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AN OUTLINE OF THE GEOLOGY AND PETROLOGY OF THE WARRUMBUNGLE VOLCANO FOR PARTICIPANTS IN THE CENOZOIC VOLCANISM FIELD WORKSHOP 7–11 DECEMBER 1986

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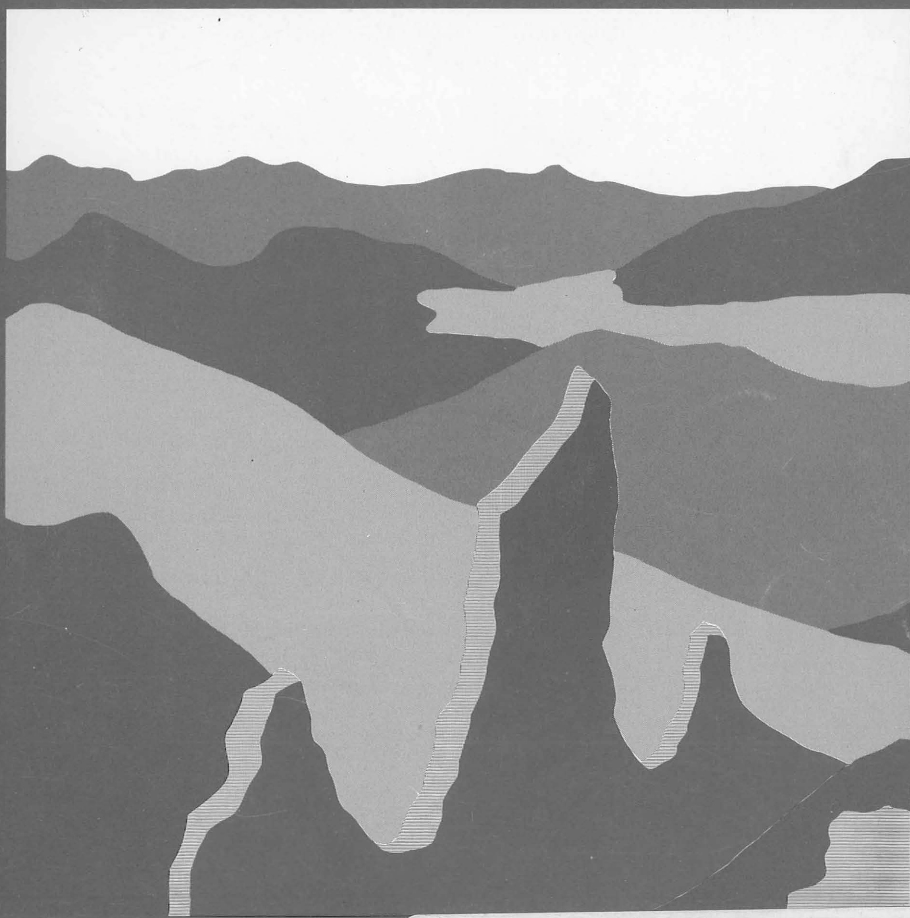

BUREAU OF MINERAL RESOURCES
GEOLOGY AND GEOPHYSICS

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THE WARRUMBUNGLE VOLCANO, CENTRAL NEW SOUTH WALES

An outline of the Geology and Petrology of the Warrumbungle Volcano

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Bureau of Mineral Resources

Note: This compilation was originally prepared for participants in a Cenozoic Volcanism Field Workshop held in the Warrumbungles from 7 to 11 December, 1986. Since then, some papers have been published which are partly based on the data included here. These are listed in the accompanying reference list under 'Additional References'.

WARRUMBUNGLE VOLCANO

The Warrumbungle Volcano represents one of the more spectacular manifestations of Cenozoic volcanic activity in eastern Australia. Located some 500 km northwest of Sydney and 40 km west of Coonabarabran, the eroded remnants of the volcano stand on the eastern edge of the very flat western plains of central New South Wales and present a spectacular vista when approached from the west. A large part of the volcano in now contained within the Warrumbungle National Park. This park was first established in 1953 with the proclamation of an area of 3360 hectares in the central portion of the present park. This has since been extended several times so that by 1982 the park area was 19650 hectares and included about 50% of the total outcrop area of the volcano.

Previous Work

The first documentation of the Warrumbungles was by the explorer John Oxley who in 1818 approached the mountains from the west and reported "To the east a most stupendous range of mountains, lifting their blue heads above the horizon...". From nearer the Warrumbungles the party observed "...very broken and rugged, detached rocks projecting like pillars and pyramids in various parts of the ranges" and later "Its elevated points were extremely lofty, and a dark, barren, and gloomy appearance; the rocks were of a dark grey, approaching black...".

The first geological study of the volcano was by Jensen (1907) who presented a geological sketch map, detailed petrographic descriptions of many of the volcanics, and descriptions of many important geological features. No other detailed studies have been published. Unpublished theses (Faulkes, 1962; MacKellar, 1980; Loxton, 1983; Hubble, 1983) describe portions of the southern part of the shield including Mount Naman, Bingie Grumble Mountain and Needle mountain. Hockley (1973, 1975) has suggested that more than one petrogenetic lineage may be present but no supporting analytical data are given. No mineralogical data on the volcano have been published.

Form and Structure

The volcano has been deeply dissected with resultant development of a pronounced radial drainage pattern (Fig. 1) and some spectacular volcanic scenery. Constructional remnants suggest that the volcano was originally a fairly symmetrical low shield reaching a height of about 1000 metres above surrounding basement, a diameter of about 50 km and a lava volume of about 500 km^3. As such it represents an intermediate size range among the central-type volcanoes of eastern Australia similar to the Nandewar Volcano to the north of the Warrumbungles and contrasts with the much larger shield of the Tweed Volcano and smaller shields such as the Comboyne and Canobolas Volcanoes (Table 1).

TABLE 1 *Estimated Size of Central Volcanoes in New South Wales*

Volcano	Height (m)	Diameter (km)	Volume (km^3)
Warrumbungle	1000	50	500
Tweed	3500	100	4000
Nandewar	1200	70	600
Canobolas	500	15	50
Comboyne	400	20	50
Ebor-Dorrigo	600	50	300

Major constructional remnants of the original shield are preserved at several points including Mt Woorut (Siding Spring Mountain), Junction Mountain, Bullaway Mountain, FIG. Mount Exmouth, Needle Mountain, Mount Caraghnan and Blackheath Mountain. In most

of these, stratified lava sequences are exposed although, in detail, outcrop is relatively poor and detailed stratigraphic data are not easily ascertained. The lava sequences normally consist of a compositionally bimodal suite broadly equivalent to hawaiite/mugearite and trachyte

respectively.

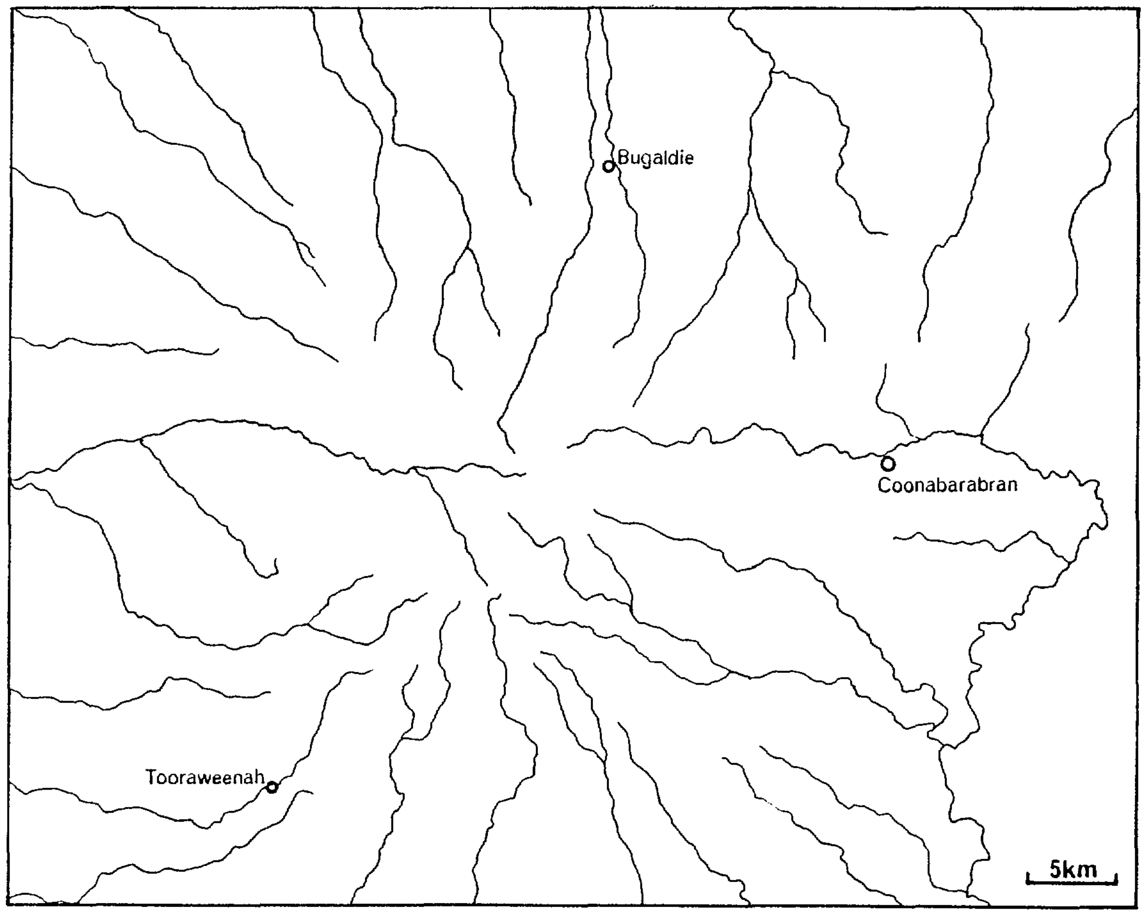

Fig. 1 *Principal streams draining the Warrumbungle Volcano illustrating the radial drainage pattern.*

The central portion of the volcano is characterised by an abundance of dykes, plugs and domes of feldspathoid or quartz-bearing peralkaline trachyte or of highly leucocratic trachyte approaching rhyolite. The plugs and dykes intrude a thick and relatively poorly bedded and poorly sorted sequence of pyroclastic tuffs and breccias.

