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WARRUMBUNGLE, NANDEWAR, AND TWEED VOLCANIC COMPLEXES

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

M.B. Duggan, J. Knutson and A. Ewart

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WARRUMBUNGLE, NANDEWAR, AND TWEED VOLCANIC COMPLEXES

by

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INTRAPLATE VOLCANISM IN EASTERN AUSTRALIA

Volcano Types and Distribution

Intermittent volcanism has taken place along the 4 400 km length of eastern Australia from about 70 Ma to 4 600 yr BP, and it represents an exceptional example of long term, widespread volcanic activity (Johnson & others, 1989). It stretches from Torres Strait in the north, along the highlands of Queensland and New South Wales, into Victoria, South Australia and Tasmania in the south (Fig. 1). The youngest rocks are found in the extreme north and south of the belt; in north Queensland (13 000 yr BP) and at Mount Gambier in South Australia (4 600 yr BP). In many of the basaltic provinces there is a remarkable abundance of mantle xenoliths and megacryts, and these represent some of the largest and most widespread quasi-continuous samplings of the mantle section on the Earth's surface, both in space and time (e.g. O'Reilly & others, 1989).

Wellman & McDougall (1974a) recognised three volcanic field types in eastern Australian, namely *central-volcano* provinces, *lava-field* provinces and *high-potassium mafic (leucitite)* provinces.

The *central-volcano* provinces are predominantly basaltic, but have conspicuous felsic (rhyolite, trachyte, or phonolite) flows and/or intrusions. The volcanic rocks, which commonly include widespread pyroclastic deposits, were produced from central vents, and in many instances built up large shield volcanoes, or volcanic complexes, such as the Warrumbungle, Nandewar and Tweed volcanoes which you will see on this excursion. This volcanism is dominated by rocks with transitional, mildly alkaline compositions, although subalkaline rocks are present in some instances, particularly in the Tweed volcano.

The *lava-field* provinces consist mainly of mafic alkali basaltic lavas, although tholeiitic basalt is present in some. Rarely, stacked lava flows up to 1000 m thick have accumulated (e.g. the Liverpool Range in east-central New South Wales), but more typically these *lava-field* provinces are characterised by thin and discontinuous flows. The younger Queensland, Victorian and South Australian *lava-field* provinces are characterised by an abundance of small scoria and lava cones and maars. The *lava-field* type volcanism has occurred throughout the eastern Australian highlands, beginning about 70 Ma ago, although the main eruptive period was between 55 and 30 Ma ago. This was followed by a period of relatively little *lava-field* volcanism until about 5 Ma when there was a resurgence of volcanic activity, particularly in northern Queensland and western Victoria. We will pass briefly through a *lava-field* province on Day 5.

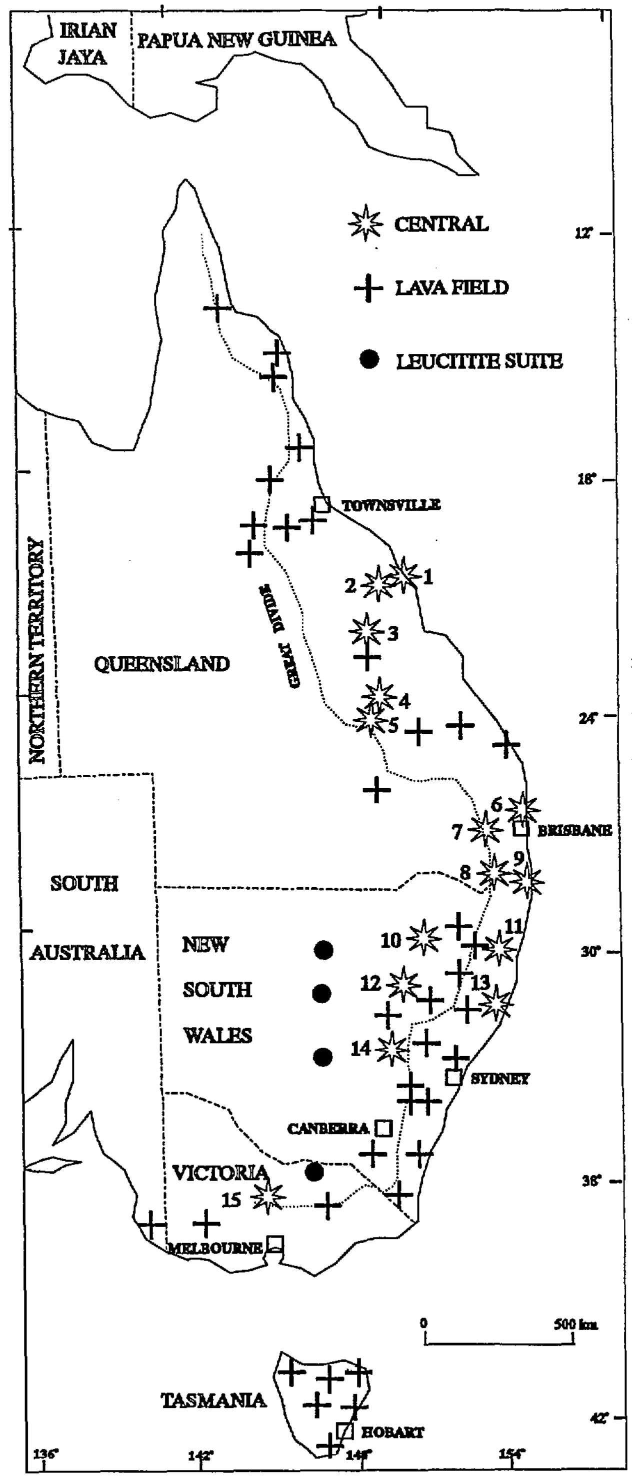

Figure 1. Central-volcano, lava -field, and leucitite-suite provinces of eastern Australia shown in relation to the Great Divide. Numbers 1-15 correspond to the following central volcanoes: 1, Hillsborough; 2, Nebo; 3, Peak Range; 4, Springsure; 5, Buckland; 6, Glass Houses; 7, Main Range; 8, Focal Peak; 9, Tweed; 10, Nandewar; 11, Ebor; 12 Warrumbungle; 13, Comboyne; 14, Canobolas; 15, Macedon.

The *high-potassium mafic* provinces are petrographically and spatially distinct from the other volcanic areas of eastern Australia and are dominated by leucitite intrusions and lavas (Fig. 1). They have a very restricted age range from about 17 to 12 Ma and are confined to a relatively short linear belt extending from northwestern New South Wales to Victoria.

The *central volcanoes* show a remarkably constant decrease in age from north to south, from the oldest (35 Ma) at Cape Hillsborough in north Queensland to the youngest (6 Ma) at Macedon in central Victoria (Fig. 1). This trend is attributed to the northward passage of the Indo-Australian plate over a hotspot in the upper mantle. This northward movement was initiated about 95 Ma ago when Australia began to separate from Antarctica. The speed of separation increased about 44 Ma ago and the calculated rate of movement (65 $\pm$ 3 mm/year) exactly matches the rate of southward progression of the central volcanoes (Fig. 2).

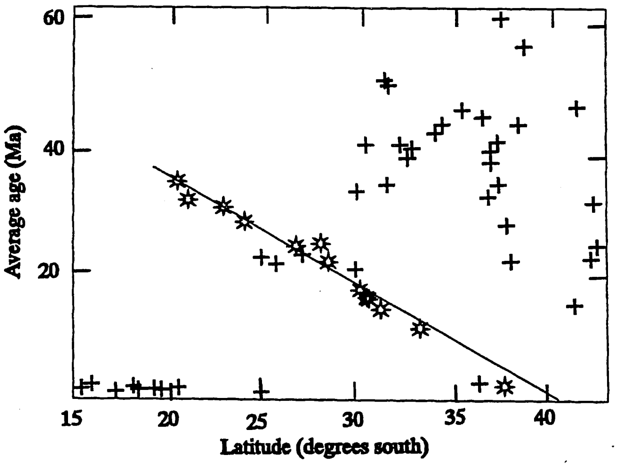

Figure 2. Age-latitude relationships for the intraplate volcanism of eastern Australia. Average ages for the central volcanoes (stars) are progressively younger to the south, corresponding to a rate of motion of 65 mm/year of the Indo-Australian plate over a mantle hot-spot. 'Zero-age' volcanism is predicted for the vicinity of Bass Strait. No spatial correlation is evident for the lava-field provinces (crosses).

The *central volcanoes* in New South Wales, and the Tweed volcano on the New South Wales/Queensland border vary widely in size (Table 1). The Tweed volcano is by far the largest with a diameter of 10 km and volume of 4 000 km^3. Warrumbungle and Nandewar are intermediate in size, and Canobolas is one of the smallest with a diameter of only 15 km and a volume of 50 km^3.

The *high-potassium mafic* (leucitite) provinces show essentially the same trend of younging southwards with time (as do the Tasmantid Guyots in the Tasman Sea) as the *central volcanoes,* whereas the *lava-field* provinces show no apparent space-time trends.

