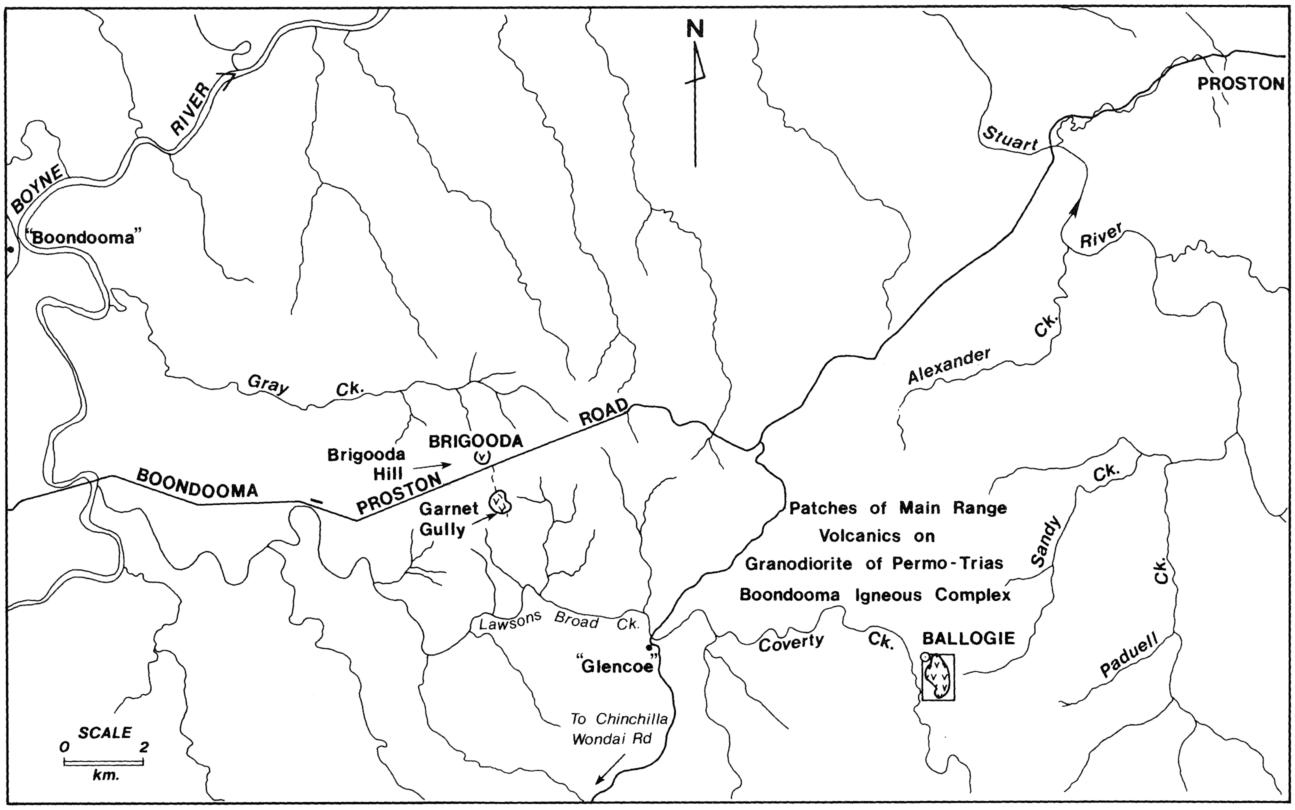

Fig. 1. Locations of Ballogie and Brigooda diatremes, Proston district, showing area of Ballogie magnetic survey.

Table 1. Comparative census of mineral inclusions in Ballogie and Brigooda volcanics.

Basalt breccia, Ballogie; Test Hole No. 1, Coarse Fraction (5 mm & over). Weight per cent.		*Massive basalt, Ballogie; NW side of hill. Volume per cent.*	
		Lherzolite xenoliths	65.2%
Total pyroxenes	78.4%	Pyroxenes	20.8%
(a) Rough pyroxenes with alterations		Anorthoclase	3.4%
46.8%		Amphibole	<1%
(b) Ablated black pyroxenes		Garnet-bearing inclusions	very rare
31.6%			
Pyrope-almandine	7.8%	*Massive megacryst basalt, Garnet Gully, Brigooda. Volume per cent*	
Pleonaste - Cr pleonaste	5.9%		
Amphibole	4.7%	Amphibole	48.7%
Magnetite	1.4%	Lherzolite	33.2%
Ilmenite	1.1%	Pyroxenes	11.0%
Anorthoclase	<1%	Garnet-bearing inclusions	3.6%
Zircon	<1%	Anorthoclase	<1%

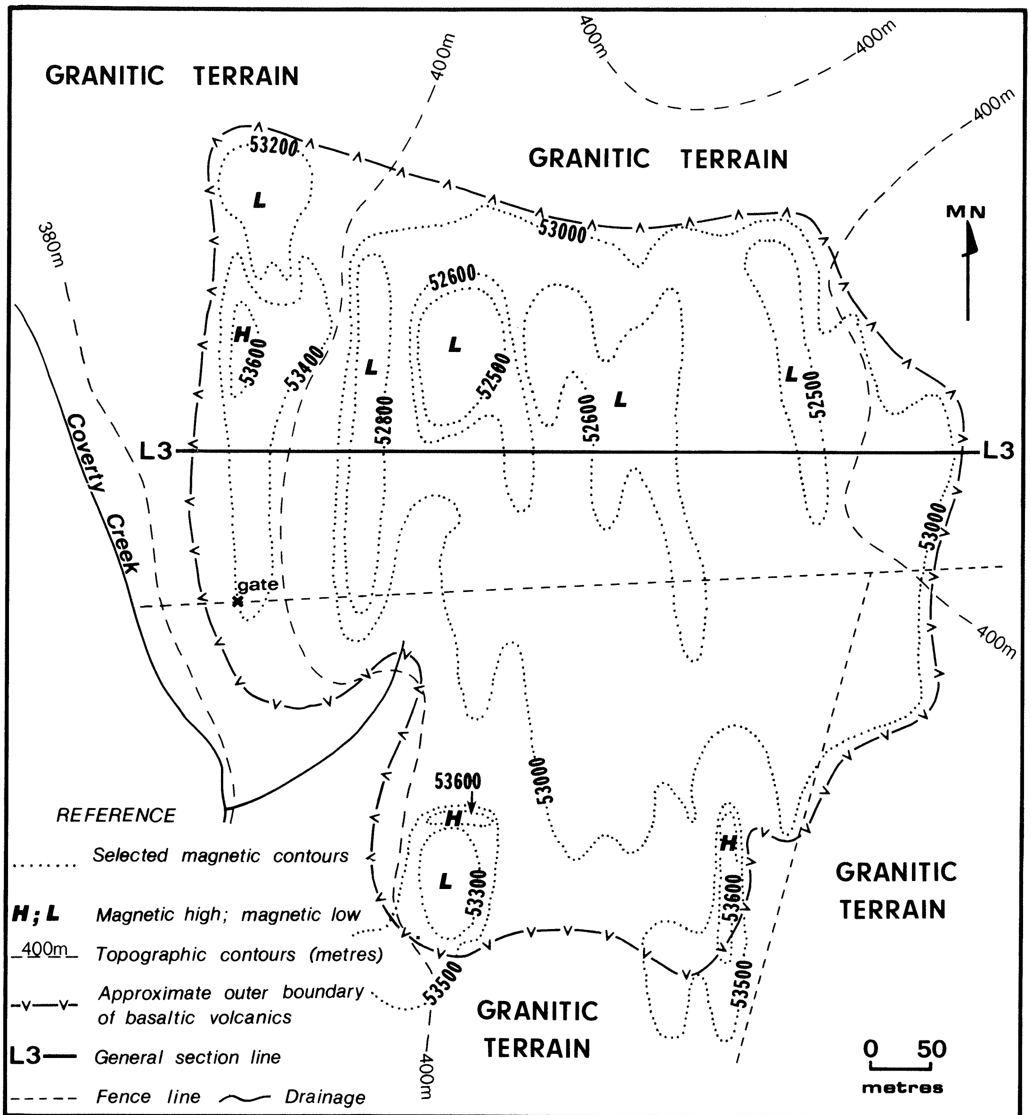

Fig. 2b. Summary diagram of magnetic survey in relation to general topography and inferred geology.