The present drainage pattern of the Castlereagh River, which initially flows east from the Warrumbungles before turning south and then in a broad arc to the west and northwest is suggestive of drainage diversion caused by growth of the Warrumbungle Volcano. However the presence of basalts similar in age to the Warrumbungle volcanism (Dulhunty, 1972) in the present valley of the Castlereagh River indicates that its present course was established much earlier.

Pyroclastic Rocks

Pyroclastic rocks are widespread throughout the shield. On the flanks they frequently form well bedded sequences interstratified with the lava sequence and sometimes associated with diatomite deposits. In the central portion, bedding is often not so well developed but relatively coarse pyroclastics are abundant and are frequently the dominant rock type into which the numerous plugs and dykes are intruded. For example they are abundantly developed along the main Grand High Tops walking track especially between Sreng Boss and the Breadknife and west of Dagda Saddle. Low to moderate dips observed in the pyroclastics may represent initial dips or may result from emplacement of nearby plugs and domes. On the outer flanks of the volcano, exposures of very well bedded pyroclastics are exposed in Shawns Creek about 3 km west of Timor Rock and overlying diatomite deposits on Chalk Mountain west of Bugaldie.

Basement Rocks

Basement rocks to the Warrumbungle Volcano are predominantly quartzose sandstones of the Jurassic Pilliga Sandstone which forms part of the sequence in the southeastern portion of the Coonamble Basin. The sandstone is extensively exposed in the eroded central portion of the volcano. Elsewhere, the Jurassic sequence includes the Garawilla Volcanics (Bean, 1974) which have many petrologic similarities to the Warrumbungle Volcano. The Garawilla Volcanics reach their maximum development some 60 km east of the Warrumbungles where they form a sequence of flows, plugs and domes of undersaturated alkaline basalts and their felsic derivatives including phonolite.

Interbedded Sediments

In addition to the widespread occurrence of pyroclastics, localised deposits of lacustrine sediments are developed at several localities, especially on the outer flanks of the volcano. For example, diatomite deposits, presumably deposited in ephemeral lakes resulting from damming by lava flows, occur at Wandiallabah Creek east of Tooraweenah and at Chalk Mountain and

Paddy McCullochs Mountain near Bugaldie (Griffin, 1961; Herbert, 1968). At Chalk Mountain, diatomite crops out at several localities around the mountain as a flat-lying sequence of up to 15 metres of diatomite, mudstone and well bedded pyroclastics (the Chalk Mountain Formation; Holmes *et al.*, 1983) underlain and overlain by hawaiite flows. The diatomite beds, which are dominated by the species *Melosira granulata*, have yielded a variety of insects, freshwater bivalves, fish (Hills, 1946), birds (Rich and McEvey, 1977) and the leaves and fruit of *Eucalyptus* species (Holmes *et al.*, 1983).

Age Data

K-Ar age data (Dulhunty and McDougall, 1966; McDougall and Wilkinson, 1967; Dulhunty, 1972; Wellman and McDougall, 1974) indicate a total range of 17-13 Ma for the Warrumbungle Volcano. Wellman and McDougall (1974) have suggested a possible southerly migration of volcanism with time within the volcano. However the trend is very poorly constrained (largely dependent on a single date of 16.6 Ma at Looking Glass Mountain in the far north) and more data are clearly needed. Dated flows of 14.5 and 17.0 Ma in the valley of the Castlereagh River indicate that volcanism occurred over most of the total time span in the southern part of the volcano. Dated trachytes are confined to a narrow age range (15.4-15.6 Ma; McDougall and Wilkinson, 1967; Wellman and McDougall, 1974).

Rock Types and Distribution

The abundance of rock types in the Warrumbungles is strongly bimodal with maxima in the hawaiite-mugearite and trachyte ranges. Alkali basalt and benmoreite are extremely rare. Hawaiite and mugearite are the dominant rock types in the outer flanks of the shield, especially in the southern and northern areas. In the southern part, they form a thin plateau-covering sequence between Coonabarabran and Tooraweenah and extending south toward Binnaway, but thicker sequences are exposed on Blackheath Mountain and nearby peaks. In the north the principal outcrops are on a series of north-trending ridges including Looking Glass Mountain and Chalk Mountain, and a series of isolated residuals toward the northwest (Black Mountain, Tenandra Hill, Square Top Mountain). The age and affinities of Magometon Hill, a further 20 km to the northwest, are unknown. At a few localities, hawaiites contain a variety of xenoliths and megacrysts dominated by pyroxene megacrysts and pyroxenite xenoliths.

Trachyte is the dominant rock type in the central portion of the volcano and the composition of the trachyte is to some extent reflected in the mode of outcrop. Relatively more mafic trachyte, characterised by the presence of Fe-rich olivine and ferroaugite, occurs in shield-building sequences of fairly thick (up to 50 metres) flows in eastern (Mount Woorut, Grassy Mountain) and western (Mount Exmouth, Dooroombah Mountain) areas. Elsewhere, similar trachyte forms small conical hills (Forked Mountain, Yarrigan Mountain) which probably represent small lava domes.

The second and equally important trachyte type is relatively leucocratic peralkaline trachyte which builds most of the important plugs, dykes and domes in the central portion (Breadknife, Bluff Mountain, Crater Bluff, Belougery Spire) and on the southern (Burrumbuckle Mountain) and eastern (Timor Rock, Mopra Rock) flanks of the volcano. Peralkaline trachyte is also by far the dominant rock type comprising the very widespread and abundant pyroclastics.

The peralkaline trachytes are characterised by the presence of sodic pyroxenes (acmite-hedenbergite solid solutions) and/or amphiboles (arfvedsonite) and may be either mildly nepheline- or quartz normative. As a general rule, the former have pyroxene > amphibole and the latter have amphibole >> pyroxene. Aenigmatite is present in both types but that in silica-undersaturated rocks is notable for being mildly to strongly depleted in Ti (Duggan, in preparation).

Geochemistry

Major and trace element analyses and CIPW norms of selected rocks from the Warrumbungles are presented in Tables 2 and 3. A full spectrum of rock compositions is represented ranging from alkali basalt (rare) through hawaiite, mugearite and benmoreite to trachyte and rhyolite. Throughout the range, silica-saturated and undersaturated compositions .pa are represented (Figs 2 and 3).

TABLE 2 *Analyses of Rocks from the Warrumbungle Volcano*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
WMB No.	171	35	219	2	136	162	188	146	158	178	169	157	100	93	161	199	181
SiO_2	44.61	47.90	47.49	50.93	52.09	53.56	57.90	58.88	62.70	59.88	61.55	65.90	58.87	61.10	62.91	65.84	70.46
TiO_2	2.25	2.12	2.65	2.43	1.58	1.58	0.55	0.61	0.33	0.20	0.13	0.08	0.04	0.07	0.18	0.21	0.17
Al_2O_3	14.18	13.83	15.56	15.10	16.11	15.95	17.16	17.44	16.93	18.13	16.57	16.25	16.39	17.14	15.78	14.75	13.18
Fe_2O_3	3.02	1.92	2.33	5.41	2.32	3.12	3.45	2.45	1.59	2.42	2.96	1.84	3.50	3.35	3.43	2.18	1.95
FeO	8.82	8.91	9.48	5.86	6.83	7.01	3.93	4.72	3.39	2.39	2.46	1.30	1.90	1.83	2.46	2.75	1.89
MnO	0.17	0.15	0.16	0.15	0.13	0.18	0.28	0.13	0.13	0.13	0.14	0.09	0.23	0.10	0.13	0.08	0.07
MgO	8.31	9.11	5.30	3.22	4.39	2.12	0.87	0.68	0.17	0.15	0.07	0.04	0.35	0.04	0.06	0.03	0.03
CaO	9.18	9.56	6.65	6.62	6.41	4.76	2.24	2.55	1.45	1.43	1.19	0.46	1.06	0.84	1.01	0.47	0.09
Na_2O	2.39	2.92	4.31	4.40	5.23	4.92	5.04	5.50	6.36	7.43	6.79	7.26	7.07	7.94	7.31	6.94	6.09
K_2O	0.65	1.31	1.91	2.33	2.44	3.51	5.57	5.60	5.71	5.52	5.3	4.81	4.69	5.18	5.08	4.80	4.48
P_2O_5	0.54	0.45	0.95	0.97	0.37	0.98	0.27	0.41	0.04	0.04	-	-	0.01	0.02	0.02	-	-
H_2O+	2.76	1.22	2.19	0.94	1.44	0.73	1.12	0.50	0.30	1.27	1.22	0.36	1.81	1.63	0.42	0.44	0.40
H_2O-	0.87	0.25	0.59	0.89	0.41	0.52	0.17	0.26	0.14	0.38	0.44	0.21	1.42	0.32	0.18	0.37	0.17
CO_2	0.72	0.03	0.17	0.21	0.17	0.02	0.40	0.05	0.04	0.12	0.20	0.04	0.28	0.11	0.02	0.20	0.04
rest	0.64	0.26	0.28	0.27	0.24	0.30	0.33	0.26	0.18	0.33	0.46	0.36	0.96	0.59	0.36	0.48	0.57
TOTAL	99.11	99.94	100.02	99.73	100.16	99.27	100.23	100.04	99.46	99.82	99.48	99.00	98.58	100.26	99.35	99.54	99.59
									CIPW Norms								
Qz	-	-	-	1.49	-	-	0.36	-	-	-	-	4.76	-	-	-	7.25	18.86
Or	3.84	7.74	11.29	13.77	14.42	20.74	32.92	33.09	33.74	32.62	31.32	28.43	27.72	30.61	30.02	28.37	26.48
Ab	20.22	24.13	31.81	37.23	35.80	41.63	42.65	45.65	53.82	46.66	54.63	56.80	53.09	48.04	52.88	49.14	42.85
An	26.04	20.76	17.47	14.57	13.27	11.07	7.75	6.36	0.78	-	-	-	-	-	-	-	-
Ne	-	0.31	2.52	-	4.58	-	-	0.48	-	8.59	0.59	-	2.76	6.11	-	-	-
Ac	-	-	-	-	-	-	-	-	-	0.31	1.53	4.08	1.44	6.93	7.90	6.31	5.64
Di	13.71	19.42	7.97	9.84	13.43	5.47	1.56	3.24	5.43	5.30	5.18	2.02	4.39	3.58	4.33	2.07	0.40
Hy	10.64	-	5.87	-	4.63	5.36	-		1.26	-	-	1.01	-	-	1.74	3.83	3.18
Ol	9.94	18.00	15.18	-	9.22	4.41	-	4.46	0.70	-	-	-	0.02	0.65	0.01	-	-
Mt	4.38	2.78	3.38	7.84	3.36	4.52	5.00	3.55	2.31	3.35	3.53	0.62	4.35	1.38	1.01	-	-
Il	4.27	4.03	5.03	4.62	3.00	3.00	1.04	1.16	0.63	0.38	0.25	0.15	0.08	0.13	0.34	0.40	0.32
Ap	1.25	1.05	2.21	2.25	0.86	2.28	0.63	0.95	0.09	0.09	-	-	0.02	0.05	0.05	-	-
Zc	0.04	0.03	0.05	0.05	0.04	0.08	0.16	0.17	0.13	0.28	0.38	0.21	0.74	0.38	0.28	0.38	0.45
$^{87}Sr/^{86}Sr$ (initial)	0.70363	0.70409			0.70409	0.70442	0.70520					0.71775		0.85054			
E_{Nd}	+3.6	+2.7			+2.0	+2.3						+1.5		+0.7			