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 Element Geochemistry

Mafic lavas dominate the Tertiary volcanic provinces of eastern Australia. They range from leucitite, nephelinite, and analcimite, through basanite, alkali basalt, *ne*-hawaiite, and hawaiite, to *ol*- and *qz*-tholeiitic basalt. The non-uniform distribution of these lavas throughout eastern Australia is shown on Figure 3. The most common mafic rock types are *ne*-hawaiite and hawaiite which make up 33% of all analysed samples (Ewart, 1989). Melilitite and nephelinite are most abundant in Tasmania where intermediate and felsic compositions are rare. Intermediate and felsic compositions are also rare in the young volcanic provinces (<5 Ma) of northern Queensland and western

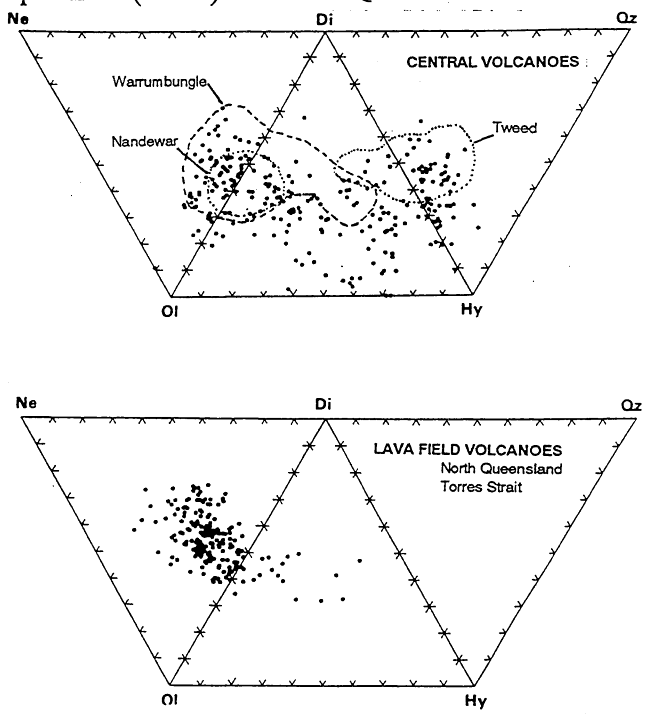

Figure 3. Normative compositions of east-Australian mafic (less than 56% SiO_2) volcanic rocks projected on the system Ne-Ol-Di-Hy-Qz.

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Victoria. They are most common in southern and central Queensland, New South Wales and central Victoria, reflecting the presence of *central volcanoes* in these areas. The *central volcanoes* are characterised by the mafic lavas being dominated by hawaiite and tholeiitic basalt. There is a greater development of near-saturated and over-saturated tholeiitic basalt in southeastern Queensland. Peraluminous rhyolites are also common in this area, and contrast with the *central volcano* provinces of New South Wales where the evolved lavas are dominated by trachytic and peralkaline felsic compositions.

Mg-ratios (100Mg/(Mg + Fe_{total}) for most basanites, nephelinites and melilitites range from 60 to 66, with a lower range of 60 to 58 for hawaiite, *ne*-hawaiite and alkali basalt. These values suggest that most of the basanites, alkali basalts and hawaiites have undergone olivine-dominated fractionation (Ewart, 1989), and only some of the more Mg-rich alkaline basalts can be considered to be primary melts. Primary tholeiitic basalts appear to be absent. The geochemical trends of the peralkaline trachytes and rhyolites in particular indicate they are strongly fractionated with extreme enrichment in Rb, Zr, Nb, Y, La and Ce, and depletion in Ba and Sr.

Sr and Nd Isotope Geochemistry

Nd and initial Sr-isotope trends for the volcanic rocks of eastern Australia are shown in Figure 4. The Tasmanian alkaline lavas generally have the most radiogenic Nd and least radiogenic Sr compared the volcanic areas of mainland Australia. Considerable isotopic differences are found in the different geographic regions, but values generally follow the main mantle trend defined by ocean-island basalt data (Ewart, 1989). As observed elsewhere, continental tholeiitic basalts generally have higher $^{87}Sr/^{86}Sr$ values and lower ε_{Nd} values than do coexisting alkali basalts (Sun & others, 1989). Compared with the more alkaline lavas, the hawaiites and tholeiitic basalts have wider isotopic ranges, and this is especially so in the *central volcanoes*. ε_{Nd} and ε_{Sr} for the basaltic rocks suggest (1) that the mantle sources were heterogeneous in regard to trace-element composition, and (2) the more alkaline lavas represent relatively small-volume melt fractions, whereas the less alkaline melts, including tholeiitic basalts, are the product of increasing degrees of melting.

The intermediate and felsic rocks have trends towards more radiogenic Sr and unradiogenic Nd-isotopic compositions that are interpreted to represent an upper-crustal component. In contrast, the distinctive isotopic and geochemical trends of the high-silica rhyolites (strongly radiogenic Sr and unradiogenic Nd) suggest they are upper-crustal melts developed in response to mafic magma emplacement (Ewart, 1989).

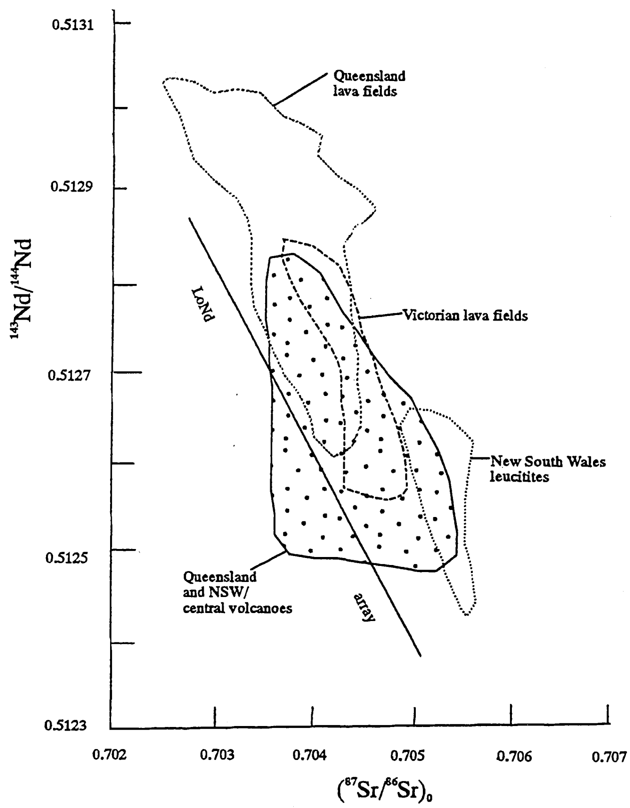

Figure 4. Generalised Nd- and Sr-isotope compositions divided into regional groups (after Ewart, 1989). LoNd array after Hart & others (1986)

The leucitites in western New South Wales also have distinctive isotopic characteristics, and Nelson & others (1986) concluded that their mantle source was contaminated by a radiogenic Sr and unradiogenic Nd component, possibly derived from either the hotspot which initiated the volcanism or an earlier metasomatic event/s.

Mantle and Crustal Xenoliths

Mantle and crustal xenoliths are widely distributed in the Tertiary volcanics of eastern Australia. Most are considered to represent accidental (non-cognate) fragments, although some may be high-pressure precipitates from basaltic magmas (O'Reilly & others, 1989). They are most abundant in the basanites and *ne*-hawaiites of the *lava-field* provinces and less common in the basaltic rocks of the *central volcanoes*. Mantle-derived xenolith suites include a relatively restricted range of rock types, but the proportions of types differ between localities. Cr-diopside spinel lherzolite is the most abundant and ubiquitous xenolith type throughout eastern Australia, mostly totalling 80-100% of the xenolith population. Other mantle-derived xenoliths include mafic, ultramafic, granulitic and

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eclogitic varieties. Lower crustal xenoliths are relatively rare, but can dominate some individual sites, particularly in the young *lava-field* provinces of northern Queensland and western Victoria. Mafic lower-crustal xenoliths in north Queensland have $^{87}Sr/^{86}Sr$ of 0.7024 to 0.7147 and ε_{Nd} of +9.6 to -6.1 and are described by Rudnick & others (1986) as having petrographic and geochemical features consistent with being cumulates which have crystallised at lower crustal pressures from a basaltic melt.

Petrogenetic Considerations

The intraplate volcanic rocks of eastern Australia are characterised by (1) a dominance of mafic magmas; (2) a diverse and complex range of magma compositions; (3) a continuity of geochemistry throughout the range of magmas; (4) geochemical differences between *central volcanoes* and *lava-field* provinces (which corresponds to differences in magma evolution, and possibly magma sources, for these two province types); (5) the importance of fractional crystallisation in magma development, particularly in the trachytic, rhyolitic and peralkaline rocks of the *central volcanoes*, and (6) relatively diverse Sr, Nd, and Pb-isotope compositions (Ewart, 1989).

Geochemical modelling shows that the more evolved hawaiites, mugearites, and benmoreites, and tholeiitic basalts and icelandites can be derived by fractionation of olivine + augite + plagioclase + magnetite + ilmenite + apatite. Apatite is important as fractionation proceeds, and the ferromagnesian minerals become increasingly Fe-enriched. Late-stage Na-enrichment (and Zr) in pyroxene is important in trachytes and low-silica rhyolites, and is extreme in the peralkaline rocks.