The Ballogie Occurrence

The basalt forms a flat-topped convex-sloped hill about 0.6 km long and 0.5 km wide, surrounded by float and granite showing NW–SE joint systems. The granites include porphyritic and graphic types with veins of tourmaline-bearing pegmatites and quartz. Gem-bearing gravels on the NW side of the hill contain both granite and basalt fragments. The relationships of the country granite to the basalt are not clearly exposed, but an anomalously high content of gem garnet is found in the NW flank. Trenching in this area exposed a volcanic breccia composed of country rock, basaltic and granitic fragments, commonly enclosed in autoliths and usually partly altered by late-stage fluids.

The basalt in the rubble is massive and contains predominant lherzolite xenoliths and pyroxene megacrysts, but garnet is exceptionally rare (Table 1). In thin section, the basalt is a fine-grained alkaline variety containing microphenocrysts of olivine in a groundmass with andesine-oligoclase laths, clinopyroxene grains and granular opaque oxides, with late-stage alkali feldspars and carbonate. It is petrograpically similar to the K-rich hawaiite-mugearite series fractionated from alkali basalt magmas within some of the Queensland provinces (Green *et al.*, 1974).

The Form of the Anomaly

The magnetometer survey of the site (grid reference 527899, Murgon 1:100,000 Topographic Sheet 9245, Queensland) covered the basaltic hill (500 × 600 m area, 15 m elevation and 400 m a.s.l.) and its immediate environs out to 800 × 800 metres. The spacing of the grid, the method of data collection and magnetic susceptibilities measured on the rocks are given in the Appendix. The data are presented in a contour plan

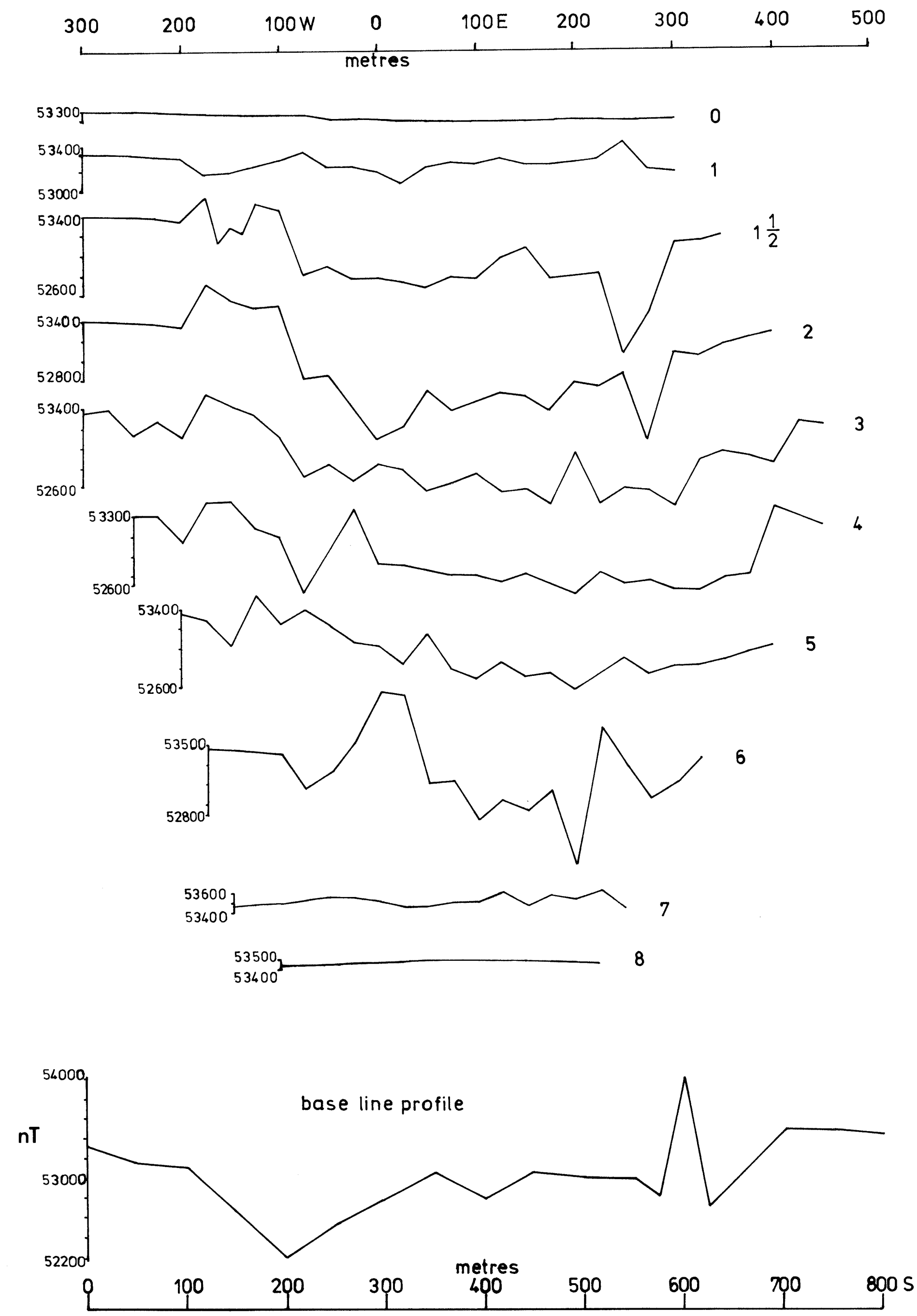

Fig. 3. Magnetic profiles based on section lines on magnetometer survey contour map.

(Fig. 2a), a summary plan (Fig. 2b) and profiles (Fig. 3). The magnetic trends and their interpretation are now discussed in some detail to reconstruct the form of the diatreme. Topographic effects due to magnetic material lying above some recording stations are considered negligible in this reconnaissance survey as the material has relatively low magnetic susceptibility.

The central feature of the contour plan is an ovoid anomaly system, about 500 × 600 metres orientated along a broad regional N to NNW trend. It is a magnetic low relative to background levels over the surrounding granite. The profile shapes and intensities suggest a body of lower magnetic susceptibility than its surroundings with width much greater than depth to its top and extending to depth. Superimposed on the main anomaly are higher frequency components representing very localized narrow near-surface features, probably basaltic intrusives.