TABLE 3 *Trace Element Analyses of Rocks from the Warrumbungle Volcano*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
	171	35	219	2	136	162	188	146	158	178	169	157	100	93	161	199	181
Ba	3080	445	625	895	825	1090	1020	465	110	22	2	-	-	-	4	-	-
Rb	25	32	36	48	50	62	129	111	144	286	364	376	595	520	263	292	380
Sr	1080	498	735	570	348	487	110	181	14	68	23	3	107	4	2	2	1
Pb	2	2	3	3	3	5	11	8	10	17	21	40	50	20	18	28	37
Zr	194	144	246	229	177	374	790	825	645	1410	1870	1060	3660	1900	1410	1910	2230
Nb	42	33	40	40	35	51	109	84	97	182	298	261	575	291	227	261	392
Y	21	22	31	32	21	37	49	35	47	48	108	110	271	213	93	126	204
La	29	25	35	36	29	48	71	66	67	101	180	200	389	374	146	285	332
Ce	64	54	81	82	62	108	145	145	134	180	336	266	775	630	285	408	336
Sc	22	20	14	17	13	14	12	8	3	1	-	-	-	-	-	-	-
V	175	167	108	106	86	13	-	-	-	-	-	-	-	-	-	-	-
Cr	231	253	72	21	90	4	2	2	2	2	2	1	2	2	2	2	1
Ni	178	183	65	18	54	2	-	3	-	1	-	-	-	-	-	-	-
Cu	64	54	39	21	33	14	15	10	4	10	12	2	5	7	9	8	-
Zn	109	96	130	115	86	145	182	118	133	174	289	451	900	600	284	370	434
Ga	19	20	23	24	22	27	28	29	33	36	46	50	90	68	43	46	51

Key to Tables 2 and 3

1. Olivine basalt, Spirey Ramp, west side of Spirey Creek (903321)*.
2. Hawaiite, north side of Black Mountain (752476). Outlier northwest of Warrumbungles.
3. Hawaiite, road cutting on Newell Highway east of Tooraweenah (803181).
4. Mugearite, cutting on road to Siding Springs Observatory, Siding Springs Mountain (383979).
5. Mugearite, south side of Tonduran Spire (887323).
6. Benmoreite, near walking track, Dows High Tops (887323).
7. Mafic trachyte, cutting on Service track just north of Danu Saddle (867338)
8. Mafic trachyte, Forked Mountain, adjacent to Oxley Highway, north-east of Coonabarabran (228421).
9. Trachyte, west side of Belougery Spire (901318).
10. Nepheline trachyte, adjacent to Service track south of Danu Saddle (864331). Norm includes 0.33% Wo.
11. Trachyte, northern end of Breadknife (898322).
12. Trachyte, near Breadknife and intruded by it, Grand High Tops (898318).
13. Trachyte, north side of Bingie Grumble Mountain near outer margin of lava dome (079333).
14. Nepheline trachyte, summit of Bingie Grumble Mountain (083324).
15. Trachyte, near walking track on east side of Bluff Mountain (881319).
16. Quartz trachyte, dyke on north side of Bridget Peak (897335). Norm includes 0.56% Ns.
17. Comendite, just east of Service track on Danu Saddle (866336). Norm includes 0.53% Ns.

* Grid references refer to the Australian Map Grid on 1:100,000 sheets 8635 (Tenandra) and 8735 (Coonabarabran).

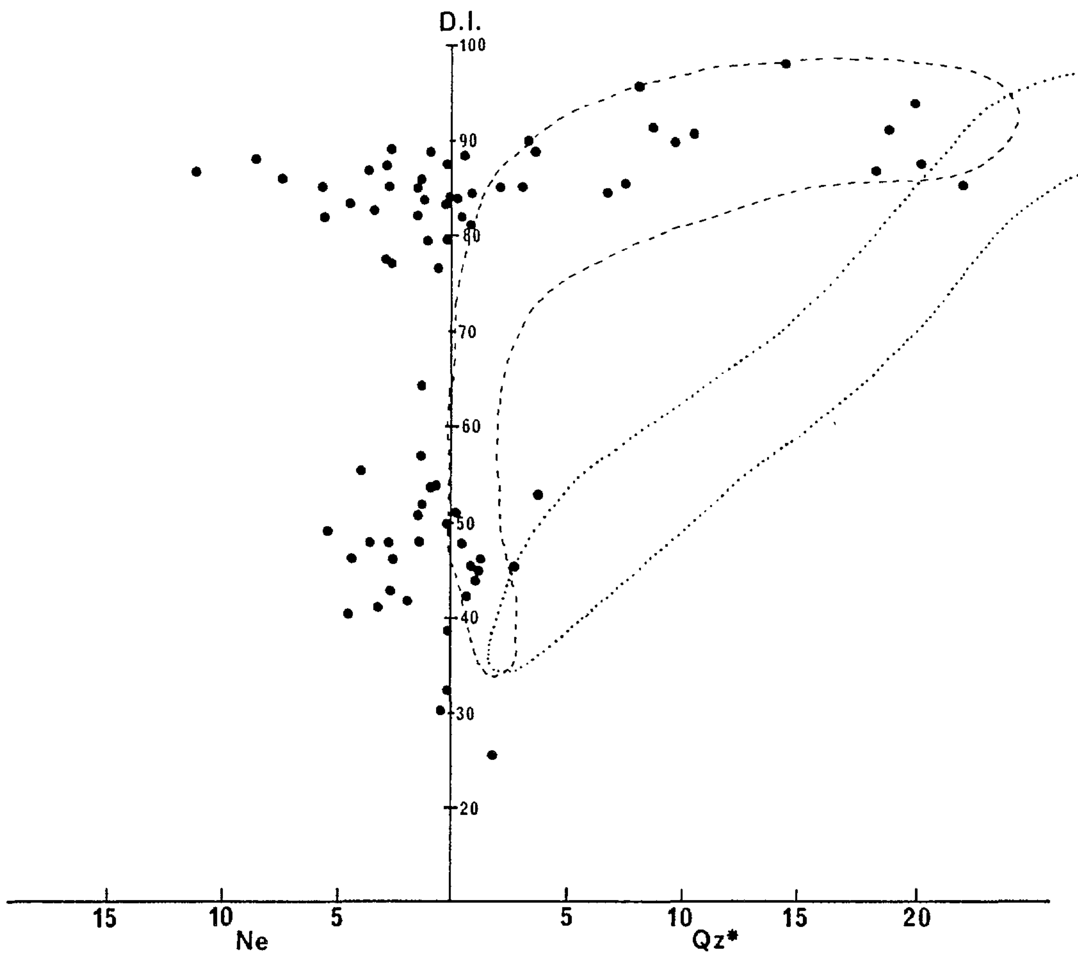

Fig. 2 *Plot of Differentiation Index vs normative nepheline quartz for rocks of the Warrumbungle Volcano. Qz* represents weight percent quartz in the norm when all hy is calculated as ol.*

The mafic rocks are broadly similar in geochemistry to equivalent rocks in other eastern Australian central-type volcanoes such as the Nandewar Volcano (Abbott, 1969; Stolz, 1985). For example there is a complete overlap of K_2O/Na_2O ratios between the two suites except that the Warrumbungle trachytes extend to slightly higher Na_2O contents (Fig. 4). Only subtle differences exist between the nepheline and quartz normative mafic rocks and no evidence has been found to support the concept of differing petrogenetic lineages in the volcano as proposed by Hockley (1968, 1969), at least for magmas in the mafic compositional range. Instead, we favour a concept of a continuous spectrum of compositions straddling the thermal divide represented by the critical plane of silica undersaturation (Yoder and Tilley, 1962) with no .pm0

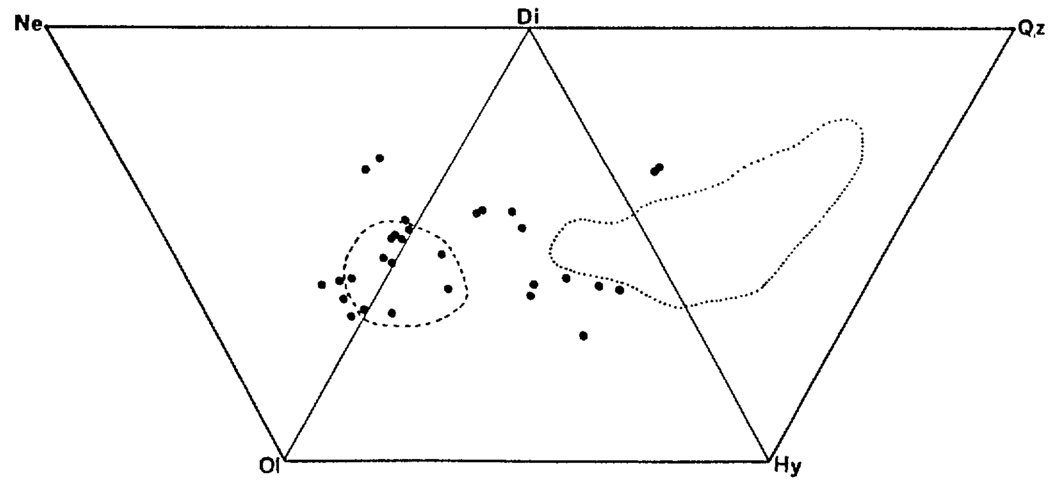

Fig. 3 *Expanded Ne-Ol-Di-Hy-Qz tetrahedron illustrating the range of silica saturation of mafic rocks of the Warrumbungle Volcano (solid circles). Also shown are fields for the Nandewar Volcano (Stolz, 1985; dashed border) and the Tweed Volcano (Duggan, 1974; dotted border).*