The common presence of corroded megacrysts and cumulates in hawaiites and tholeiitic basalts (and more rarely, mugearites) of the *central volcano* provinces throughout eastern Australia has led to the suggestion that at least some of these formed by crystal fractionation in the lower crust. The megacrysts and cumulates consist of olivine, aluminous and subcalcic augite, diopsidic augite, aluminous bronzite, plagioclase, anorthoclase, spinel (including magnetite), ilmenite, amphibole, mica, apatite, corundum and zircon. Modelling calculations and experimental work (Duggan & Wilkinson, 1983; Irving, 1974; Knutson & Green, 1975; Ellis, 1976; Ewart & others, 1980) indicate these precipitated from a mafic magma in the lower crust (at about 6 to 16 kbar) prior to the rapid ascent of the derivative magmas into the upper crust and to the surface. Upper-crustal crystal fractionation was particularly important for the more silica-saturated and oversaturated intermediate and felsic lavas (Ewart, 1989).

Basaltic Magma Sources

Trace element and isotopic characteristics have been used to identify (1) a mantle plume, (2) the shallow asthenosphere, (3) the lithospheric-mantle, and (4) the crust, as the four source components involved in the generation of the eastern Australian intraplate magmas (Sun & others, 1989).

The plume component composition is defined by the least-fractionated *central volcano* basalts; (e.g. Warrumbungle, Nandewar and Tweed volcanoes); the shallow-asthenosphere component is defined by the older *lava-field* alkali basalts (old and/or distant lava-field alkali basalts, e.g. Tasmania, New England and Monaro); and the lithospheric mantle is defined by the leucitite provinces of New South Wales. The effects of crustal contamination is evaluated by coupled changes in isotopic and trace-element characteristics and is particularly evident in the more evolved silica-saturated lavas of the *central volcanoes*.

The primary and near-primary basalts of the eastern Australian intraplate volcanism have chemical and isotopic systematics largely similar to those recognised in ocean-island basalts, and the differences can be explained by the involvement of continental lithosphere, including the crust. The tholeiitic basalts, and particularly those that are highly fractionated, commonly have a crustal geochemical signature from which it is difficult to distinguish between the effect of crustal assimilation/fractional-crystallisation and lithospheric mantle modified subduction-zone processes (Sun & others, 1989).

Sun & others (1989) interpret the *central volcano* and some of the nearby *lava-field* basalts of similar ages as being derived mainly from a mantle plume, with plume material being channelled to adjacent fracture systems to allow *central-volcano* and *lava-field* eruptions to take place away from the main hotspot trace. An alternative explanation is that the *central volconoes* were generated by more than one mantle plume (Wellman & McDougall, 1974a; Sutherland, 1983).

WARRUMBUNGLE VOLCANO

The Warrumbungle Mountains represent the eroded remnants of roughly circular shield volcano approximately 50 km in diameter. Scattered outliers of basaltic rocks extend greater distances to the northwest to near the township of Coonamble and to the southwest toward the western limit of the Liverpool Range, a thick pile of older (35-42 Ma) basaltic lavas.

The Warrumbungle volcano is deeply dissected, with the remnant outer flanks displaying a pronounced radial drainage pattern. The residual constructional remnants indicate that the original volcano developed as a broad shield, consisting of a thin outer apron of predominantly mafic lavas surrounding a higher central massif of predominantly felsic lavas and pyroclastics. The profile envisaged is similar to that still preserved in the younger and smaller Canobolas volcano some 300 km to the south, and was typical of many of the *central-type* volcanoes of eastern Australia, including the others to be visited on this trip (the Nandewar and Tweed volcanoes). Like the Nandewar volcano to the north, it is intermediate in size between the largest (Tweed) and the smaller (Canobolas and Comboyne) *central volcanoes* in New South Wales (Table 2).

The Warrumbungle shield apparently reached a height of about 1000 m above basement, although the apparent height probably has been exaggerated by significant updoming of basement beneath the central part of the volcano (Wellman, 1986). Major constructional remnants of the original shield are preserved at several points on the flanks of the shield, including Mount Exmouth (Wambelong), Siding Spring Mountain (Woorut) and Blackheath Mountain, on each of which stratified sequences of lavas and pyroclastics are preserved.

The central portion of the volcano is characterised by an abundance of dykes, plugs and domes of feldspathoid- and quartz-bearing trachytes intruding a relatively poorly bedded and poorly sorted sequence of tuffs and breccias. The pyroclastic rocks, containing angular fragments of green trachyte mostly less than 10 cm but up to 50 cm in diameter, are well exposed at several points along the main Grand High Tops walking track. Well-bedded pyroclastic rocks are almost exclusively confined to the outer flanks of the volcano where they are mostly restricted to the lower half of the remaining section and may frequently be redeposited.

In addition to the widespread occurrence of pyroclastic rocks, localised deposits of lacustrine sediments are developed at several localities on the outer flanks of the volcano. Diatomite deposits, presumably formed in ephemeral lakes resulting from damming by lava flows, are found at Chalk Mountain on the northern flanks and elsewhere (Herbert, 1968). The Chalk Mountain deposits crop out at several localities around the mountain in flat-lying sequences up to 15 m thick, including interbedded horizons of mudstone and well-bedded tuffs, underlain and overlain by hawaiite flows. The diatomite beds, dominated by *Melosira granulata*, have yielded a range of fossils including insects, freshwater bivalves, fish (*Maccullochella macquariensis*) and the leaves and fruit of *Eucalyptus* species.

Age Data

K-Ar age data (Dulhunty and McDougall, 1966; McDougall and Wilkinson, 1967; Dulhunty, 1973; Wellman and McDougall, 1974b) give a total range of 17-13 Ma for the Warrumbungle volcano. Wellman and McDougall (1974a) 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. Flows in the valley of the Castlereagh River south of the volcano dated at 14.5 and 17.0 Ma 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 (16-15 Ma; McDougall and Wilkinson, 1967; Wellman and McDougall, 1974a).

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 dominant on the outer flanks of the shield, especially in the southern and northern areas. In the southern part, they form a thin plateau sequence between Coonabarabran and Tooraweenah and extend south toward Binnaway, but thicker sequences are exposed on Blackheath Mountain and nearby peaks. In the north, the principal outcrops form a series of north-trending ridges, including Looking Glass Mountain and Chalk Mountain, and several isolated residuals to the northwest (Black Mountain, Tenandra Hill, Square Top Mountain). At a few localities, hawaiites contain a variety of xenoliths (mostly pyroxenite) and megacrysts (aluminian augite and ilmenite).

Trachyte is the dominant rock type in the central portion of the volcano. Relatively more mafic trachyte, characterised by Fe-rich olivine and ferroaugite, occurs in shield-building sequences as fairly thick flows (up to 50 metres) 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 are probably small lava domes.

The major plugs, dykes and domes are mostly confined to the central parts of the volcano (Breadknife, Bluff Mountain, Crater Bluff, Belougery Spire) and to the southern (Berrumbuckle Mountain) and eastern flanks (Timor Rock, Mopra Rock) of the volcano. Peralkaline, and to a lesser extent metaluminous trachyte, comendite and mugearite, are the dominant rock types in these bodies. Peralkaline trachyte is also dominant in the very widespread and abundant pyroclastics. The peralkaline trachytes contain sodic pyroxene (aegirine-hedenbergite solid solution) and/or amphibole (arfvedsonite) and may be either mildly nepheline- or quartz normative. As a general rule, silica-undersaturated trachytes have pyroxene > amphibole and quartz-normative trachytes have amphibole >> pyroxene. Aenigmatite, or in silica-undersaturated Ti-poor trachytes, wilkinsonite, is present in most peralkaline trachytes (Duggan, 1990).

Geochemistry

Major and trace element analyses and CIPW norms of selected rocks from the Warrumbungles are presented in Table 1. 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 are represented. The mafic rocks are broadly similar in geochemistry to equivalent rocks in other eastern Australian central-type volcanoes, in particular the Nandewar volcano (see below). 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.

A characteristic of the mafic rocks of the Warrumbungles, which is shared by all of the major *central-type* complexes of eastern Australia, is the absence of more primitive (Mg-rich) basaltic compositions. Thus, the most Mg-rich rock (in which pryoxene megacrysts and pyroxenite xenoliths have certainly increased Mg) has an Mg-number of 64.6. Rocks with Mg-number > 55 are scarce, are almost exclusively confined to the outermost flanks of the volcano, and almost invariably carry xenolith and megacryst debris.

Only subtle geochemical differences exist between the nepheline and quartz normative mafic rocks and new geochemical data do not 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 corresponding to the critical plane of silica undersaturation (Yoder and Tilley, 1962), with no systematic variation among K/Na ratios, Mg/Fe ratios and the level of silica saturation (cf Coombs and Wilkinson, 1969).

The more felsic rocks mostly also lie close to the plane of silica saturation with occasional specimens extending to more nepheline- and quartz-normative compositions. They include both metaluminous and peralkaline variants. 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 mafic trachyte with only one sample collected falling in the compositional field of benmoreite.

Mineralogy

Olivine is ubiquitous in rocks from hawaiite through to mafic trachyte. As 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 $Fo_{70\text{-}80}$ in the hawaiites, $Fo_{30\text{-}40}$ in benmoreite and Fo_{20} in the mafic trachytes.