In view of the occurrence of breccia at the site, the geometry of the anomaly suggests a pipe-like diatreme, completely surrounded by granite and injected by minor basaltic intrusives towards its margins. The bulk of the

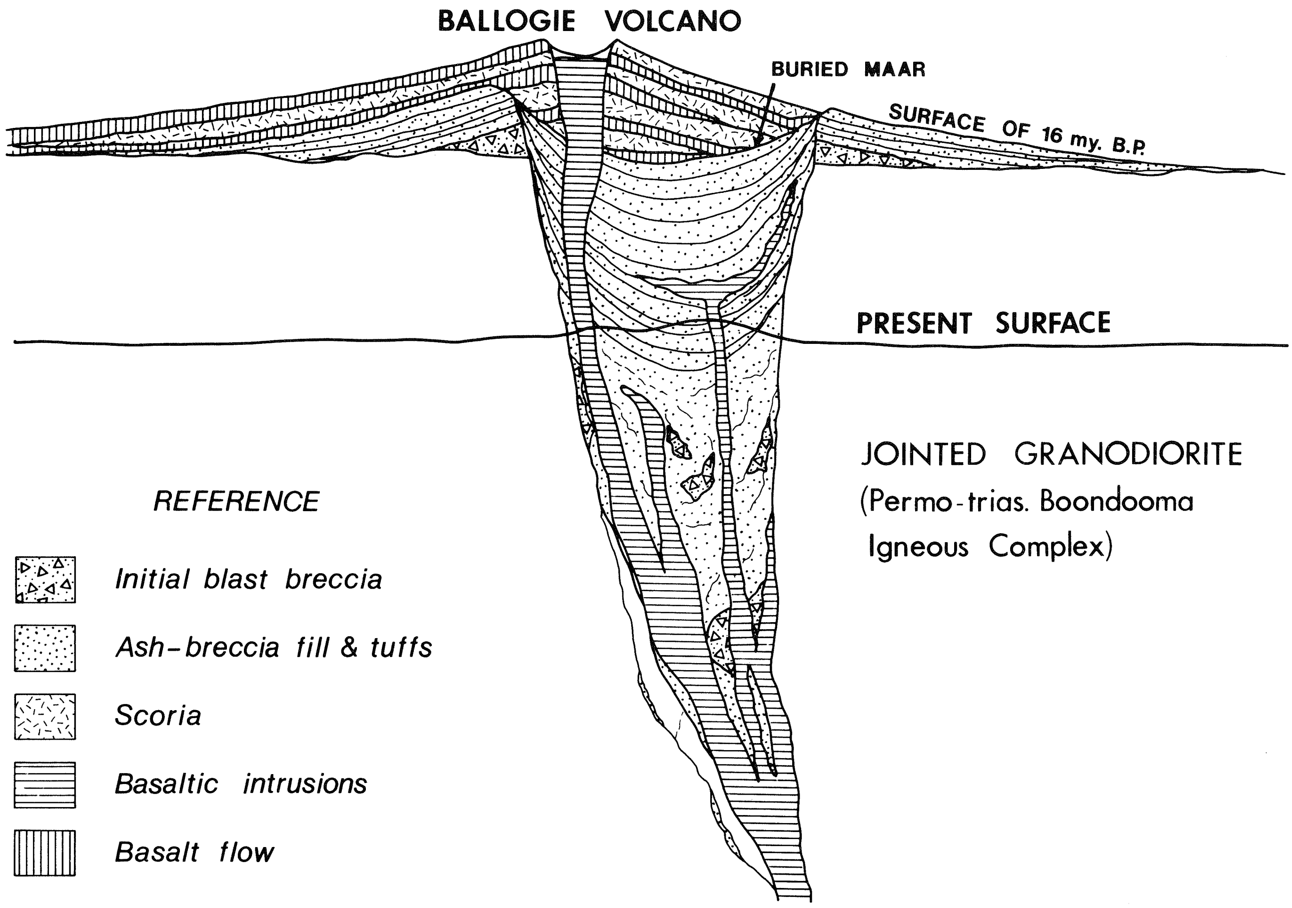

Fig. 4. Hypothetical reconstruction of the Ballogie volcano. Section shows present level of erosion exposing an ash-breccia-filled diatreme and associated basaltic intrusions.

inferred pipe is enclosed within the 53,000 nT contour line and the contour plan indicates internal complex inhomogeneities of unknown nature.

The core of the anomaly (450 × 550 m) is well-defined with high gradients at its edges (e.g. 75–100 m W, lines 1–4). It divides into smaller and more intense magnetic lows, especially towards its northern edge (e.g. 0 m and 75 m E, line 2, and 250 m W, line 1½). Their precise nature is unclear due to poor exposure, but complex brecciated or tuffaceous material on available evidence seems more likely than extensive alteration zones in massive basalt. The more intense lows (e.g. 0 m, between lines 6 and 7) may represent limited shallow inhomogeneities with little or no basaltic content.

A small poorly defined magnetic low (100 × 50 m) occupies flatter land adjoining the NW edge of the main anomaly. Nine test pits here revealed tuffaceous or brecciated volcanics at shallow depth (0.6–1.1 m). A vesicular, hornblende-rich basaltic breccia (pit No. 4) marks a spot high in the magnetic low. Pulverized granite breccia lies near the granite contact (pit No. 7, at 186 m W, line 1).The zone therefore contains material of variable composition, and could involve complex intrusive relationships near the granite contact.

Narrow linear highs and separate small isolated highs occur along the W and S margins of the pipe over three main areas of rubbly basalt scree. The linears are traceable for up to 300–400 m as northerly trending zones a few tens of metres wide (N and S of 175 m W, line 2); more restricted anomalies occur at 0 m, line 6 and 175 m E, line 7 (40 m basalt spur). The sharpness and small wave-length of the magnetic signature patterns suggest localized shallow sources. A similar linear feature on the NE boundary of the pipe traceable over 150 m, however, is a magnetic low of unknown cause. The N-S elongations in the anomaly pattern may partly reflect effects from the rectangular grid pattern of the survey.

All profiles (Fig. 3) show similar broad features—almost flat curve segments over granite at the extremes and a trough of variable width (250 to 600 m) in the middle. The trough narrows N and S. Several smaller scale troughs and peaks can be correlated across traverse lines, defining northerly-trending linear features. Small irregular peaks may represent localized intrusives. The N-S base-line has a high peak at 600 m S (over basalt rubble) and a small trough at 200 m S (repeated on traverse lines 6 and 2). The base-line low lies on the northern slopes of the hill, near a shallow saucer-like depression.

The relative magnetic susceptibilities of the rocks are basalt > granite > breccia and the magnetic readings over the structure (Appendix) are compatible with a breccia pipe, structurally emplaced along a fracture pattern in the intruded granites. This pipe gives a 1400–1500 nT negative anomaly below the granite background levels. A generalized reconstruction of the form of the various rock units that make up the pipe is given in Fig. 4. This is based on the section line in the summary map of the magnetic and geologic data shown in Fig. 2b.

The Mineral Suite

The Ballogie volcanics contain many large grains of red garnet, bright green to brown and black clinopyroxenes, dull green to black orthopyroxene, dark kaersutite, white to clear feldspar and opaque oxides including spinel, ilmenite, titano-magnetite and magnetite. Olivine (Mg_{90}) is common, disaggregated from abundant lherzolite xenoliths, but is generally decomposed to greenish chlorite and serpentine. The garnet, both types of pyroxenes and anorthoclase include gem quality material, but not the olivine. A census of mineral species in typical breccia and the main minerals found in the massive basalt at Ballogie are compared in Table 1.

Table 2. Garnet xenocryst analyses, Ballogie and SE Queensland occurrences.