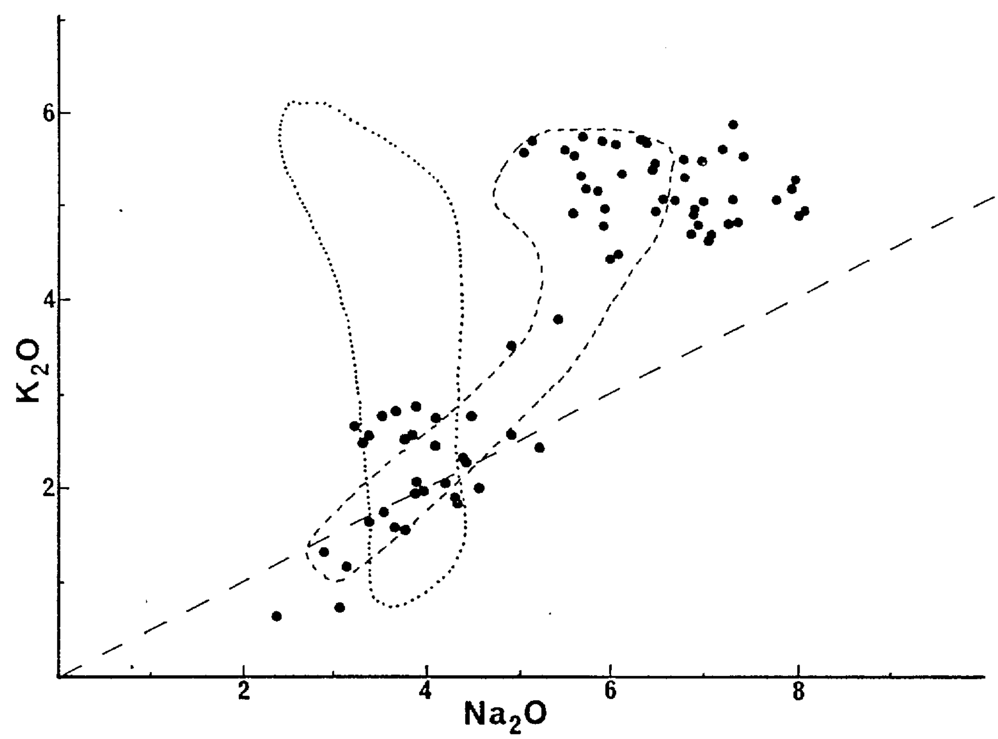

Fig. 4 *K_2O vs Na_2O diagram for all rocks of the Warrumbungle Volcano. Symbols as in Fig. 2.*

systematic variation among K/Na ratios, Mg/Fe ratios and the level of silica saturation (cf Coombs and Wilkinson, 1969).

The more felsic rocks are also close to the plane of silica saturation with occasional

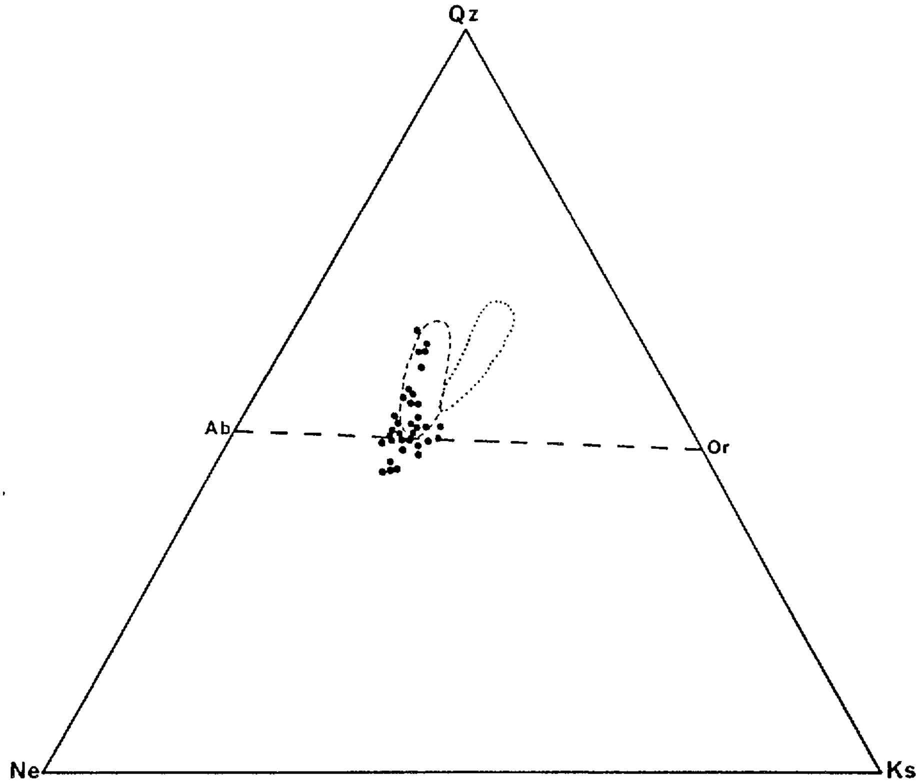

Fig. 5 *Ne-Ks-Qz diagram for felsic rocks (D.I.>75) of the Warrumbungle Volcano. Symbols as in Fig. 2.*

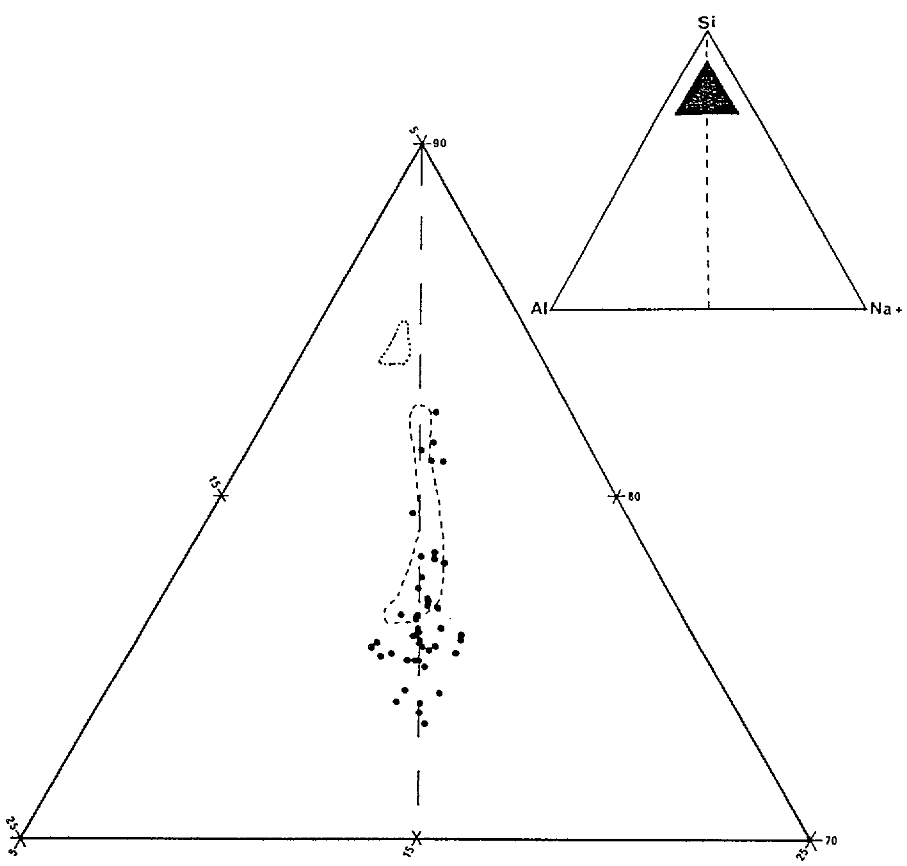

Fig. 6 *Si-Al-(Na+K) diagram for felsic rocks (D.I.>75) of the Warrumbungle Volcano. Symbols as in Fig. 2.*

specimens extending to more nepheline- and quartz-normative compositions (Fig. 5) and .lh8 include metaluminous and peralkaline variants (Fig. 6). However, neither the quartz-normative nor the nepheline- normative felsic rocks closely approached the respective minimum melt compositions in the system Ne-Ks-Qz.

There is a distinct hiatus in the abundance of rocks in the compositional range between mugearite and the mafic trachytes with only one specimen collected falling in the compositional field of benmoreite (in fact a tristanite in the classification of Coombs and Wilkinson, 1969).

Mineralogy

Acquisition of microprobe data on the volcanics is still in progress but sufficient data are now in hand to make some broad generalisations.

Olivine is ubiquitous in rocks from hawaiite through to mafic trachyte. As would be expected, it becomes progressively more Fe-rich with decreasing Mg-number of the host rock. Thus the most Mg-rich olivine is typically in the range Fo_{70-80} in the hawaiites, Fo_{30-40} in benmoreite and Fo_{20} in the mafic trachytes.

Clinopyroxene is present in all rocks except for the most leucocratic rhyolitic rocks (which may have undergone some hydrothermal alteration) and a few amphibole-bearing quartz trachytes. In the mafic rocks it is typically mildly titaniferous augite occurring as small intergranular groundmass prisms or as larger grains subophitically enclosing plagioclase laths. It becomes progressively more Fe-rich in the benmoreite and mafic trachytes where it approaches ferroaugite in composition. Clinopyroxene in the peralkaline trachytes is sodic hedenbergite trending to acmite.