Clinopyroxene is present in all 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 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. A similar trend in other eastern Australian felsic volcanics and has been attributed to the influence of very low oxygen fugacities during crystallisation (Ewart & others, 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, containing up to 14 wt % ZrO_2, which is almost twice the previously reported maximum Zr content of pyroxene and represents more than 50% of a Zr-pyroxene end member molecule (Duggan, 1988). Enrichment in Zr is accompanied by depletion in Fe and is restricted to pyroxenes showing significant enrichment in acmite over hedenbergite. Zr enters sodic pyroxenes in a coupled substitution of the form $ZrFe^{2+} = 2Fe^{3+}$, representing the theoretical end-member $NaFe^{2+}{}_{½}Zr_{½}Si_2O_6$. This substitution is also consistent with low fO_2, but other important controls include relatively high Zr content of the host rocks (up to 3 000 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

Table 2. *Analyses of rocks from the Warrumbungle volcano*

	(1) 035 Hawaiite	(2) 221 Hawaiite	(3) 190 K-Hawaiite	(4) 136 Mugearite	(5) 162 K-Mugearite	(6) 146 Mafic trachyte	(7) 093 Peralk. Ne trachyte	(8) 161 Peralk. trachyte	(9) 199 Peralk. Qz trachyte	(10) 181 Comendite
SiO_2	47.90	47.54	50.33	52.09	53.56	58.88	61.10	62.91	65.84	70.46
TiO_2	2.12	2.69	2.58	1.58	1.58	0.61	0.07	0.18	0.21	0.17
Al_2O_3	13.83	15.56	15.56	16.11	15.95	17.44	17.14	15.78	14.75	13.18
Fe_2O_3	1.92	2.58	3.21	2.32	3.12	2.45	3.35	3.43	2.18	1.95
FeO	8.91	9.39	7.41	6.83	7.01	4.72	1.83	2.46	2.75	1.89
MnO	0.15	0.17	0.15	0.13	0.18	0.13	0.10	0.13	0.08	0.07
MgO	9.11	5.15	3.61	4.39	2.12	0.68	0.04	0.06	0.03	0.03
CaO	9.56	6.17	6.96	6.41	4.76	2.55	0.84	1.01	0.47	0.09
Na_2O	2.92	4.57	4.10	5.23	4.92	5.50	7.94	7.31	6.94	6.09
K_2O	1.31	2.02	2.46	2.44	3.51	5.60	5.18	5.08	4.80	4.48
P_2O_5	0.45	1.04	0.62	0.37	0.98	0.41	0.02	0.02	nd	nd
H_2O+	-	2.19	0.52	1.44	0.73	0.50	1.63	0.42	0.44	0.40
H_2O-	0.25	0.57	0.45	0.41	0.52	0.26	0.32	0.18	0.37	0.17
CO_2	0.03	0.06	1.43	0.17	0.02	0.05	0.11	0.02	0.20	0.04
rest	0.26	0.28	0.25	0.24	0.30	0.26	0.59	0.36	0.48	0.57
Total	99.94	99.98	99.64	100.16	99.28	100.04	100.26	99.35	99.54	99.59
Mg No.	60.4	43.9	38.5	46.7	27.8	14.9	1.4	1.9	1.1	1.4
an/ab+an	46.0	32.6	31.9	27.9	21.0	12.2	-	-	-	-
Trace elements (ppm)										
Ba	445	665	530	825	1090	465	nd	4	2	nd
Rb	32	40	47	50	62	111	520	263	292	380
Sr	498	620	545	348	487	181	4	2	2	1
Pb	2	3	3	3	5	8	20	18	28	38
Th	2.8	5.7	4.9	5.0	5.6	10.8	29	36.0	36.0	66
U	0.4	1.0	0.8	2.0	1.4	2.0	4.6	7.0	9.8	9
Zr	144	262	270	177	374	825	1900	1410	1910	2230
Nb	33	44	41	35	51	84	291	228	261	393
Y	22	32	28	21	37	35	213	93	125	204
La	25	38	34	29	48	66	374	147	298	332
Ce	54	86	76	62	108	145	630	285	412	336
Nd	26	47	39	na	55	63	330	na	230	na
Sc	20	14	17	13	14	8	0.1	nd	nd	nd
V	167	102	131	93	86	106	nd	nd	nd	nd
Cr	253	64	29	90	4	2	2	2	nd	1
Ni	183	57	36	54	2	3	nd	nd	nd	nd
Cu	54	37	26	33	14	10	7	9	8	nd
Zn	96	134	131	86	145	118	600	284	370	434
Ga	20	22	23	22	27	29	68	43	46	51
Sb	nd	nd	nd	na	nd	0.3	0.8	na	0.7	na
Hf	nd	5.2	5.4	na	nd	18.5	48	na	44.0	na
Ta	1.9	2.6	2.7	na	3.0	5.6	18	na	15.0	na
Cs	0.2	0.7	0.5	na	0.7	nd	4.6	na	1.9	na

nd - not detected   na - not analysed

many mafic trachytes. It shows considerable variation in composition, especially with respect to Ti which varies antipathetically with Fe through Ti-poor aenigamtie and Ti-rich wilkinsonite to pure end-member wilkinsonite ($Na_2Fe^{2+}{}_4Fe^{3+}{}_2Si_6O_{20}$). Mount Bingie Grumble, on the southeastern flanks of the volcano, is the type locality for wilkinsonite (Duggan, 1990). The variation in Ti in aenigmatite-wilkinsonite solid solutions is clearly a function of host rock composition. Ti approaches the theoretical one atom per formula unit (ca. 9 wt % TiO_2) in quartz-bearing trachytes with significant TiO_2 but decreases significantly in response to lower TiO_2 and lower levels of silica saturation in the host rock so that in exceptional cases Ti is very low or even totally absent. Solid solution between aenigmatite and wilkinsonite represents the coupled substitution $2Fe^{3+} = Fe^{2+}Ti$. A full discussion of the relationships between Ti contents of wilkinsonite and aenigmatite and host-rock chemistry (Ti-content, silica activity, peralkalinity and oxygen fugacity) is given in Duggan (1990). A further notable feature of some aenigmatites and wilkinsonites is their 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.

NANDEWAR VOLCANO

There have been two major studies on the Nandewar volcano; by Abbott (1965, 1967a,b, 1969) and Stolz (1983, 1985, 1986). They recognised that the volcano consists of a suite of transitional alkaline rocks ranging in composition from mildly *hy*-normative hawaiite, K-hawaiite, and K-mugearite, through trachyte to alkali rhyolite and comendite, and Stolz (1985) concluded that most of the mafic rocks were derived from a common upper-mantle source with specific major and trace element characteristics.

Rock Types and Distribution

The products of the Nandewar volcano cover an area of about 800 km^2 and crop out in a belt 50 km long and up to 30 km wide, approximately 125 km northeast of the Warrumbungle volcano. The present day maximum thickness of these products is estimated to be 800 metres, although the original thickness would have been considerably greater. Both magnetic and Bouguer gravity anomaly data indicate that the Nandewar volcano rests on a basement high caused by the emplacement of a central intrusive complex (Wellman, 1986).

The rhyolite magmatism appears to fall into two distinct episodes. The older and more voluminous alkali rhyolites are slightly porphyritic with anorthoclase and sanidine phenocrysts totalling up to 15%. These rhyolites form domes and flows which were apparently extruded along a linear north-northwest fracture in the central part of the volcano. Some are vesicular and have associated breccias suggesting they were extruded, possibly as large exogenous domes, during the early stages of volcanism. They were emplaced onto an irregular basement of Palaeozoic sedimentary and volcanic rocks on the eastern side, and onto Mesozoic sedimentary rocks on the western side of the Nandewar volcano. Several of the rhyolitic domes in the region between Killarney Gap and Mount Kaputar display concentric banding, and others show a strong NNW-SSE lineation. These features are interpreted to reflect the viscous flow of magma through restricted conduits and fissures respectively (Stolz, 1986). In the vicinity of Mount Lindesay the rhyolites are up to 600 m thick and occupy much of the central area of the volcano where they have been exposed by erosion of the main shield-forming lavas. A peralkaline plug dated at 18 Ma, intrudes these older rhyolites 5 km northeast of Killarney Gap. This age, together with a age of 17 Ma determined for an alkali rhyolite from the northern part of the volcano, indicates that these younger alkali rhyolites where emplaced during the main shield-forming episode. The younger group of rhyolitic rocks includes mildly peralkaline, metaluminous and peraluminous varieties of limited volumetric extent. Sanidine or anorthoclase are the only phenocryst phases in all rhyolitic types.

The oldest dated rocks of the Nandewar volcano include a 21 Ma trachyte flow which overlies a teschenite sill north of Killarney Gap. This trachyte forms a prominent bluff and is capped by K-hawaiite and intruded by a small peralkaline-rhyolite plug.

The main shield-forming lavas range in composition from hawaiite, K-hawaiite and K-mugearite, to trachyte and peralkaline rhyolite. They appear to have been erupted from a central vent in the vicinity of Mount Lindesay, as flow boundaries and pyroclastic horizons dip radially away from this area at about 5-10°. There is also a small, high-level monzonitic intrusion and many small dykes ranging in composition from K-hawaiite to rhyolite, suggesting a concentration of intrusive magmatic activity, and the area possibly being a feeder zone for the volcanic rocks. Relative proportions of the main rock types are: older rhyolites and trachytes ~ 24%; hawaiite, K-hawaiite, and K-mugearite ~ 70%; mafic and peralkaline trachyte ~5%; and rhyolite and peralkaline rhyolite ~ 2%.