Locality:	Bal.158	Bal.161	Bal.191	Bal.194	Brig.I.J.	Nan.G21	Low.5/1	WOW 3/1
SiO_2	40.86	41.22	41.03	41.93	40.48	41.46	41.38	40.79
TiO_2	0.50	0.42	0.46	0.42	0.47	0.24	0.41	0.66
Al_2O_3	23.59	23.38	23.55	22.86	22.98	22.57	23.36	22.62
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.30	0.05	0.02
Fe_2O_3					1.56			
FeO (see note)	12.55	11.79	10.65	11.26	12.07	10.32	10.55	14.19
MnO	0.36	0.33	0.34	0.34	0.43	0.24	0.32	0.36
MgO	17.87	18.24	18.79	17.91	16.54	18.10	18.56	15.88
CaO	5.34	5.29	5.19	4.91	5.35	5.16	5.19	5.54
Na_2O	0.05	0.05	0.03	—	—	0.05	—	—
TOTAL	100.12	100.72	100.04	99.64	99.88	98.44	99.82	100.06
Cation								
Si	5.8586	5.9079	5.8897	6.0415	5.892	6.0675	5.9458	5.9571
Ti	0.0535	0.0457	0.0496	0.0456	0.052	0.0263	0.0443	0.0721
Al	3.9862	3.9490	3.9837	3.8812	3.942	3.8700	3.9557	3.8929
Cr	—	—	—	—	—	0.0345	0.0059	0.0019
Fe^{3+}					0.110			
Fe^{2+} (see note)	1.5051	1.4126	1.2791	1.3574	1.470	1.2548	1.2675	1.7326
Mn	0.0436	0.0404	0.0418	0.0420	0.052	0.0293	0.0389	0.0447
Mg	3.8195	3.8974	4.0219	3.8464	3.588	3.9240	3.9716	3.4556
Ca	0.8202	0.8117	0.7977	0.7977	0.834	0.8040	0.7995	0.8666
Na	0.0150	0.0136	0.0096	—	—	0.0143	—	—
TOTAL	16.0997	16.0783	16.0731	16.0118	15.940	16.0247	16.0281	16.0235
Cation ratios:								
Mg	62	64	66	64	60	65	53	45
Fe	25	23	21	23	25	21	32	40
Ca	13	13	13	13	14	13	15	15

Bal.: Ballogie; Brig: Brigooda; Nan: Stony Pinch, Nanango; Low: Lowood; WOW; Pheasants Creek, Wowan. Ballogie & Nanango analyses, J.D. Hollis; Brigooda analyses, I. Jackson, Research School of Earth Sciences, Australian National University; Lowood and Wowan analyses, L. Rayner, Geology Dept, Sydney University. Electron microprobe analyses, with Fe as total FeO except for the Brigooda analysis. Cation contents are based on 24 oxygens. Cation ratios show the relative ionic proportions of three selected components.

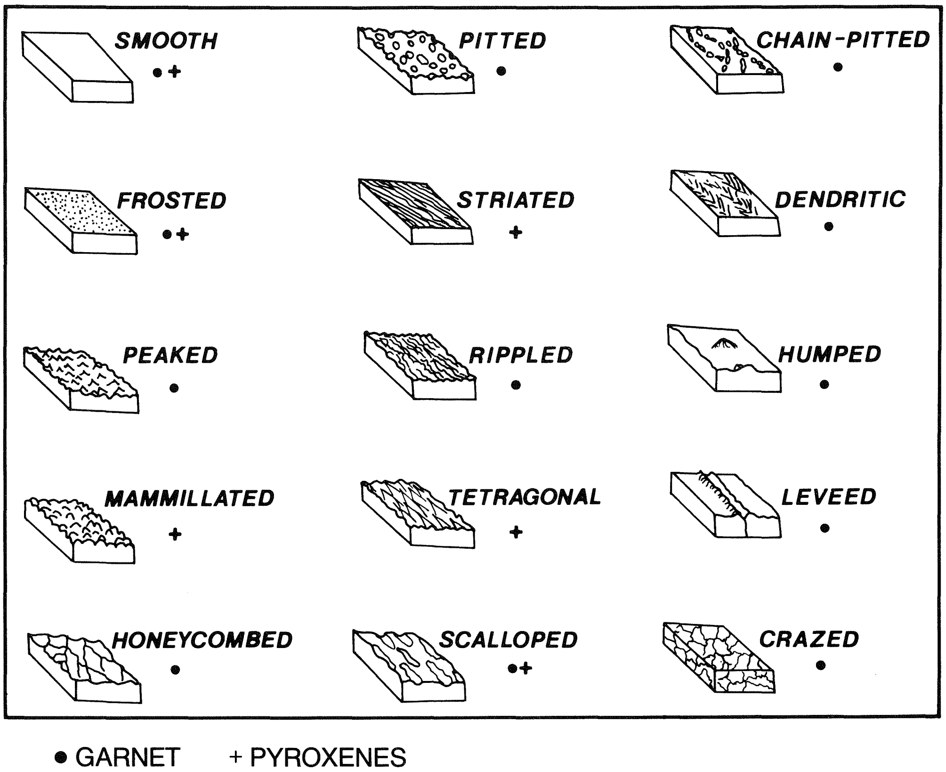

Fig. 5. Types of surface features observed on mineral grains in the Ballogie and Brigooda diatremes. For scale, the front width of units represents 3 mm and the side length 5 mm.

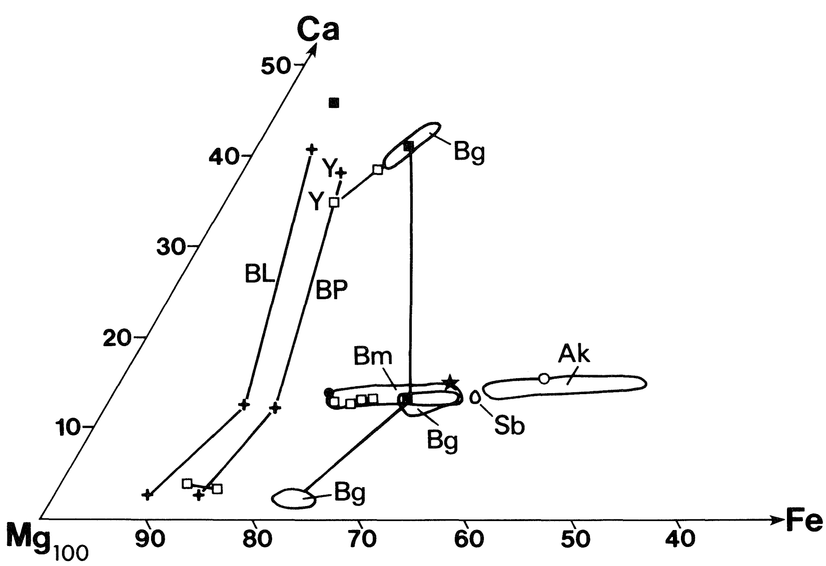

Fig. 6. Comparative Ca-Mg-Fe plots of pyroxene and garnet xenocrysts from Queensland occurrences (points) in relation to fields of these minerals from selected E. Australian xenolith sites (closed areas). Xenocryst plots are shown from Ballogie (open squares) Brigooda (closed squares), Nanango (closed circle), Lowood (asterisk), Wowan (open circle) and Yatton Creek (Y). Xenolith fields are shown for Bow Hill garnet lherzolite (BC) and garnet pyroxenite (Bp), Tasmania; Brigooda garnet pyroxenites (Bg) and S. Mt. Barngogo, Monto, garnet pyroxenite (Sb), Queensland; Bullenmerri garnet pyroxenites (Bm) and Anakie E. Hill felsic to mafic granulites (Ak), Victoria.

Distinctively sculptured surfaces are found on many of the mineral grains, similar to those described from kimberlites of Yakutia, Siberia (Frantsesson, 1970). Textures observed at Ballogie and on grains from the similar Brigooda pipes are given in Fig. 5. These surface features may be caused by corrosion in a gaseous medium, abrasion due to collisions with particles and etching occasioned by alteration planes through crystals. They provide a record of the origin and transportation history of the grains.