The expected Na-enrichment trend in clinopyroxenes of the peralkaline rocks is strongly suppressed and occurs only after extreme Fe-enrichment (Fig. 7). A similar trend is evident in other eastern Australian volcanics and has been attributed to the influence of very low oxygen fugacities during crystallisation (Ewart et al., 1976). This is consistent with other mineralogical evidence in the Warrumbungle trachytes.

A notable feature of many of the sodic pyroxenes is significant enrichment in Zr with up to

TABLE 4 *Analyses of Pyroxenes and Aenigmatites*

	(1)	(2)	(3)	(4)	(5)
WMB No.	141	165	130	100	100
SiO_2	49.31	51.19	39.61	40.55	40.03
TiO_2	0.45	4.30	1.29	-	1.92
ZrO_2	13.87	9.32	0.41	0.14	0.49
Al_2O_3	0.08	0.10	1.02	0.40	0.60
FeO^*	19.36	18.17	47.66	47.34	43.53
MnO	1.13	1.14	1.15	1.17	1.25
MgO	-	-	-	0.02	0.04
CaO	1.29	0.63	0.34	0.11	0.17
Na_2O	12.26	12.57	7.01	7.20	7.16
K_2O	0.04	0.08	-	0.07	0.02
Nb_2O_5	-	0.47	0.80	-	2.98
TOTAL	97.80	97.97	99.30	97.00	98.28
Fe_2O_3@	13.26	8.45	17.31	19.93	9.91
FeO@	7.43	10.55	32.08	29.41	34.61
TOTAL	99.13	98.82	101.03	99.00	99.27

Cation Proportions#

	(1)	(2)	(3)	(4)	(5)
Si	1.995	2.035	5.709	5.922	5.876
Ti	0.014	0.129	0.140	-	0.212
Zr	0.274	0.181	0.029	0.010	0.035
Al	0.004	0.005	0.173	0.069	0.104
Fe^{3+}	0.395	0.254	1.874	2.120	1.099
Fe^{2+}	0.260	0.350	3.871	3.662	4.244
Mn	0.039	0.038	0.140	0.145	0.155
Mg	-	-	-	0.004	0.009
Ca	0.056	0.027	0.053	0.017	0.027
Na	0.962	0.969	1.959	2.039	2.038
K	0.002	0.004	-	0.013	0.004
Nb	-	0.008	0.052	-	0.198

1. Zr-rich acmite in quartz trachyte WMB141, east side of Mt Naman (855266).
2. Zr-Ti-rich acmite in quartz trachyte WMB165, Western High Tops (874332).
3. Ti-poor aenigmatite in nepheline trachyte WMB130, Black Mountain (886202).
4. Ti-free aenigmatite in sodalite trachyte WMB100, Bingie Grumble Mountain (079333).
5. Ti-poor aenigmatite in sodalite trachyte WMB100, Bingie Grumble Mountain (079333).

FeO^* - Total Fe as FeO

@ FeO and Fe_2O_3 recalculated assuming stoichiometry.

Cation proportions calculated on the basis of 4 cations and 6 oxygen atoms (pyroxene), and 14 cations and 20 oxygen atoms (aenigmatite) anhydrous.

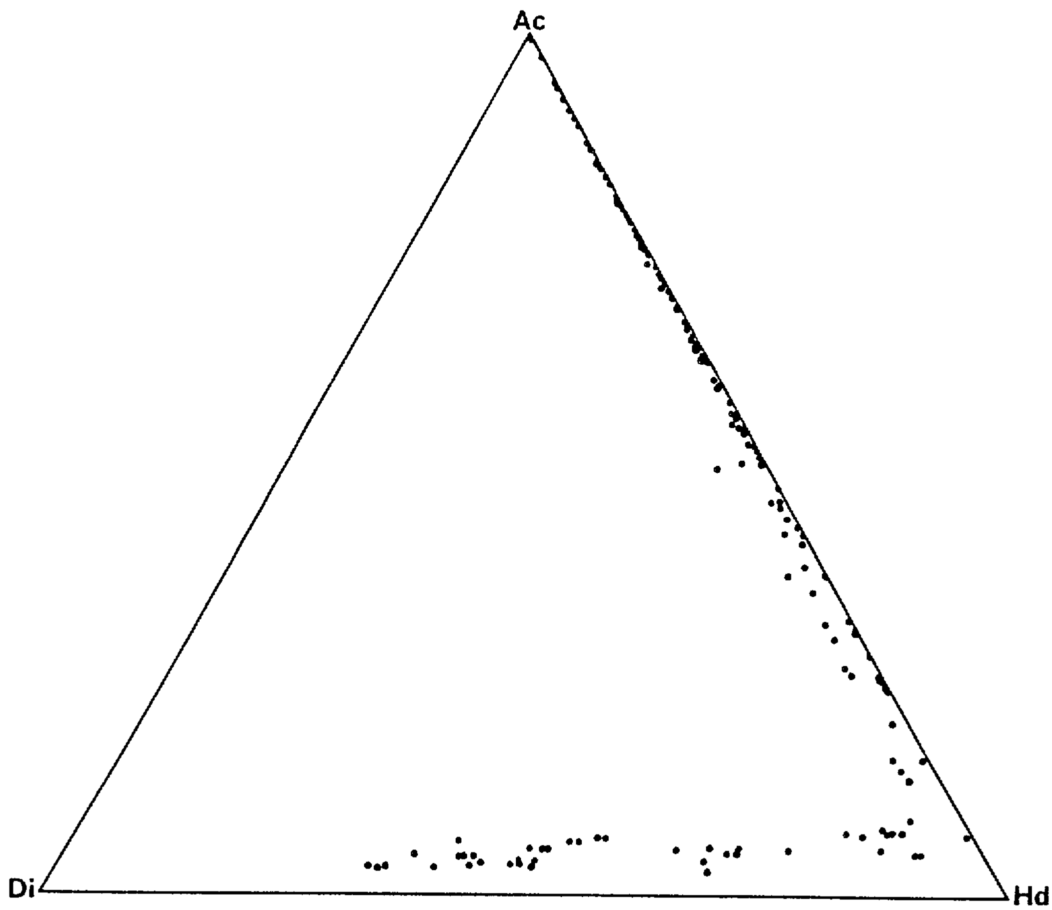

Fig. 7 *Di-Hd-Ac diagram for pyroxenes in felsic rocks from the Warrumbungle Volcano.*

14 wt % ZrO_2 (Table 3, Nos 1,2) which is almost twice the previously reported maximum Zr .pa content of pyroxene and represents more than 50% of a Zr-pyroxene end member molecule (see below). Enrichment in Zr is accompanied by depletion in Fe (Fig. 8) and is restricted to pyroxenes showing significant enrichment in acmite over hedenbergite. It is now well established that Zr enters sodic pyroxenes in a coupled substitution of the form $ZrFe^{2+}=2Fe^{3+}$ representing the theoretical end-member $NaFe^{2+}_{0.5}Zr_{0.5}Si_2O_6$ (Jones and Peckett, 1980). This substitution is also consistent with low fO_2, but other important controls include relatively high Zr content of the host rocks (up to 3000 ppm Zr) and concentration of Zr in small and highly localised interstitial domains during crystallization.

Aenigmatite is a common component of the peralkaline trachytes and is a minor component of many mafic trachytes. It shows considerable variation in composition, especially

with respect to Ti which varies antipathetically with Fe (Fig. 9). This variation is clearly a function of host rock composition. Ti approaches the theoretical one atom per formula unit (ca. 9

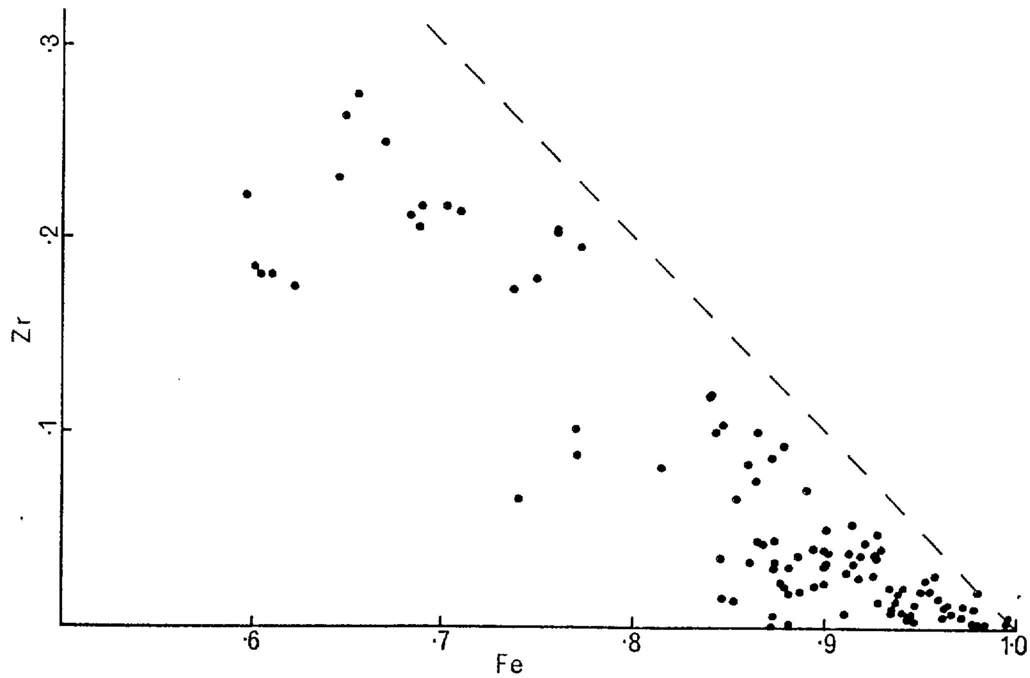

Fig. 8 *Zr vs Fe for sodic pyroxenes in felsic rocks from the Warrumbungle Volcano. The dashed line represents ideal substitution of the molecule* $NaFe^{2+}{}_{.5}Zr_{.5}Si_2O_6$ *in acmite-hedenbergite. The presence of other elements (eg., Ti, Al) will displace the points downward and to the left of this line.*