The main shield-forming lavas were erupted over a relatively short time interval from 18 to 17 Ma (Stipp & McDougall, 1968; Wellman & others, 1969; Wellman & McDougall, 1974b), with the earliest being hawaiite, followed by K-hawaiite, K-mugearite, trachyte, peralkaline rhyolite, and then more K-mugearite and trachyte. Flow thickness ranges from 2 to 20 m - mafic flows are relatively thin (2-10 m) and the trachyte flow units are commonly the thickest (10-20 m). Several of the more massive flows crop out laterally for 6-8 km as prominent bluffs on the southern flank of the volcano. Trachyte is relatively scarce in the northern areas of the volcano relative to the southern areas.

Pyroclastic rocks intercalated with flows are relatively abundant in the southern part of the volcano. The tuffs are typically weathered, and when associated with hawaiite, K-hawaiite and K-mugearite, consist of highly vesicular lapilli-sized fragments of nearby lavas, crystal debris and ash. Pyroclastics associated with trachyte typically are agglomeratic, consisting of ejected blocks up to 1 m in diameter, ranging in composition from K-hawaiite to rhyolite, and set in a matrix of smaller clasts, lapilli-sized fragments and ash (Stolz, 1989).

High-level alkaline and peralkaline trachyte ring dykes, dykes, and plugs have intruded both the volcanic pile and basement rocks possibly during the waning stages of eruption of the main shield-forming lavas. Ages of about 17 Ma (Stipp & McDougall, 1968) were determined for peralkaline trachytes intruding basement rocks 10 km west and 12 km southwest of Mount Kaputar. Rocks of similar composition form ring dykes (Mount Yulladunida) and plug-like intrusives (Mount Kaputar) into the main shield-forming lavas, and must be of comparable age or slightly younger and to have cooled and crystallised under very shallow cover. These trachytic intrusives are largely confined to the southern part of the Nandewar volcano, and contrast with the major occurrence of the younger group of alkali rhyolite and comendite extrusives and intrusives in the northern area.

The younger alkaline and peralkaline rhyolites also form high-level ring dykes, dykes and plugs intruding the volcanic pile, one of which has been dated at 18 Ma. This, plus an age of 17 Ma for an alkali rhyolite in the northern area of the volcano (Stipp & McDougall, 1968), indicates that these felsic rocks were emplaced during the main shield-forming episode. Alignment of several small comendite intrusions along a NNW-SSE trend in the eastern part of the complex suggests a strong structural control. The younger alkali rhyolites are typically more leucocratic than the peralkaline rhyolites, and their commonly vesicular character suggests that, in general, they were probably extruded as exogenous domes.

Geochemistry

The mafic rocks of Nandewar volcano are mostly transitional hawaiite or K-rich hawaiite and there is a continuum of compositions from hawaiite, mugearite, through to rhyolite. Representative analyses are given in Table 2. Mafic rock types include both sodic and moderately potassic ($K_2O/Na_2O < 0.5$) types, although the more felsic rocks are all moderately potassic. Mg-ratios are mostly less than 60, but range up to 65. Plotted on the 'basalt tetrahedron' (Yoder & Tilley, 1962) the Nandewar mafic rocks straddle the critical plane of silica undersaturation, illustrating their transitional character (Coombs, 1963). The more salic rocks are *qz*-normative and there is an absence of *ne*-normative types. Major and minor element trends on variation diagrams are relatively smooth, curved and continuous except for a significant break at F.I. 53-65, which broadly coincides with the so-called 'Daly Gap' delineated by Chayes (1963). Zr contents increase dramatically from hawaiite through to comendite (155 to 1245 ppm).

The more mafic rocks have relatively flat and considerably enriched REE abundances with negligible change in LREE/HREE ratios. REE abundances in the trachytes are highly variable; two are depleted in LREE compared with the more mafic rocks, whereas others are enriched. The first evidence of Eu depletion is in the peralkaline trachytes. Most rhyolites are enriched in HREE relative to the more mafic rock types, whereas LREE enrichment is much more variable. All rhyolites are characterised by negative Eu anomalies (Stolz, 1985).

Mineralogy

In a detailed study of the mineralogy of the Nandewar volcano, Stolz (1986) found that olivine, pyroxene, amphibole, and feldspar compositions varied systematically and continuously throughout the suite as functions of the host-rock compositions. He concluded that tschermakitic subcalcic pyroxene and aluminous bronzite phenocrysts, and possibly also some titanomagnetite and plagioclase phenocrysts, in some K-hawaiites crystallised from their host melts at about

Table 3. *Analyses of rocks from the Nandewar volcano*

	Hawaiite	K-Hawaiite	K-Mugearite	Mafic Trachyte	Peralk.-Trachyte	Comendite	Alkali Rhyolite*	Alkali Rhyolite
SiO_2	49.99	50.99	57.46	61.51	67.05	72.82	65.76	74.55
TiO_2	2.65	2.30	1.00	0.75	0.38	0.14	0.40	0.27
Al_2O_3	14.55	15.92	17.46	16.98	14.56	12.95	15.52	13.82
Fe_2O_3	1.77	4.04	3.49	2.21	3.64	2.35	5.09	0.87
FeO	8.90	6.56	2.85	3.17	1.58	0.85	0.10	0.20
MnO	0.13	0.14	0.90	0.15	0.09	0.03	0.11	0.01
MgO	8.18	3.27	1.30	0.28	0.03	0.03	0.07	0.01
CaO	8.97	6.54	3.14	1.71	0.31	0.19	0.38	0.12
Na_2O	2.80	4.47	5.16	5.38	6.51	5.32	5.77	4.82
K_2O	1.43	2.49	4.75	5.56	5.04	4.37	5.41	5.10
P_2O_5	0.47	1.24	0.60	0.28	0.04	0.02	0.03	0.02
H_2O+	2.03	0.94	1.23	0.52	0.19	0.27	0.68	0.16
H_2O-	0.83	1.06	1.08	0.61	0.47	0.47	0.36	0.24
Total	99.70	99.96	99.61	99.34	99.89	99.81	99.70	100.19
Mg No	62.1	40.3	35.9	12.3	-	-	-	-
an/ab+an	49.2	29.8	19.3	11.2	-	-	-	-
Trace Elements ppm								
Li	8	11	8	6	26	53	13	11
Sc	-	12	10	12	-	0.37	4.60	1.20
V	205	120	17	16	n.d.	n.d.	3	n.d.
Cr	176	1	6	3	2	2	2	2
Ni	120	n.d.	11	n.d.	n.d.	12	4	5
Cu	50	18	7	10	8	7	7	2
Zn	95	130	115	125	130	260	135	62
Rb	26	49	54	81	156	294	130	190
Sr	659	755	399	189	n.d.	2	8	n.d.
Y	20	37	22	36	35	130	63	73
Zr	178	293	308	367	833	1245	785	870
Nb	44	72	38	63	179	282	132	163
Cs	-	n.d.	1.06	0.92	-	1.42	0.60	2.06
Ba	297	591	879	953	n.d	4	298	4
La	33	55	49	49	105	48	92	41
Ce	63	117	99	93	172	103	154	72
Nd	32	60	50	30	76	59	72	27
Sm	-	11.8	9.7	5.9	-	14.5	14.5	4.4
Eu	-	3.3	3.5	2.7	-	0.18	1.2	0.30
Tb	-	1.3	0.82	0.96	-	3.7	0.82	0.65
Yb	-	2.6	2.0	2.7	-	9.7	5.5	6.4
Lu	-	0.36	0.33	0.41	-	1.56	0.82	0.93
Hf	-	5.7	4.9	6.3	-	29.1	11.9	16.5
Ta	-	3.9	2.7	3.9	-	18.8	7.1	9.5
Pb	4	6	7	11	19	17	17	29
Th	2.0	5.5	4.3	7.8	18	35	16	19
U	-	1.0	1.5	2.3	-	5.9	4.3	7.5
K/Rb	457	422	730	570	268	123	346	223

* - denotes member of older rhyolite group   n.d - not detected

6-8 kbar. The voluminous older rhyolites appear to have undergone pervasive oxidation during eruption. Relatively low fO_2 conditions appear to have favoured coprecipitation of arfvedsonite $\pm$ aenigmatite in peralkaline melts, whereas higher fO_2 conditions appear to have favoured crystallisation of Na-rich pyroxene only.

Olivine composition ranges from Fo_{88} in the K-hawaiites to Fo_{10} in trachytes. Phenocrysts and microphenocrysts are common in the hawaiites and K-hawaiites, less common in K-mugearites and trachytes and absent in rhyolites. Fayalite in some peralkaline trachytes is rimmed by clinopyroxene similar in composition to groundmass clinopyroxene, suggesting that the early-crystallising olivine was in reaction with the liquid (Stolz, 1986).