The gem garnets for which Ballogie is noteworthy reach up to 4 cm across and come from the pyroclastics. They are pyrope almandines ($n = 1.754$; all refractive indices were measured in the D-line of Na and corrected to 20°C, with error ± 0.003) and have relatively high Ti and low Ca and Cr contents, showing a limited compositional range (Table 2, Fig. 6). They are magnesian, but close to garnets from the adjacent Brigooda occurrence, and in some garnet pyroxenites in eastern Australian alkali basalts (Sutherland & Hollis,

Table 3. Pyroxene xenocryst analyses, Ballogie and Queensland occurrences.

Locality:	Bal.192	Bal.193	Bal.198	Bal.199	Brig.I.J.	Brig.A8	Yat.C2	Yat.C2a
SiO_2	51.66	54.36	54.09	50.71	49.84	52.03	50.98	51.97
TiO_2	0.45	0.14	0.28	0.85	0.94	0.50	0.44	0.24
Al_2O_3	6.70	4.78	5.76	8.54	9.23	6.55	9.04	7.47
Cr_2O_3	0.37	0.52	0.00	0.00	0.00	0.91	0.02	0.02
Fe_2O_3					1.50			
FeO	5.86	7.57	9.35	6.87	5.60	2.96	5.28	4.81
MnO	0.14	0.12	0.16	0.15	—	0.05	—	—
MgO	17.75	29.59	28.23	15.24	14.88	14.96	16.86	18.23
CaO	15.38	1.97	1.73	16.45	16.61	19.84	16.67	16.12
Na_2O	1.21	0.23	0.20	1.43	1.52	1.68	0.73	0.47
TOTAL	99.57	99.30	99.79	100.26	100.11	99.48	99.99	100.91
Cation								
Si	1.8740	1.9086	1.8995	1.8393	1.810	1.868	1.8347	1.8643
Ti	0.0122	0.0038	0.0074	0.0233	0.026	0.014	0.0120	0.0066
Al	0.2865	0.1979	0.2383	0.3652	0.395	0.277	0.3833	0.3158
Cr	0.0105	0.0144	—	—	—	0.026	—	0.0196
Fe^{3+}					0.041			
Fe^{2+}	0.1777	0.2223	0.2747	0.2084	0.170	0.089	0.1589	0.1443
Mn	0.0043	0.0037	0.0048	0.0047	—	0.001	—	—
Mg	0.9597	1.5489	1.4778	0.8242	0.805	0.801	0.9043	0.9749
Ca	0.5979	0.0742	0.0650	0.6393	0.646	0.763	0.6429	0.6195
Na	0.0854	0.0155	0.0134	0.1009	0.107	0.117	0.0511	0.0326
TOTAL	4.0082	3.9893	3.9809	4.0053	4.000	3.956	3.9872	3.9776
Cation ratios:								
Mg	55	84	81	49	48	48	53	56
Fe	10	12	15	13	13	6	9	8
Ca	35	4	4	38	39	46	38	36

Temperature determinations from pyroxene pairs:

	Cpx 192 + Opx 193	Cpx 199 + Opx 198
Wood & Banno temp. (°C)	1248	1152
Wells temp.	1236	1141

Bal.: Ballogie (192 and 199 Cpx, 193 and 198 Opx); Brig.: Brigooda (Cpx); Yat.: Yatton Creek (Cpx). Ballogie analyses, J.D. Hollis; Brigooda analyses, I. Jackson, Research School of Earth Science, Australian National University; Yatton Creek, unpublished analyses, F.L. Sutherland (Sutherland, 1980). T for pyroxene pairs Bal. 192-193 and Bal. 198-199 from Wood and Banno (1973) and Wells (1977) methods. Electron microprobe analyses, with Fe as total FeO except for Brigooda analysis. Gemmy pyroxenes are Bal. 192 (green Cpx) and Bal. 199 (amber brown Opx). Analysis A8 is a Cr-bearing diopside xenocryst from lherzolite for comparison. Cation contents are based on 6 oxygens.

1982). However, the sizes of the masses found at Ballogie and Brigooda are associated with garnetites.They contain interlocking anhedra up to 10 cm diameter with vague banding and provide cuttable gems to over a hundred carats weight.

The pyroxenes reach over 10 cm across, and are the commonest species in the heavy mineral concentrates. Most are dull greyish to shiny black augites and bronzites (Table 3), but over a bright light they separate into semi-transparent green Cr-bearing endiopsidic augite (α 1.682, β 1.687, γ 1.706) and amber brown bronzite (α 1.677, β 1.680, γ 1.685).

The amphiboles are almost as common as pyroxenes and show TiO_2 contents typical of kaersutites (α 1.677 pale yellow-brown, β ~1.685 brown to red-brown, γ 1.708 dark yellow-brown). Kaersutite megacrysts from Queensland occurrences vary considerably in composition, but those from Ballogie are relatively rich in alkalis and define a limited homogeneous field (Table 4). This field falls across typical kaersutite compositions for megacrysts elsewhere in eastern Australia (Sutherland & Hollis, 1982) for Mg-Fe-Ti.

Feldspars of the K-oligoclase/anorthoclase series are common associates of the fractionated Queensland basalt lineages (Table 5). The Ballogie feldspar is sodic anorthoclase (α 1.529, β 1.532, γ 1.534).

Opaque oxides at Ballogie include black spinel as a low Cr-pleonaste which may be euhedral, Mg-bearing ilmenite and members of the magnetite-ulvospinel series (Table 6). Other rare minerals in the suite are biotite, zircon and corundum.

Origin of the Minerals

The lherzolite xenoliths in the Ballogie basalt indicate transport in fractionated magma eruptions from the mantle. Clinopyroxene xenocrysts are similar in compositional range to the brown to greenish xenocrysts derived from spinel clinopyroxenite in a basalt plug at Yatton Creek, North Queensland (Sutherland, 1980).

Table 4. Amphibole megacryst analyses, Ballogie and Queensland occurrences.

Locality:	Bal.1A	Bal.3A	Bal.5	Brig. 1	SB 2R	Nebo 2	Nebo 3	Mt. Mit.
SiO_2	39.87	40.01	40.14	39.93	39.58	41.63	39.82	39.8
TiO_2	5.06	4.96	4.90	5.52	5.06	5.47	5.74	4.6
Al_2O_3	14.42	13.81	14.02	14.31	13.97	16.36	15.14	14.2
FeO^T	11.96	15.61	15.16	11.62	11.99	10.36	12.61	13.0
MnO	0.10	0.15	0.23	0.01	0.12	<0.02	<0.02	<0.2
MgO	12.06	9.60	9.60	11.62	11.51	9.55	11.43	11.9
CaO	10.22	9.79	9.60	9.79	10.03	10.39	10.42	9.8
Na_2O	2.90	2.93	3.00	3.17	2.93	4.71	2.72	2.8
K_2O	2.08	2.05	2.07	2.07	1.83	1.42	1.99	1.3
TOTAL	98.69	98.91	98.66	98.04	97.02	99.89	99.87	97.4
Cation								
Si	5.695	5.820	5.802	5.642	5.9300	5.9869	5.8075	
Ti	0.544	0.542	0.534	0.587	0.5701	0.5923	0.6296	
Al	2.428	2.368	2.389	2.383	2.4676	2.7727	2.6027	
Fe^{2+}	1.429	1.899	1.833	1.378	1.5024	1.2458	1.5375	
Mn	0.012	0.018	0.029	0.001	0.0152	—	—	
Mg	2.569	2.082	2.069	2.448	2.5700	2.0478	2.4855	
Ca	1.564	1.527	1.486	1.483	1.6102	1.6016	1.6280	
Na	0.802	0.828	0.840	0.868	0.8512	1.3145	0.7696	
K	0.380	0.380	0.380	0.373	0.3498	0.2603	0.3711	
TOTAL	15.423	15.464	15.353	15.163	15.8665	15.8219	15.8315	
Cation ratios:								
Mg	57	46	47	56	55	53	53	
Fe	31	42	41	31	34	32	33	
Ti	12	12	12	13	11	15	14	

Bal.: Ballogie; Brig:Brigooda; SB: South Mt. Barngogo; Nebo 2: Weetalaba; Nebo 3: Redcliffe Tableland; Mt. Mit.: Mt. Mitchell. Ballogie & Brigooda analyses, F.L. Sutherland; Nebo analyses unpublished from Sutherland (1980); South Mt. Barngogo analysis, L.M. Barron; Mt. Mitchell analysis from Green *et al.*, (1974). Electron microprobe analyses, with Fe as total FeO. Cation contents are based on 23 oxygens.