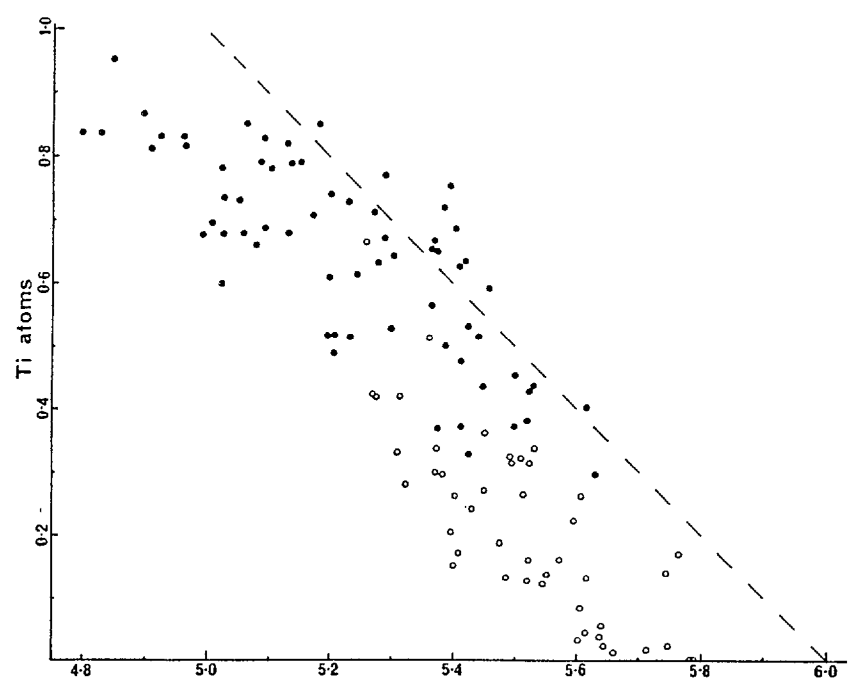

Fig. 9 *Ti vs Fe for aenigmatites in felsic rocks from the Warrumbungle Volcano. The dashed line represents ideal substitution of the ferri-aenigmatite* ($Na_2Fe^{2+}{}_4Fe^{3+}{}_2Si_6O_{20}$) *molecule. Displacement from the line results from the presence of other elements (below) and from substitution of Fe in tetrahedral co-ordination.*

wt % TiO_2) in quartz-bearing trachytes with significant TiO_2 but decreases significantly in .lh8 response to lower TiO_2 and lower levels of silica saturation in the host rock (Fig. 10) so that in exceptional cases Ti is very low or even totally absent (Table 3, Nos 3-5). Decreasing Ti represents the coupled substitution $2Fe^{3+}=Fe^{2+}Ti$ and entry of the ferri-aenigmatite end member $Na_2Fe^{2+}{}_4Fe^{3+}{}_2Si_6O_{20}$. Paradoxically however, the presence of this Fe^{3+}-bearing end member also indicates low fO_2 during crystallisation. Ferri-aenigmatite has been synthesised (Ernst, 1962) but its stability field is very greatly restricted, especially in the range of fO_2 (near or below the wustite-magnetite buffer curve) compared to "normal" aenigmatite which is stable over a wide range of T/fO_2 conditions (Thompson & Chisholm, 1969; Lindsley, 1971).

In fact fO_2 in these low-Ti trachytes may be buffered by the reaction

$$\underset{\text{acmite}}{6NaFeSi_2O_6} = \underset{\text{ferri-aenigmatite}}{Na_2Fe^{2+}{}_4Fe^{3+}{}_2Si_6O_{20}} + \underset{\text{glass}}{2Na_2Si_2O_5} + \underset{\text{glass}}{2SiO_2} + \underset{\text{gas}}{O_2}$$

which indicates that the stability of ferri-aenigmatite will also be favoured by low $aSiO_2$ and only very mild peralkalinity.

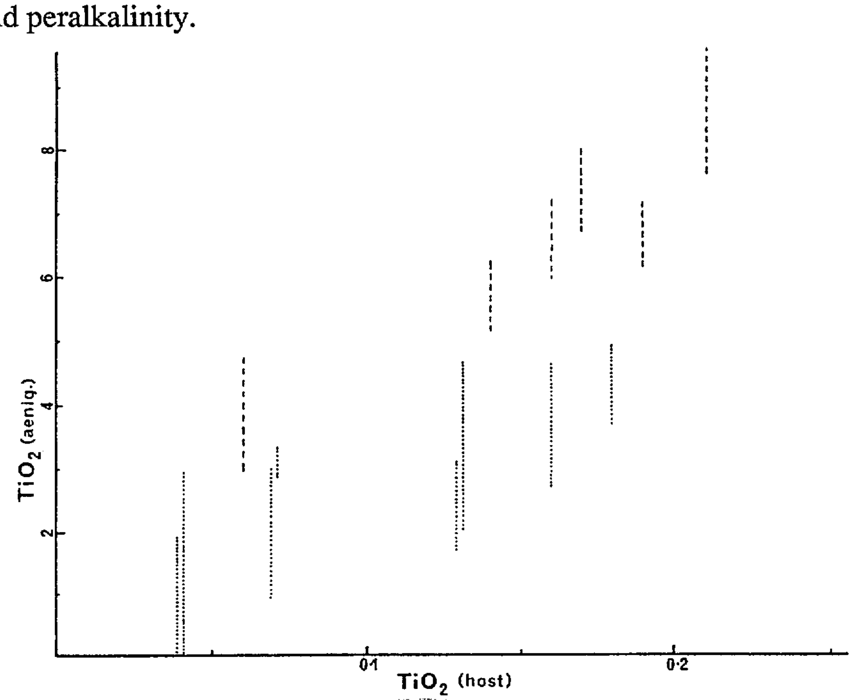

Fig. 10 *TiO_2 (weight %) in aenigmatite vs TiO_2 (weight %) in host rock for felsic rocks from the Warrumbungle Volcano. Vertical lines indicate measured ranges of aenigmatite compositions in individual host rocks. Dashed lines - quartz-bearing rocks. Dotted lines - quartz-free rocks (nepheline-, analcime- or sodalite-bearing).*

A further notable feature of some aenigmatites is abnormally high concentrations of Nb (up to 4.5 Wt % Nb_2O_5; Table 3, No. 5), some two orders of magnitude higher than previously reported levels. Other elements (Ca, Al, Mn, Zr, Mg, K) are present in only minor to trace amounts.

Amphibole is common in some peralkaline quartz trachytes and rhyolites but in other peralkaline trachytes it is greatly subordinate to sodic pyroxene. In either case it is an alkali amphibole corresponding to arfvedsonite or ferro-eckermannite (depending on the $Fe^{3+}/(Fe^{3+}+Al)$ ratio and hence on the method of recalculation from microprobe analyses. A couple of *ne*-normative trachytes contain occasional early-formed amphibole phenocrysts (alumino-kataphorite) mantled by clinopyroxene and opaques.

Petrogenetic Aspects

An important rôle has traditionally been assigned to fractional crystallisation processes in the evolution of volcanic rock series extending from mafic to felsic compositions as typified by the Warrumbungle Volcano. Certainly there are many mineralogical and geochemical features consistent with such a model including the close geochemical coherence of many incompatible

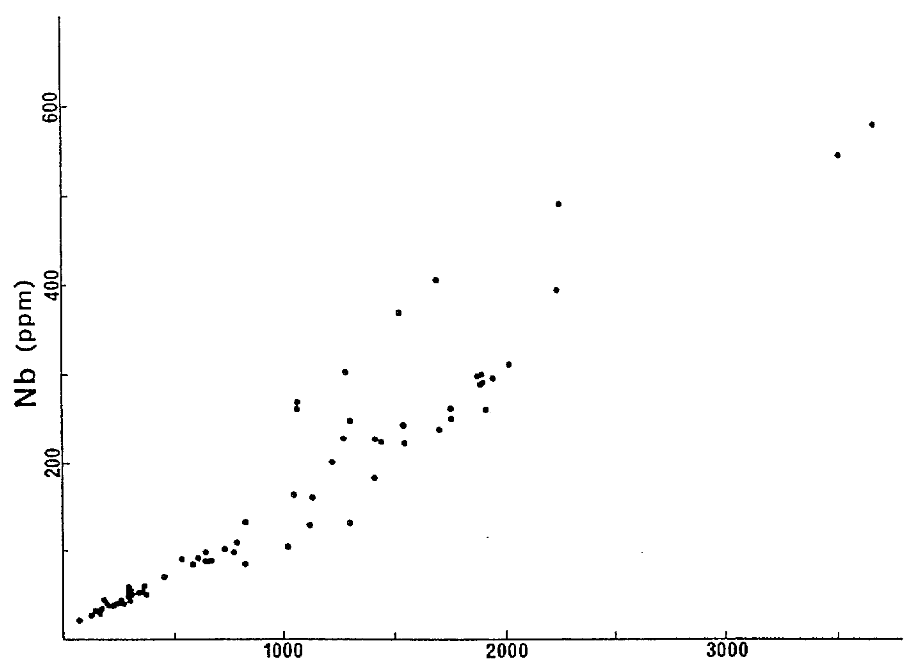

Fig. 11 *Nb vs Zr for rocks from the Warrumbungle Volcano.*

elements (*eg*. Zr vs Nb; Fig. 11) from mafic through to felsic rocks and the chemical variation trends among major, minor and trace elements in the rocks and their component minerals. However, recent studies of other eastern Australian central-type volcanoes have called into question the importance of crystal fractionation, at least as the sole process in linking the mafic and the more felsic representatives. For example, many of the peraluminous rhyolites of the Tweed Volcano are considered to be products of crustal melting (albeit modified by fractionation; Ewart, 1983). Fractionation alone has also been found to be inadequate to explain the spectrum of compositions observed in the Nandewar Volcano by Stolz (1985) who presents an excellent summary of the petrogenetic aspects of this and other eastern Australian central-type volcanoes. Problems are also encountered in attempting to apply a fractional crystallisation model as the sole process in the evolution of the Warrumbungle Volcano. Some of these difficulties are discussed briefly below.