Pyroxene occurs as three main types: (1) as Ca-rich and Ca-poor partially resorbed megacrysts of inferred high-pressure origin; (2) as low-pressure Ca-rich pyroxene phenocrysts; (3) as groundmass pyroxenes which range in composition from Ca-rich to acmitic types. Al contents of clinopyroxene megacrysts typically are higher than those of low-pressure Ca-rich pyroxenes, although some groundmass pyroxenes have Al contents similar to that in megacrysts. The Ca-rich pyroxene phenocrysts are generally less abundant than olivine phenocrysts in the hawaiites, and are subordinate to plagioclase and anorthoclase phenocryts in K-hawaiites and trachytes. Ca-rich groundmass pyroxenes are replaced by Na-rich pyroxenes in peralkaline trachytes and comendites.

Amphiboles occur as groundmass minerals in the K-hawaiites through to comendites, and range in composition from sodic-calcic to sodic. Na contents increase as Ca and Al contents decrease in the transition from edenite in the mafic rocks through to arfvedsonite in the peralkaline rocks.

Fe-Ti oxides. Titanomagnetite is the dominant Fe-Ti oxide phase throughout the compositional range of the Nandewar volcanic rocks, although ilmenite occurs occassionally as groundmass, and rarely as microphenocrysts, in hawaiite through to trachyte. Titanomagnetite phenocrysts in some K-hawaiites may be moderate pressure cognate precipitates. They are characterised by higher Mg, Al, Cr and V than the groundmass spinels.

Aenigmatite occurs in the groundmass of the peralkaline trachytes and comendites and occasionally rims titanomagnetite and ilmenite microphenocrysts. TiO_2 varies from 7.33 to 8.57 weight percent.

Feldspars. Plagioclase phenocrysts are subordinate to olivine in the hawaiites, but are dominant over olivine and clinopyroxene in the K-hawaiites and K-mugearites. Reversed-zoned plagioclase phenocrysts coexist with aluminous clinopyroxene and orthopyroxene megacrysts, suggesting they also represent moderate-pressure precipitates.

Anorthoclase and sanidine become important in the trachyte through to comendite range. A concentration of compositions between Or_{34} and Or_{42} corresponds broadly with the minimum in the Ab-Or series (Tuttle & Bowen, 1958)

Petrogenesis

The following 'Conclusions' are quoted from the paper *The role of fractional crystallisation in the evolution of the Nandewar Volcano, north-eastern New South Wales, Australia,* Stolz (1985):

"Major, minor and trace element isotopic data indicate that the moderately potassic members of the Nandewar suite were derived from a common upper mantle source with specific trace element and isotopic characteristics. Mass balance calculations cast doubt on the efficacy of a genetic model for the more 'evolved' members based on closed-system fractional crystallisation. Mass-balance constraints are especially evident for the hawaiites-trachyandesites [K-hawaiites] and peralkaline trachytes-comendites whose compositions cannot be bridged by reasonable crystal extracts based on observed phenocryst assemblages. Genesis of the hawaiites and trachyandesites [K-hawaiites] by differential partial fusion of discrete relatively Fe-rich lherzolitic sources with variable modal pargasitic amphibole ($\pm$ mica) and apatite might provide an alternative explanation, but as yet is unsupported by experimental data and the occurrence of 'pristine' Fe-rich lherzolites in the upper mantle xenolith suites. Mass balance calculations are consistent with the production of tristanites [K-mugearites] and trachytes by fractional crystallisation of the most evolved trachyandesites [K-hawaiites] but there is scant evidence of complementary crystal extracts. Although the trachytes and comendites may be related by some form of liquid-state differentiation process such as thermo-gravitational diffusion, it is difficult to evaluate the control in even a semi-quantitative manner. Late-stage volatile loss has significantly modified some rhyolitic compositions and volatile enrichment may be responsible for the highly irregular trace element contents evident in several comendites.

If the conclusion that closed-system fractional crystallisation does not provide a satisfactory explanation for the genesis of the entire Nandewar suite is accepted, the vexing problem of suitable alternative controls still remains. Further studies of similar suites aimed at quantifying in more detail postulated parent-daughter relationships are clearly required and should either reinforce or weaken the now widely-held view that crystal fractionation is the dominant control in generating melt compositions more 'evolved' than basalt."

THE TWEED VOLCANO

Introduction

Despite its age (20.5 - 23.5 Ma), the Tweed volcano is still recognisable as a volcanic shield. Mount Warning, 14 km southwest of Murwillumbah (N.S.W.), is a prominent peak (1156 m) at the centre of the Tweed Volcano, composed of trachyandesite and surrounded by plutonic rocks. The mountain mass is isolated from the remaining parts of the volcanic shield by a deep erosion caldera, which exposes the underlying Palaeozoic and Mesozoic rocks. To the north, west and south of Mount Warning, precipitous cliffs, largely of basaltic lava flows with interlayered rhyolites, border the erosion caldera. The rim of the caldera is highest in the north, where there is a maximum thickness of about 1000 m for the lava flows.

From the caldera rim, the surface of the Tweed volcano gradually decreases in all directions away from Mount Warning at slope angles between 1 and 3°. Much of the eastern part of the volcano has been removed by erosion, but basaltic remnants crop out on the coast at several places (Burleigh, Tweed Heads, Fingal Point) and are known to exist below present sea level. Basalts presumed to have been erupted from the vicinity of Mount Warning extend for distances of up to 50 km to beyond Canungra to the north and Lismore to the south.

The intrusive complex of Mount Warning has been studied by Paterson (1970), Smart (1970), and Gould (1970), mostly east of the summit, and by Bruce (1978) who worked on the southern slopes. These studies are summarised in Ewart & others (1987). Work on areas near Springbrook (Watt, 1971) and Binna Burra (Uttley, 1972) provided new details for the higher rhyolitic formations at these localities and added to the known occurrences of the tholeiitic andesite and dacitic lavas, and to data on the chemical differences within the basalts. Mapping in the Kyogle district N.S.W. was described by Duggan (1975) and Duggan and Mason, (1978). The geochemistry of the Tertiary lavas is discussed by Ewart, Oversby and Mateen (1977), dealing specifically with the northern part of the shield, while papers by Ewart (1981, 1982) deal with the more general geochemistry of southeast Queensland Tertiary volcanics. Overviews are given also in Johnson & others(1989).

Tweed Volcano - Volcanic Formations

Beechmont Basalts: These represent the earliest basalts of the Tweed volcano, on the northern side, forming the Beechmont Plateau. The upper limit of the formation is marked by the Binna Burra Rhyolite, but where this is absent, the Beechmont Basalt is difficult to distinguish from the overlying basalts. On the west side of the erosion caldera, west of Mount Warning, there is an apparently unbroken basaltic succession over 1000 m thick.

The best described succession in the Beechmont Basalt is located along Flying Fox Creek, Canungra, and in the Mount Tamborine area to the north (Green, 1964) where 15 to 25 flows have been recognised. Of five units mapped at Mount Tamborine, two, the Eagle Heights Member near the top and the Cameron Falls Member near the base, are thick flows (24 m and 20 m respectively), distinctive physiographically as cliff-forming lavas, and mineralogically, the former because of its large plagioclase phenocrysts, and the latter for its secondary minerals. Thin sedimentary beds, largely shales and diatomite, are intercalated in the lowermost flow units on Mount Tamborine, and also near Beechmont. Except at the base of the succession, where dips may be locally up to 25° in basalt flows which filled irregular depressions, the general dip of the formation is northerly at a shallow angle (~3°).

Lismore Basalt: On the south side of the Tweed volcano, the Lismore Basalt correlates with the Beechmont Basalt and similarly overlies earlier Tertiary volcanics from other sources. The Lismore Basalt forms the underlying unit over wide areas of low relief between Lismore, Ballina and Coraki. Much of the upper part of the succession in this area has been removed by erosion. Like the Beechmont Basalt, the Lismore Basalt is predominantly tholeiitic, with occasional alkaline types; flows rarely exceed 10 m in thickness. Some examples of ropy surfaces indicate pahoehoe lavas, while other occurrences suggest aa types. The source of these lavas is not definitely known, but presumably came mainly from the direction of the Mount Warning Central Complex.

Binna Burra Rhyolite: This formation, which outcrops on the northern side of the border in the Lamington National Park, consists of thick rhyolite flows with conspicuous tuffs at the base of the succession, and also locally, at the top of the formation (e.g. White (Talangai) caves area).

In the type area near Binna Burra, there are at least five individual rhyolite flows, each up to 100 m thick. Both upper and lower surfaces of the flows are usually glassy. The upper selvedges (2-10 m) are perlite, usually with obsidian cores. The lower selvedges consists of glassy auto-breccias or agglomerates, and pumiceous agglomerates, usually perlitic. Flow layers and flow folding are well developed, as are spherulitic structures near the base of flows (e.g. Koolanbilba Cave).

Bryan (1941, 1954) studied these spherulitic structures and proposed the name 'spheruloid' for spheroidal bodies in the rhyolite, which differ from spherulites by the lack of a radial structure. He distinguished four groups of spheruloids, each group 'restricted to one particular flow': (1) Small spheruloids, up to 2.4 cm diameter, with a smooth glossy surface, occurring as clusters along particular fluxion planes which penetrate them. (2) Large spheruloids, up to 30 cm, spherical, hollow, in a groundmass of perlitic glass. (3) Mostly irregular, roughly ellipsoidal, more closely-spaced and numerous than in (2), non-cavernous, loose textured, each with a distinct crust. Growth and amalgamation of spheruloids were figured. (4) Large spheruloids, closely packed in black glass, dense or cavernous or loose textured.