The Yatton Creek basalt only contains spinel lherzolite xenoliths, suggesting a mantle association for such clinopyroxenes. The Ballogie orthopyroxenes (Mg_{84-88}) typify those commonly found within mantle-derived xenoliths in eastern Australia (Mg_{78-90}; Bullenmerri; Griffin *et al.,* 1983) and are more Mg-rich than those typical of crustal granulites (Mg_{54-76}; Nebo, Anakie E. and Tasmania; Sutherland, 1980; Sutherland & Hollis, 1982; Wass & Hollis, 1983). If it is assumed that the pyroxene pairs crystallized together, then temperatures of equilibration fall within the range 1140°C–1250°C (Table 3).

The garnets at Ballogie have restricted Ca/Mg + Ca + total Fe and fall within an almost straight line relationship with other garnet xenocryst plots from other basaltic occurrences in eastern Australia (Fig. 6). This relatively constant Ca compositional range tends to show increasingly higher pressure associations with increasing Mg relative to Fe (Hollis and Sutherland, 1983). The Ballogie garnets lie between the fields of high Mg garnet xenoliths (c. 22–24 kb origin, Bow Hill, Tasmania; Sutherland *et al.,* 1983) and transitional crustal garnet granulite fields (12–18 kb, Anakie E.; Wass & Hollis, 1983), and close to garnet compositions in mantle pyroxenites from Bullenmerri (1000–1110°C, 14–15 kb; Griffin *et al.,* 1983).

Further pressure constraints for the Ballogie suite are provided by the kaersutites. Recent experimental work (Oba *et al.,* 1982) suggests that the Ti content in this mineral reflects the approximate pressure of crystallization (P) according to the equation $Ti = -0.013\ (\pm 0.005)\ P + 0.69\ (\pm 0.07)$. The exact constants of this are dependent on the general composition of the kaersutites. The Ballogie compositions are closest to those studied from Kakanui, New Zealand, for which Ti is $-0.006\ P + 0.63$ (K. Yagi, pers. comm.). This is the first application of this geobarometer to Australian kaersutites, which at Ballogie gave a P range within 10–17 kb and mostly between 12–14 kb.

The pressure data indicate that most of the Ballogie suite crystallized at mantle depths. The anorthoclase, euhedral zircon and corundum, however, are more likely to be of crustal derivation (Stephenson, 1976; Hollis, 1982; Hollis & Sutherland, 1982), although anorthoclase can crystallize experimentally at pressures up to 15 kb in the presence of CO2 (Arculus *et al.,* 1977).

The role of CO_2 in the crystallization of some of the minerals expelled in the Ballogie diatreme is indicated by abundant fluid inclusions with CO_2 in the pyroxenes and amphiboles. These are closely comparable to fluid inclusions found in mantle xenoliths at Wallabadah Rocks, New South Wales (Wass & Pooley, 1982) Anakie E. and Bullenmerri, Victoria (Wass and Hollis, 1983;

Table 5. Feldspar megacryst analyses, Ballogie and Queensland fractionated basalts.

Locality:	Bal.172	Nebo 1	Nebo 3	Nebo 4	Nebo 5	Nebo 7	AP 67	Mt. Mit.
SiO_2	67.03	65.77	64.74	64.77	69.11	64.68	64.38	65.3
Al_2O_3	20.47	20.85	21.87	21.91	16.58	22.05	22.03	21.7
FeO^T	0.10	< 0.02	< 0.02	< 0.02	<0.02	< 0.02	< 0.02	< 0.1
CaO	0.76	1.26	2.33	2.23	3.34	2.45	1.89	1.8
Na_2O	9.32	8.11	8.87	8.63	8.92	8.90	8.28	7.5
K_2O	2.56	4.01	2.01	2.46	2.05	1.92	2.87	2.3
TOTAL	100.23	100.36	99.42	99.75	99.56	99.85	100.05	98.7
Cation								
Si	11.7979	11.6425	11.4435	11.4433	12.1771	11.4113	11.450	
Al	4.2452	4.3505	4.5420	4.5618	3.4419	4.5821	4.619	
Fe^{2+}	0.0143	—	—	—	—	—	—	
Ca	0.1434	0.2398	0.4405	0.4214	0.6313	0.4632	0.360	
Na	3.1822	2.7846	3.0308	2.9551	3.0497	3.0451	2.855	
K	0.5741	0.9045	0.4531	0.5528	0.4604	0.4318	0.615	
TOTAL	19.9571	19.9219	19.9099	19.9344	19.7604	19.9335	19.899	
Cation ratios:								
Ca	4	6	11	11	15	12	9	10
Na	82	71	77	75	74	77	75	75
K	15	23	12	14	11	11	16	15

Bal.: Ballogie basalt, breccia; Nebo 1: Mt. St. Martin K-rich nepheline hawaiite; Nebo 3: Mt. Leslie K-rich nepheline mugearite; Nebo 4: Weetalaba K-rich mugearitic hawaiite; Nebo 5: Redcliffe Vale K-rich hawaiite; Nebo 7: Redcliffe Vale K-rich mugearitic hawaiite; AP 67; Arthur Peak hawaiite (Stephenson & Griffin, 1976). Mt. Mitchell nepheline benmoreite from Green *et al.* (1974). Ballogie analysis, J.D. Hollis; Nebo analyses, F.L. Sutherland, unpublished in Sutherland (1980). Cation contents are based on 32 oxygens.

Griffin *et al.*, 1983). These inclusions and the presence of amphibole and mica indicate significant amounts of volatiles were present in the mantle below these diatremes.

The available evidence suggests that most of the Ballogie xenocrysts come from a volatile-bearing mantle dominated by spinel lherzolite containing unusual layered pyroxenite-garnetite pegmatite intrusions. The minerals define an atypical Ti-rich, Cr-poor region of the eastern Australian mantle.

Discussion

The Ballogie volcano was one of several maar-producing outbursts north-west of Proston. These centres are of considerable interest as they document upper mantle petrology and include possible diamond sources, e.g. Brigooda (Geol. Surv. Qld, 1981). The apparent association between diamonds and alkali basaltic centres in eastern Australia has still to be proven, although growing evidence supports this association (Hollis & Sutherland, 1983). Experimental temperature-pressure determinations when applied to Ballogie-Brigooda inclusions indicate upper mantle origins shallower than 60–70 km. For diamonds to be present in pyroclastics there would have to be at least a small component of much higher pressure (> 35 kb) mantle sampled. Other high pressure phases from this regime may be present, but equally rare and less distinctive to identify.

Geomagnetic data for Ballogie indicate a typical diatreme structure, the pyroclastics having been intruded by basalts at a later stage (Fig. 4.). Similar structures are widespread in eastern Australia; documented examples including Ruby Hill, Bingara (Lovering, 1964), Minchinbury, near Sydney (Crawford *et al.*, 1980) and some of the western Victorian maars (Ollier & Joyce, 1964). Isolated diamonds are found in all these provinces (e.g. McNevin, 1977).