1. Parent Magma

No analysed rock adequately fulfils the requirements of a primitive mantle derived magma (100Mg/(Mg+Fe)>68). Nor are there any known occurrences of mantle-derived peridotitic xenoliths. Only one rock (WMB171) is a true basalt in the classification of Coombs and Wilkinson (1969) but even this rock has an Mg-number of 62.7 and some unusual chemical characteristics including strong enrichment in Ba and, to a lesser extent, Sr. Other potential candidates are all hawaiites with Mg-numbers less than 65.

2. Relative Rock Volumes

Ideally, in a volcanic rock series produced by fractional crystallisation, successively more evolved fractions should be present in decreasing abundance. Furthermore, the presence of any evolved rocks implies the existence, perhaps at depth, of a complimentary crystal fraction. In the Warrumbungles, felsic rocks are estimated to comprise more than 50% of the remaining volcanic pile. Furthermore, the peralkaline trachytes and associated rocks are enriched in some incompatible elements by factors of up to 25 relative to potential mafic parents. This implies the hidden existence of huge and probably quite unreasonable quantities of complimentary crystal fractions. There is little evidence for their existence.

3. Fractionation Modelling

Modelling calculations to test the efficacy of crystal fractionation processes have been widely applied in the past few years. Such calculations are probably of limited intrinsic value in the present case where the volcano is deeply eroded, stratigraphic control is poor and the volcanism spanned some 4 million years. However some preliminary calculations, mainly using least-squares mixing equations, have been undertaken. These have so far failed to produce satisfactory models, with some unacceptably large residuals and certain elements such as phosphorus behaving contrary to expectations based on observed phenocryst phases.

4. Isotope Data

$^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ data are available on selected representatives throughout the series (Table 2). These data suggest that a significant crustal component has been involved in evolution of the more felsic rocks. In the more extreme cases (WMB157 and WBM93), Sr is very low and calculation of initial $^{87}Sr/^{86}Sr$ ratios is subject to considerable error and data on feldspar separates is required to confirm the high initial $^{87}Sr/^{86}Sr$ ratios. However, in other trachytes (*eg*., WMB 188) the initial ratio is well constrained and not consistent with closed system fractional crystallisation.

Given the above objections to a fractionation model, the problem nevertheless remains to suggest a more viable process for evolution of the series. To date this has been singularly unsuccessful. Most suggested processes (magma mixing, volatile transfer, thermogravitational diffusion, melting of primary Fe-rich mantle) are poorly defined, not amenable to quantitative testing, are unlikely to retain the strong geochemical coherence evident for many element pairs or, most importantly, raise more problems than they solve.

ROUTE GUIDE

Field activities during the workshop will concentrate on the central and eastern portions of the volcano (Fig. 12). These areas and the southern flanks are better known than the northern flanks where access is often more difficult and no field studies have been undertaken. However no part of the volcano has been studied in more than reconnaissance detail and knowledge of the structure and volcanic stratigraphy is at best rudimentary.

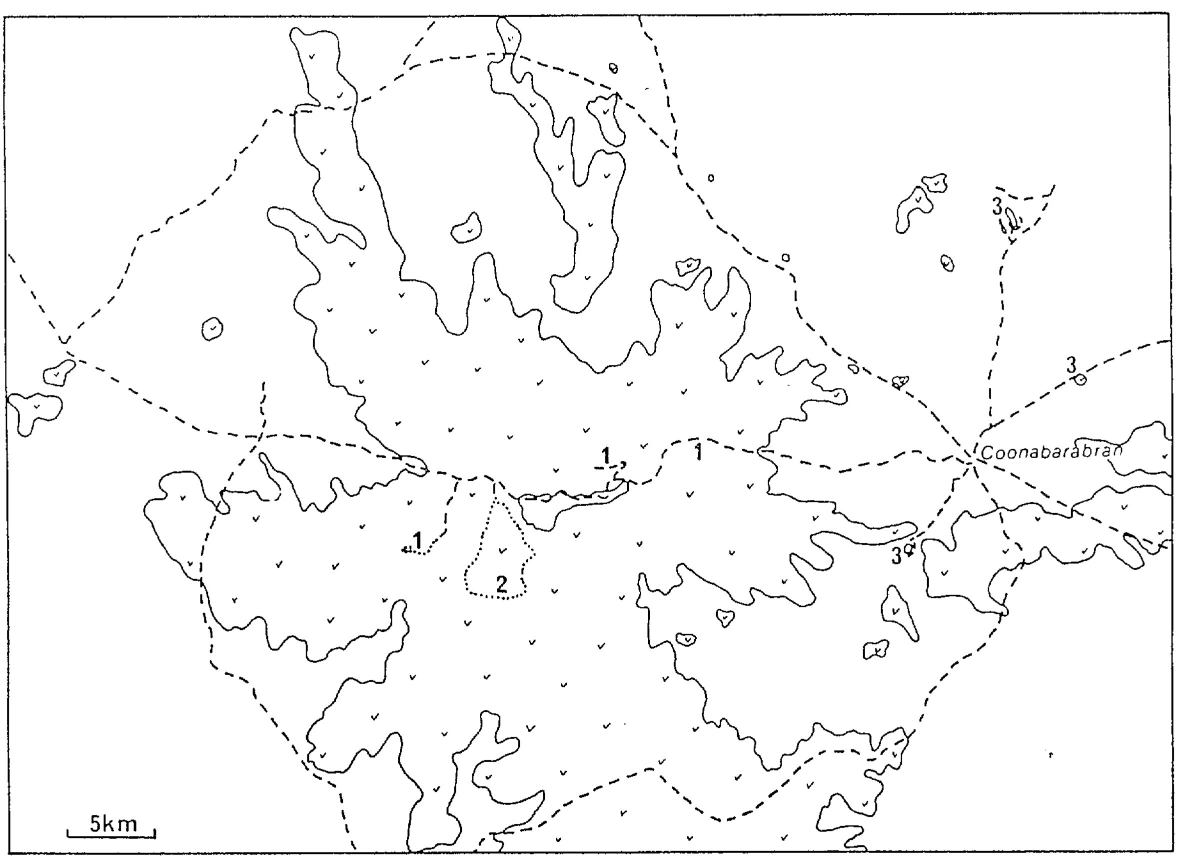

Fig. 12 *Outline of the Warrumbungle Volcano showing the principal roads and the areas to be visited during the workshop.*

DAY 1

This day commences with a stop for a panoramic view of the central portion of the Warrumbungle Volcano from Siding Springs Mountain, a remnant of the eastern portion of the lava shield. We will then move to Mount Exmouth on the western side for a traverse through the lava shield sequence and a panoramic view from the western side of the volcano. The afternoon will be spent examining flank deposits on the eastern side of the volcano.

1.1 Siding Springs Mountain (a)

From this point near the 3.9 metre Anglo-Australian optical telescope an excellent view is obtained of all the peaks, domes and spires in the deeply eroded central portion of the volcano that have made the Warrumbungle National Park so well known.

1.2 Siding Springs Mountain (b)

This is a brief stop to enable collection of a fairly typical mugearite. The rock (Table 2, No. 4) contains phenocrysts of plagioclase, olivine and minor clinopyroxene and apatite in a groundmass of plagioclase, clinopyroxene, opaque oxides and alkali feldspar.

1.3 Mount Exmouth - Summit

This point again provides a spectacular vista of virtually every significant topographic feature in the Warrumbungle volcano. In addition to the better known central part, important features of the southern and southwestern portions may be observed. In particular note the denuded flat plateau of Mount Naman (a strongly jointed thick trachyte flow remnant) and Tonduran Spire (a mugearite plug). The poorly known northern and northeastern portions are visible in the distance. It may also be possible to see the Mesozoic Garawilla Volcanics 80 km to the east and, on a very clear day, the Nandewar Volcano some 180 km to the north.

The rock at the summit of Mount Exmouth is a highly vesicular and partly brecciated hawaiite often containing abundant chabazite. Where the walking track reaches the summit ridge, the lava sequence is locally steeply dipping with features suggestive of the remnants of a local vent structure.

1.4 Mount Exmouth - Cliff Base

The interpretation of this spectacular outcrop will be left in the hands of the workshop participants. To date it has not been studied in detail but cursory examination suggests that mass flow processes may be involved.

1.5 Danu Saddle

A variety of felsic rocks are developed in close proximity to Danu Saddle. At the saddle the rock is a blue peralkaline rhyolite (comendite; Table 2, No. 17) but lower down on the vehicle track to the south is a nepheline trachyte (Table 2, No. 10). In the road cutting immediately north of the saddle is a mafic trachyte (Table 2, No. 7) forming part of the sub-horizontal lava sequence of Mount Exmouth.

1.6 Bookshelf Mountain

This is another excellent outcrop, the nature and significance of which have not been ascertained. The outcrop appears to be a near vent facies consisting largely of featureless trachytic breccia but close examination reveals some internal structure.

1.7 Shawns Creek

In Shawns Creek just east of Tibuc homestead a bedded pyroclastic sequence appears to be predominantly air-fall in origin. Bedding is very well developed on a centimetre to decimetre scale over a thickness of at least 40 metres. Cross bedding is observed but rare.

1.8 Timor Road

This spectacular road cut exposes a clastic sequence apparently deposited along a precursor to the present Shawns Creek. The lower unit is a boulder bed approximately 2 metres thick composed of clast-supported boulders up to a metre in diameter showing evidence of high energy fluvial processes including pronounced imbrication and a paucity of fines. Overlying this unit is an essentially clast-free muddy horizon about 0.5 metres thick followed by the upper unit which is an unsorted deposit of matrix-supported boulders reaching 2 metres in diameter in a muddy matrix. This is probably a mass-flow deposit resulting from a lahar.

DAY 2

Day 2 will be spent walking the main tourist route of the National Park. This route, the Grand High Tops Circuit (Fig. 13), passes through some of the most spectacular volcanic scenery with outstanding vantage points. On leaving the carpark, the track follows Spirey Creek for 4 km (mostly through exposures of quartzose sandstones of the Jurassic Pilliga Sandstone) before climbing through the volcanic sequence.