The rhyolite flows are underlain by tuff beds, ranging from 20 to 120 m in thickness, and forming steep, smooth, convex cliffs. The tuffs are almost all of ash-fall type, in which graded bedding is common and is especially well seen by grading in basaltic fragments, ranging from boulders to lapilli. Rhyolite, rhyolite glass, and sandstone boulders also occur. Marked disconformities are present in the tuffs in the Kurraragin Valley, indicating contemporaneous stream erosion (Uttley, 1972).

Tuffs on either side of the Coomera River Valley are underlain by an ash flow deposit up to 10 m thick. Carbonised tree trunks and branches occur in the basal part of the deposit. Assuming that the orientation of the logs is perpendicular to the flow direction, the latter has been determined as along the valley, in a direction slightly west of north. The ash flow deposit is massive, vertically jointed, has uniform lithology and overlies basalt. It does not show cores of strong welding, devitrification or eutaxitic structures.

On the western side of Mount Roberts, near Binna Burra, up to 70 m of tuff lies disconformably on southerly-dipping rhyolite, on agglomerate and tuff horizons, and also on Beechmont Basalt. The lower rhyolite flow is thought to have terminated here against a hill of Beechmont Basalt.

The best exposures of the localised upper tuff horizons are at White Caves and along the track to the Swimming Pool. It is a well bedded ash-fall tuff with thin bands of lapilli. The lower part lacks drape structures and is thought to be a lacustrine deposit; it grades upwards into beds of possible aeolian origin (Uttley, 1972). The lowest 3 m of the upper tuff contains large angular boulders of fragmented rhyolite and dark glass. It is underlain by a thin layer of dense welded ash (1 m) and this in turn is underlain by boulder agglomerate, which is thickest at Kweebani Cave. The agglomerate is here intruded by rhyolite glass, suggesting that this is a cross-section of a vent.

On the same stratigraphic level as the Binna Burra Rhyolite, but farther to the southeast, a flow of dacite, approximately 20 m thick with a glassy upper margin, is associated with a glass boulder tuff about 10 m thick. It is best exposed at Bushrangers Cave, located on the caldera wall. This flow is of interest as it shows evidence for partial mixing between rhyolitic and basaltic magmas.

On the western slope of the Springbrook Plateau, basalt is intercalated between two major rhyolitic flow units, each about 100 m in thickness. The upper rhyolite is topographically higher than the rhyolitic sequence at Binna Burra and may be slightly younger; the name Springbrook Rhyolite, is used. This is mineralogically and chemically distinct from the Binna Burra Rhyolite.

Nimbin Rhyolite: This is described by Duggan and Mason (1978). The Nimbin Rhyolite is the counterpart of the Binna Burra Rhyolite on the south side of Mount Warning, occupying a similar area (estimated at 400 km^2), and with a maximum thickness of 500 m. The flows, which are of both porphyritic and aphyric rhyolite, vary in thickness from 50 m to 150 m, and are interstratified with rhyolite tuffs and agglomerates in beds up to 20 m thick. Although individual flows may have a considerable lateral extent with little change in thickness, there are instances of rapid thinning. The base of most flows is composed of pitchstone with little devitrification. Pyroclastics show evidence of fluvial reworking and include blocks of rhyolite, tholeiitic volcanics, and sedimentary material. Some basaltic flows are intercalated with the rhyolites. A rhyodacite 3 km ESE of Nimbin is included in the formation.

The source of the rhyolite flows seems to be from the north, where thickening is marked and where several small intrusive plugs occur (e.g. Doughboy Mountain).

Hobwee Basalt: The highest basaltic formation on the north side of Mount Warning, termed the Hobwee Basalt, comprises a maximum of nearly 600 m of basalt which overlies the Binna Burra Rhyolite formation. At least twenty flows can be counted in the cliffs close to Mount Hobwee indicating an average of 30 m for each flow. The flows of the lower part of the Hobwee Basalt are similar to those of the upper part of the Beechmont, in being plagioclase phyric, whereas earlier flows (of the lower part of the Beechmont Basalt) are less porphyritic and later flows (of the upper part of the Hobwee Basalt) are more strongly porphyritic in plagioclase and olivine.

Basaltic rocks with large, closely-packed plagioclase phenocrysts, presumably a lava flow belonging to the Hobwee Basalt, occur on the road to O'Reilly at about 550 m, and at higher elevations on the Duck Creek Road and near O'Reilly's guest house. A similar lithology has been quarried much farther east near the Antarctic Beech stand in Wiangaree National Park (south of the State border) at 920 m.

Watt (1971) has recorded basaltic pyroclasts above the Springbrook Rhyolite, and Uttley (1972) notes two horizons of similar rocks, presumably in the lower part of the Hobwee Basalt at 800 m and 600 m in the Beechmont and Sarabah Ranges, respectively.

Blue Knob Basalt: On the south side of Mount Warning, this basaltic formation is the highest stratigraphically, and forms cappings on many higher areas near Nimbin. Like the Hobwee Basalt, it was probably erupted long enough after the rhyolites to occupy depressions in a highly irregular land surface. The maximum thickness of about 350 m is attained at Blue Knob, where the basalt lies on petrologically similar Lismore Basalt.

Mount Warning Central Complex

This igneous complex occurs at the centre of the Tweed volcano and forms a prominent peak which is surrounded by lowlands of the erosion caldera and farther out by the cliffs of the caldera rim. It is situated on a steeply dipping unconformable junction between the folded and metamorphosed Carboniferous Neranleigh-Fernvale beds and west-dipping Triassic strata (including Chillingham Volcanics at the base) which at this point changes from almost north-south (north of Mount Warning) to NNW.-SSE. on the south side of Mount Warning. The bend may, in part, result from the intrusion of the igneous mass on the Mesozoic strata.

Mount Warning (Fig. 5) represents the eroded remains of a large magma chamber system. The overall shape of the igneous complex (excluding Mount Nullum) is nearly circular with a maximum east-west diameter of nearly 8 km, and a north-south diameter of 6 km. Gabbroic rocks form a complete belt of variable width surrounding a central mass of syenite, which in turn encloses a core of trachyandesite forming the summit of Mount Warning. The gabbros extend to the outer margin of the complex, except where intruded marginally by a predominantly syenitic ring dyke at the western margin, and a monzonite intrusion at the eastern margin. The ring dyke has been emplaced as a prominent, although discontinuous intrusion.

The gabbros constitute the oldest exposed rocks of the complex. Two main series of gabbros are recognised in the eastern and southern portions of the complex, evidently separated by the ring dyke. The sequence of intrusion, based on currently available field data, is inferred to be:

Early gabbros, laminated gabbros, monzonite, central syenite, trachyandesite, tholeiitic andesite dyke-sill phase (S. area), multistage ring dyke, and comendite dykes (youngest).

A contact metamorphic aureole is present in the Palaeozoic country rocks along the eastern margin of the complex, some 1.5 km wide. The highest grade attained is hornblende hornfels facies.

Two K/Ar dates are available, one from a laminated gabbro giving an age of 22.9-23.7 Ma (Webb, Stevens and McDougall, 1967, corrected to constants of Steiger and Jager, 1977). The second, based on a whole rock trachyandesite sample, gives an age of 23.4 Ma (D.C. Green, pers. comm.). Both ages suggest the Mount Warning igneous complex to be slightly older than the surrounding volcanic shield sequence (the Hobwee and Beechmont Basalt formations, and the Binna Burra and Springbrook Rhyolites) which have been dated at 20.5-23.5 Ma.

As the Mount Warning complex is at the eroded geographic centre of the volcano, it has been naturally interpreted as the eruptive centre. The K/Ar dates, however, suggest that the presently exposed igneous rocks of the Mount Warning complex do not represent the primary magma chamber from which the lavas were erupted, a conclusion in accord with the petrology and chemistry of the lavas (Ewart & others, 1977).

To the east of Mount Warning occurs a second intrusive complex, the Mount Nullum Complex (Gould, 1970), comprising fine-grained granite, granite and monzonite. This intrusion is interpreted, on field evidence alone, to be Tertiary.

The Gabbros - 1: Older Series: These are recognised in both the outer eastern part of the complex and the southern part, comprising a series of petrographically distinct gabbro types which do not, however, form clearly defined zones or bands in the field.