High-pressure mantle minerals from many diatremes frequently contain inclusions and cavities rich in CO_2. Although many maars have involved groundwater from aquifer strata and surface drainage (Lorenz, 1973), the Ballogie eruptions were propagated via joints in a

Table 6. Opaque oxide xenocrysts, Ballogie and SE Queensland occurrences.

Locality:	Bal.196	Bal.197	Bal.150	Bal.149	Bal.195	Nan.Il	Mt. Mit.	Mt. Mit.
SiO_2	0.00	0.00	0.00	0.00	0.00	0.02	0.0	0.0
TiO_2	0.94	1.19	35.11	51.23	46.77	49.98	51.5	25.4
Al_2O_3	58.60	1.05	1.51	0.21	0.50	0.84	0.3	1.6
FeO^T	25.08	91.45	56.24	44.96	50.39	42.69	42.7	67.0
MnO	0.10	0.31	0.35	0.45	0.34	0.14	0.9	0.9
MgO	15.43	0.29	2.86	3.71	2.04	4.24	3.8	2.5
NiO	0.07	0.00	0.00	0.00	0.00	0.08	0.0	0.0
CaO	0.00	0.00	0.00	0.00	0.00	0.02	0.0	0.0
TOTAL	100.22	94.29	96.08	100.57	100.04	98.01	99.2	97.4
Cation								
Si	—	—	—	—	—	0.0009		
Ti	0.0189	0.0295	0.9864	1.9112	1.8083	1.8313		
Al	1.8524	0.0407	0.0666	0.0125	0.0302	0.0489		
Fe^{2+}	0.5626	3.5229	1.7568	1.8653	2.1666	1.7569		
Mg	0.6167	0.0142	0.1595	0.2745	0.1566	0.3111		
Ni	0.0016	—	—	—	—	—		
Ca	—	—	—	—	—	—		
Mn	0.0016	0.0087	0.0110	0.0191	0.0149	0.0006		
TOTAL	3.0549	3.6160	2.9803	4.0826	4.1766	3.9497		
Cation ratios:								
Mg	51	1	5	7	4	8		
Fe	47	98	61	46	52	45		
Ti	2	1	34	47	44	47		

Bal.: Ballogie; Nan.: Stony Pinch, Nanango; Mt. Mit.: Mt. Mitchell. Bal. 196 pleonaste spinel, Bal. 197 magnetite, Bal. 150 ulvospinel, Bal. 149 ilmenite lamellae in ulvospinel, Bal. 195 ilmenite, Nan. Il ilmenite, Mt. Mit. ilmenite core with titano-magnetite rim. Ballogie and Nanango analyses, J.D. Hollis; Mt. Mitchell analyses from Green *et al.*, (1974). Electron microprobe analyses, with Fe as total FeO. Cation contents for magnetite-ulvospinels are based on 4 oxygens and for ilmenite on 6 oxygens.

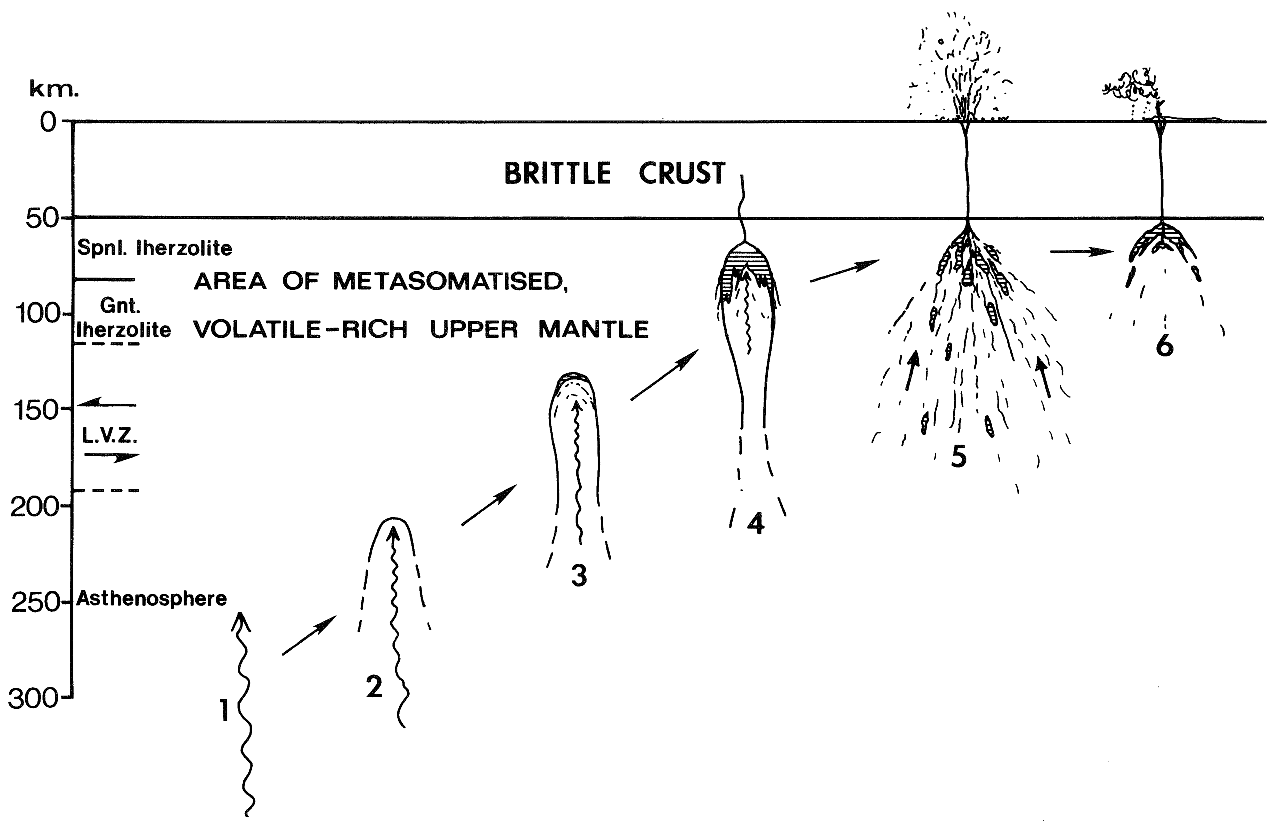

Fig. 7. Model depicting emplacement of magmas as composite diatremes, showing propagation of mantle heat anomaly and subsequent volcanism: Stage 1—deep asthenospheric 'hot spot' rises to produce 'thermal' above hot plume—Stage 2. Stage 3 shows 'thermal' rising to form diapir with associated low-degree of partial melting of mantle rocks. Magma and volatiles begin to accumulate (hatched zone). Stage 4 sees volatiles forcing crack to the surface via brittle or deep-faulted crust. Stage 5 involves immediate sudden and extensive outgassing; this rapidly brings up small amounts of deeper mantle material from 150 km to the surface. Maar develops at the surface with gentle, ash-producing eruptions, followed by nested cone formation and basaltic eruptions—Stage 6. The diatreme is partly intruded by alkaline magmas generated with larger-scale partial melting in the mantle above 80 km.

relatively elevated granitic topography. Mantle CO_2 is thus indicated as the major source of volatiles producing the Ballogie maar and possibly others in the district. The abundant amphiboles in the Ballogie breccia also suggest a volatile-rich and hydrous mantle beneath this part of Queensland. The amphibole content would vary and become minimal in the later basaltic eruptions as volatiles were expended (Table 1). Similar volatile-enriched mantle also occurs in other parts of eastern Australia (Sutherland, 1981; Wass & Hollis, 1983).