2.1 Bridget Peak - Bress Peak

The track to Bridget and Bress Peaks involves a short but steep climb on a spur off the main track. The track initially climbs along the spine of a several metres wide peralkaline trachyte dyke (Table 2, No. 16). After briefly levelling out there is a further steep climb through medium grained dolerite to Bridget Peak. Bress Peak, immediately west of Bridget Peak, is composed of bleached and deeply weathered trachyte.

2.2 Spirey View

This short detour from the main track offers a fine view of Belougery Spire and the Breadknife.

2.3 Spirey Ramp

A basalt flow at the base of the volcanic sequence is exposed at the point where the track

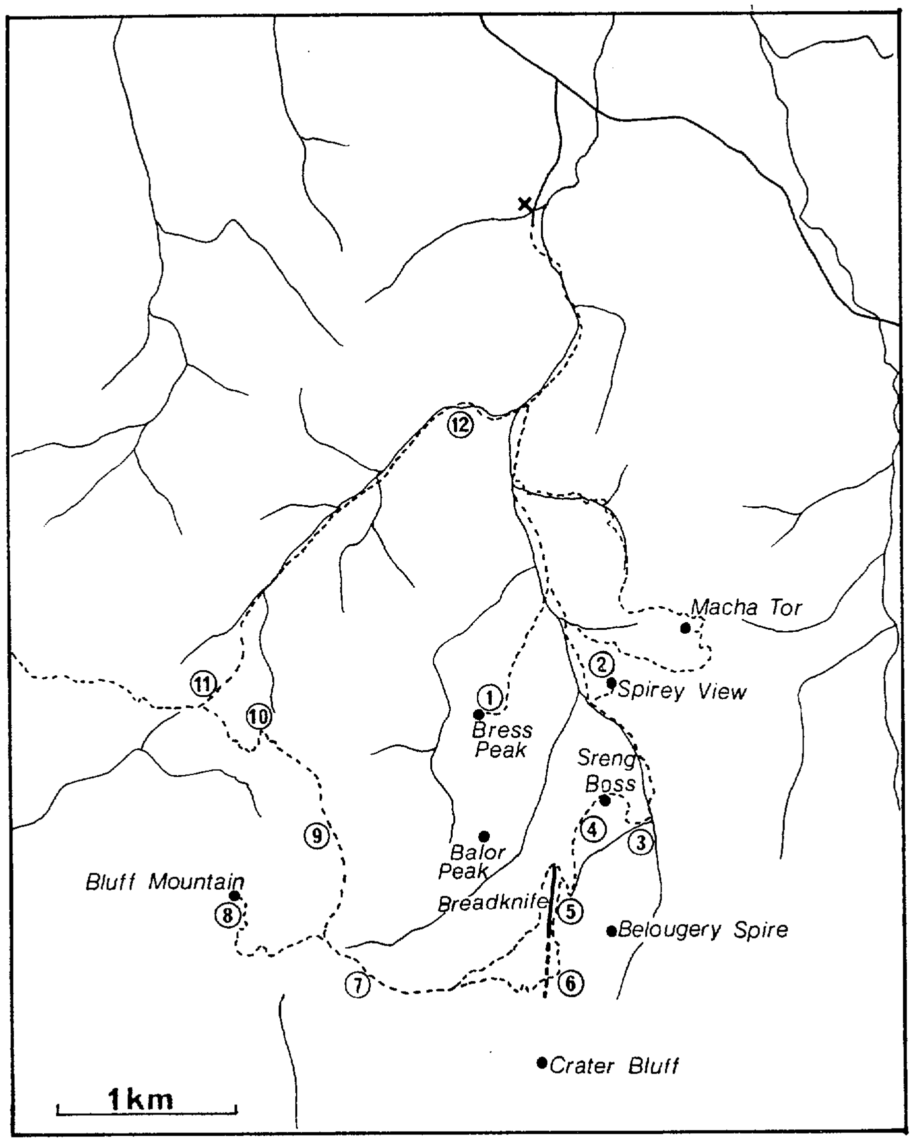

Fig. 13 *Route map for the Grand High Tops circuit. Stop numbers refer to those in the text for Day 2.*

leaves Spirey Creek and begins to climb to the Grand High Tops. This rock (Table 2, No. 1) has the most primitive composition of any in the volcano.

2.4 Sreng Saddle

Shortly before reaching Sreng Saddle, the first exposures of trachytic pyroclastics are encountered. In this area, the pyroclastics are mostly featureless tuffs and breccias containing abundant angular fragments of fine grained green trachyte. Sreng Saddle provides an outstanding vantage point for views of Belougery Spire, a trachyte plug with mineralogical and chemical characteristics (Table 2, No. 9) intermediate between the mafic and peralkaline trachytes.

2.5 The Breadknife

The track passes along the eastern side of this, the most spectacular topographic feature in the volcano. The Breadknife is an acmite-bearing peralkaline dyke (Table 2, No. 11) only a couple of metres wide and up to 60 metres high which can be traced for almost a kilometre. Contact relationships are very well exposed adjacent to the track where the dyke intrudes pyroclastic rocks in the lower (northern) portions and blue arfvedsonite trachyte in the upper (southern) portions.

2.6 Grand High Tops

This is an outstanding vantage point from which many of the principal features of the volcano are visible. The rock is an arfvedsonite-bearing quartz trachyte (Table 2, No. 12). Crater Bluff, some 500 metres south across a small valley, is a green acmite-bearing trachyte similar to the Breadknife which may be a radial dyke from it.

2.7 Dagda Ramp

After descending to Dagda Saddle, the track climbs steadily to Nuada Saddle. Along most of the ascent, the track traverses bedded pyroclastics including some blocks up to 30 cm in diameter. In this area the pyroclastics frequently have low to moderate dips, at least part of which almost certainly results from associated intrusive activity.

2.8 Bluff Mountain

The ascent of Bluff Mountain is an optional extra for those of average to above average fitness. Bluff Mountain is one of the largest bodies of peralkaline trachyte in the Warrumbungles and probably represents a lava dome. The rock (Table 2, No. 15) is a silica saturated trachyte containing approximately equal amounts of acmite and arfvedsonite.

2.9 Dows High Tops

From Nuada Saddle the track follows a ridge separating the southern and central watersheds of the park. For the most part the track passes through bleached and highly weathered trachytes and pyroclastic equivalents but at one point a small outcrop of benmoreite is exposed. This rock (Table 2, No. 6) contains phenocrysts of Fe-rich olivine, augite and sodic plagioclase in a very fine grained groundmass of feldspars, pyroxenes and opaque oxides.

2.10 Point Wilderness

A brief stop to view Mount Exmouth and the northwestern portion of the volcano.

2.11 Ogma Ramp

On the descent from Ogma Saddle, a long section of well-bedded pyroclastics is exposed on the side of the track. Here the pyroclastics are very steeply dipping. Near the lower end of the exposure, a trachyte dyke crosses the track in at least two places.

2.12 West Spirey Creek

The track descends to West Spirey Creek. Along this section the track passes only through Pilliga Sandstone. Shortly before the junction with Spirey Creek there is an exposure of quartzose sandstone showing strong silicification. These features are unusual in the Mesozoic sediments and presumably result from the inevitable hydrothermal activity and at least minor tectonism accompanying the volcanism.

DAY 3

The principal objectives of this day are to study two contrasting trachyte bodies on the outer flanks of the shield. The first of these, Scabby Rock, is an oval shaped body approximately 600 metres long, 300 metres wide and 40 metres high surrounded by a more or less complete annular ring of Paleozoic metasediments succeeded outwards by Pilliga Sandstone. The second body, Bingie Grumble Mountain, is an extrusive lava dome of acmite-hedenbergite and sodalite bearing trachyte approximately kilometre in diameter and 150 metres high.

3.1 Scabby Rock - North

The steep exposures on the northern side of Scabby Rock show evidence of forceful injection of highly viscous trachyte in the form of abundant slickensiding. In this area the Paleozoic metasediments are poorly exposed but fragments are abundant in the soil.

3.2 Scabby Rock - East

This is a specimen collecting stop. The rock is an orthophyric trachyte consisting of abundant blocky anorthoclase, minor arfvedsonite and a trace of acmite and quartz.

3.3 Scabby Rock - South

Here the Paleozoic metasediments occupy a shallow valley between the trachyte and a low ridge of Pilliga Sandstone. A number of prospecting pits and shallow shafts have been opened up in the metasediments which have been extensively intruded by quartz veins. Minor sulphide mineralisation is observed in the quartz. Along part of the low ridge to the south, a dyke of olivine analcimite (the most undersaturated mafic rock so far found in the Warrumbungles) cuts the Pilliga Sandstone.

3.4 Forked Mountain

This conical hill adjacent to the Oxley Highway is composed of mafic trachyte (Table 2, No. 8) virtually identical in composition to the mafic trachyte lava flows forming a large part of the shield.

3.5 Bingie Grumble Mountain - North

The extrusive relationships are not clear on this side of the mountain but a track to a telecommunications station on the summit provides excellent exposures for specimen collecting. The outer 200 metres are relatively fine grained trachyte (Table 2, No. 13) consisting of phenocrysts of anorthoclase and sodalite in a groundmass of anorthoclase, acmite-hedenbergite, Ti-depleted aenigmatite, sodalite and traces of arfvedsonite, eudialyte and other complex Zr-silicates. The grainsize increases markedly toward the interior of the body.

3.6 Bingie Grumble Mountain - South

In a small gully cutting into the south side of the dome is an excellent outcrop which seems to unequivocally demonstrate the extrusive nature of the dome. The gully exposes heavily iron-stained sandstone which in the upper parts of the outcrop contains some large to very large blocks of slabby trachyte dipping generally away from the dome. The sequence is overlain by coarse trachyte breccia. Approximately 200 metres to the south (away from the dome) the sandstone is flat-lying and undisturbed. The sequence of events is interpreted as

1. Near-surface emplacement of the first phase of the lava dome causing at least some updoming of the Pillaga Sandstone
2. Continued emplacement of the dome, predominantly extrusive, with formation of talus deposits composed of larger blocks of trachyte and sandstone
3. Explosive volcanism in the waning stages to produce the overlying trachyte breccia.

3.7 Nandi Hill

The trachyte in a small quarry on the south side of Nandi Hill is quite felsic and rapidly produces a peculiar oxidation rind on exposure of the initially grey-green trachyte to air.

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