The distributions of high-pressure inclusions in diatremes like Ballogie show marked heterogeneity, with initial eruptive products containing the highest proportion of deep-seated inclusions (e.g. Bullenmerri; Hollis, 1981). These materials tend to be deposited as an initial agglomerate ring around the maar that is soon removed by erosion. If, as appears likely, diamonds are concentrated with initial blast materials, they will be comparatively rarer in subsequent ejecta and alluvial concentrates will contain grades higher than the deeper existing levels of the eroded pipes. Relics of initial blast material in diatremes tend to be concentrated around the country rock contacts. Some of the highest diamond grades are found in these situations in the Kimberley Pipes of NW Australia (Kimberlites and Carbonatites, 6th Australian Geological Convention Symposium, Canberra, 1983). A similar pattern is anticipated for diatremes in eastern Australia.

In conclusion, the Ballogie occurrence suggests a model to explain propagation and emplacement of silica undersaturated magmas as composite diatremes (Fig. 7).Though CO_2 is the main volatile involved in this process at Ballogie, no carbonate replacement was noted in any alteration zones. Even if confined to fluid inclusions, the volume of CO_2 may have been substantial if gathered from a large region of metasomatized mantle. In the proposed model, crack propagation (Anderson, 1979) provides for sudden 'outgassing' at the head of a rising diapir. The depressurization may extend to depths well below the main zone of partial melting and xenolith entrainment, which is situated above 80 km. A fluidized system may entrain and rapidly transport (updrag) rare fragments of very deep material from the diamond stabilty zone, including diamonds. Such material should be sought at Ballogie.

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Appendix: Magnetometer Survey Details

The survey grid comprised an 800 m N-S (magnetic) base line, and nine E-W (325–750 m long) traverse lines at 100 m intervals numbered 0 to 8. A traverse line was added between lines 1 and 2 to show more detail in a particularly interesting region.

Data Collection

Readings were taken with a Scintrex MP-2 Proton Precession Magnetometer which measures total magnetic field to resolution ± 1 nT. For latitude 26°S, the earth's undisturbed total field magnitude is about 52,500 nT and the geomagnetic inclination is about 55° S (Breiner, 1973, figs 3, 4). Data was collected at 25 m intervals on the E-W traverse lines, with spacings occasionally reduced to 12.5 m for finer detail. The N-S base line was read at 50 m intervals.

A base station on granite at Station 0 on Line 0 was occupied at approximately 1-2 hourly intervals to provide diurnal drift correction data. As far as could be determined, all survey lines were commenced and terminated over granite, judging by observable trends in soil and rock outcrop. As aids to interpretation, the drift-corrected data was presented in profile and contour plan formats.

Magnetic Susceptibility Implications

Magnetic susceptibilities were measured on selected samples giving: fresh basalt (W side of hill) 1500×10^{-6} c.g.s. units; relatively fresh amphibole basalt (S side of hill) 800×10^{-6} c.g.s. units; weathered amphibole basalt breccia (NW side of hill, Pit No. 4) 2000×10^{-6} c.g.s. units. A light-coloured breccia from the Brigooda pipe, similar to that at Ballogie but fresher, gave 600×10^{-6} c.g.s units. Susceptibilities for the basalts are towards the low end of the known range for this rock type (Parasnis, 1972, table 1).

These susceptibilities give the breccia pipe a wide, low to moderate negative anomaly (trough with min. 51950 nT on line 1½ relative to surrounding granite, max. 53495 nT). Basalts produced the highest range of readings (52950–54035 nT).

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Parasnis, D.S., 1972. Principles of Applied Geophysics, 2nd ed. Chapman & Hall, London. Table 1 (Volume susceptibilities), p.6.

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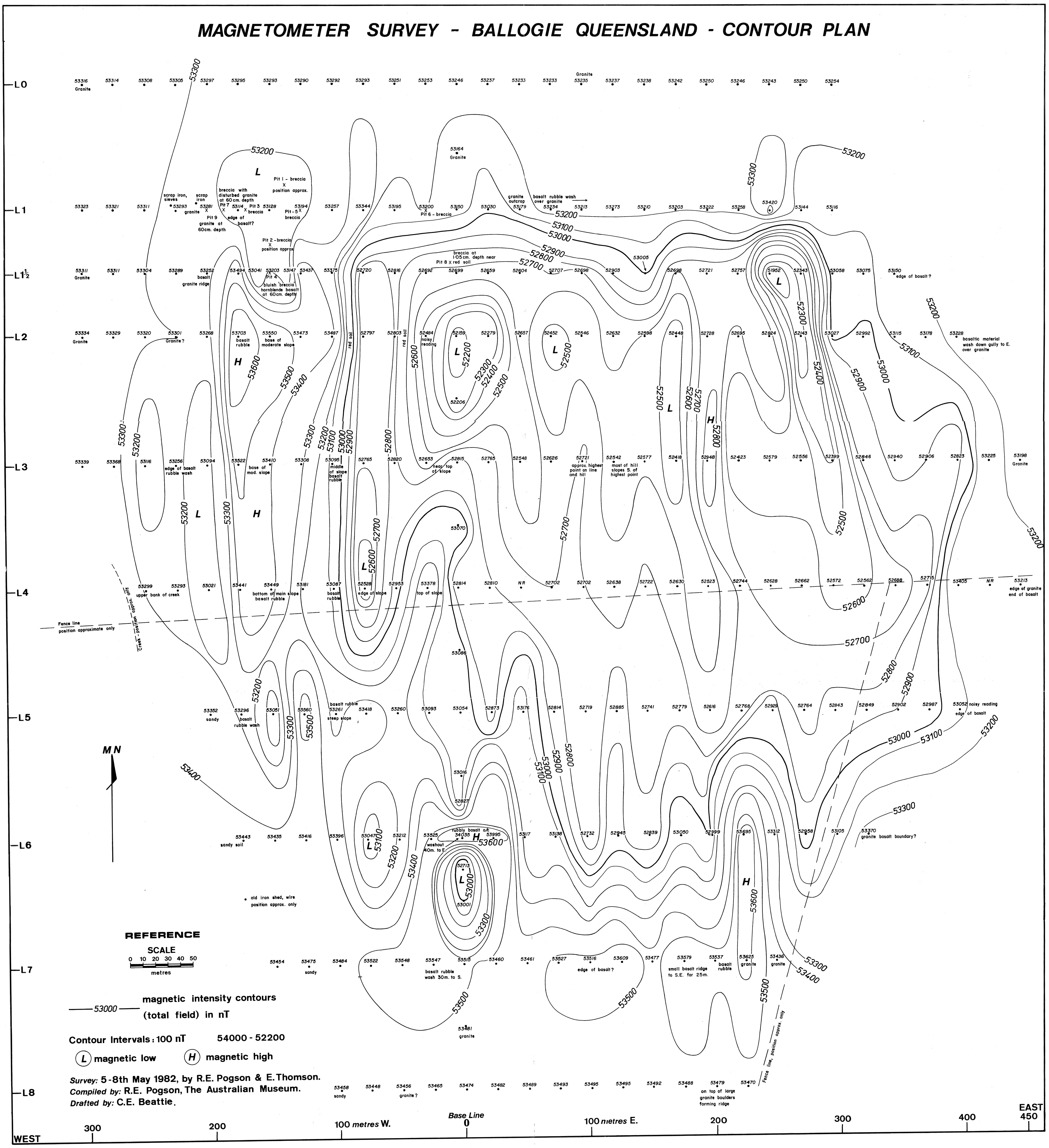

Fig. 2a. Magnetometer survey, contour map, Ballogie gem prospect.