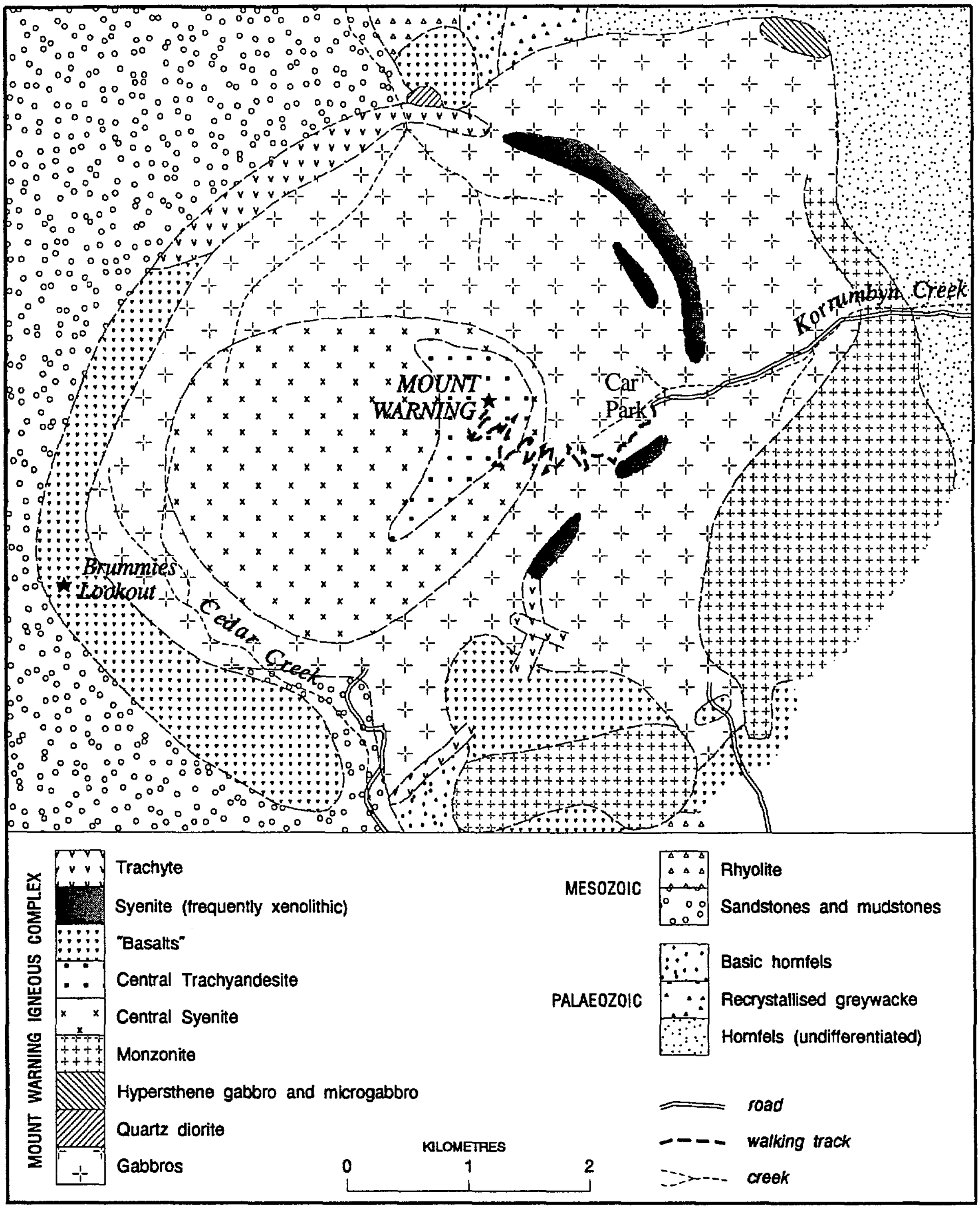

Figure 5. Geological map of the Mount Warning Central Intrusive Complex. Geology after Solomon (1956), Smart (1970), Paterson (1970) and Bruce (1977).

The main gabbro types recognised here are the so-called normal coarse-grained gabbros and microgabbros. These two textural varieties are intimately associated in the field, and field observations indicate that the microgabbro phase predates the coarser phase, but it is nevertheless considered that both types represent part of a single intrusive phase. There is wide variation in texture and mineral proportions within these gabbros. The mineralogy is typically andesine-labradorite, augite (with fine exsolution lamellae), inverted pigeonite, orthopyroxene, olivine, titanomagnetite, biotite, and accessory apatite and titanite, and sometimes minor amounts of interstitial quartz.

Leucogabbro is recognised as a second variant, found as xenoliths in the ring dyke, in the monzonite, and as discontinuous outcrops (presumably xenoliths) within the younger gabbro series. It is characterised by relatively coarse grain size and cumulate textures; mineralogically, it is dominated by plagioclase and augite, with accessory olivine, orthopyroxene, biotite, magnetite, potash feldspar, and quartz. This gabbro is presumed to represent the original intrusive phase.

Andesine gabbro is recognised as an additional although localised intrusive phase situated close to the margin of older and younger gabbro series, being exposed inside and immediately adjacent to the eastern segment of the ring dyke, and could possibly represent a marginal phase of the younger gabbro core. Mineralogically, it contains andesine, augite, bronzite, olivine, magnetite, and relatively abundant biotite, with accessory apatite.

At the topographically highest parts of the outer eastern part of the complex, these older gabbros are overlain by laminated gabbros belonging to the younger gabbro series.

Within the southern (Cedar Creek) area of the complex, the normal coarse-grained gabbro constitutes the dominant type, and is exposed in a 400-500 m wide zone surrounding the central syenite; a foliation (due to alignment of feldspars) is present which dips towards the centre of the Mount Warning complex at 20-30°. Syenitic veins cut the gabbro, both as linear veins and earlier irregular networks of stringers, the latter apparently injected before complete solidification of the gabbro. Petrographically, these gabbros consist of plagioclase, augite, Fe-Ti oxides, minor olivine, biotite, and uralite (interpreted to be predominantly after orthopyroxene, which is absent as an unaltered phase in these rocks).

2: Younger Series: These outcrop at the higher elevations of the gabbro outcrops, within the ring dyke. A wide variation of petrographic types is again found, including normal gabbro (plagioclase + augite + accessory olivine + Fe-Ti oxides), olivine gabbro (essential plagioclase + augite + olivine), ferrigabbro (essential plagioclase + augite + Fe-Ti oxides), troctolite (essential plagioclase + olivine), leucogabbro (essential plagioclase + uralite), and layered gabbros. These various types may occur in varying combinations even in the same outcrop, and are intruded by numerous dykes, including the ring dykes, composed of syenite and rhyolites.

The younger gabbros consistently exhibit a well defined lamination, due to preferred orientation of plagioclase, pyroxene, and biotite. These laminated gabbros overlie the older gabbro series in both the eastern and southern parts of the complex. The lamination dips inwards towards the core of the complex, with dips mostly <25° (up to 50° just inside the ring dyke) in the eastern part, and up to 45° in the southern area, thus defining an overall saucer-like structure. True layered gabbros appear to be confined to the topographically highest parts of the gabbro body; their structure again conforms to saucer-shaped, although local, small scale 'cross-bedding' and 'slump' structures are found in these layered gabbros in the eastern area. Isolated outcrops of leucogabbro occur sporadically throughout the younger gabbros, and evidently represent xenoliths of the older gabbro phases, in some cases exceeding 30 m in diameter.

The principal minerals of the younger gabbros are plagioclase, augite, olivine, Fe-Ti oxides, orthopyroxene, uralite (after orthopyroxene), biotite, hornblende, apatite, and interstitial potash feldspar and quartz. Cumulate textures are developed. The leucogabbros are rather coarse grained, with large randomly oriented plagioclase laths (up to 2 cm) and uralitized, poikilitic pyroxenes; felsic veins commonly cut these leucogabbros, and contain andesine, potash feldspar, biotite, green fibrous amphibole, and secondary chlorite, calcite, and epidote. Olivine occurring within the gabbros frequently exhibits marginal zones enriched in minute magnetite granules, and reaction rims of orthopyroxene are also found. Orthopyroxene also occurs, however, as discrete subhedral crystals in virtually all gabbros examined. Of petrographic interest in these gabbros is the persistent presence of biotite. Rare hornblende occurs as reaction rims on some titanomagnetites and pyroxenes.

Monzonite: The monzonite extends irregularly, in a lensoid form, around the eastern and southern rims of the complex, having been intruded between the gabbro and the hornfels country rocks. Its outcrops form the high peaks of Mount Uki, presumably The Sisters, through to Cedar Creek. No lineation or banding is recognised within the monzonite, and the overall grain size tends to remain almost constant. Three sets of joint patterns are extremely well developed, one subhorizontal, and two very steeply dipping. The monzonite is cut by numerous felsic veins (potash feldspar, quartz, altered augite, and Fe-Ti oxides). Slight displacement of these veins along joints is consistent with upward movement beneath Mount Warning (Paterson, 1970). Thin veinlets of monzonite penetrate the gabbro at the contact. The numerous xenoliths in the monzonite can be divided into four groups: leucogabbros (up to 200 m long), fine grained gabbros (near the gabbro contact, up to 50 cm across), hornfelsed gabbro, and hornfelsed country rock.

Petrographically, the monzonite is rather variable in terms of its textures and mineral proportions. When fresh, it is a dark grey to blue grey, massive rock. Two dominant types can be distinguished, normal quartz monzonite, and fayalite-quartz monzonite, which cannot, however be distinguished in the field. The fayalitic variety contains relatively higher proportions of plagioclase and total mafics, and occurs adjacent to the gabbro contact. The minerals present are plagioclase (oligoclase-andesine), potash feldspar (microperthitic, forming mantles around plagioclase as well as discrete crystals), interstitial quartz, augite, hornblende, apatite, magnetite, ilmenite, and biotite, fayalitic olivine, and micrographic intergrowths. Uralitization of the pyroxene is commonly developed.

Central Syenite: This unit forms a concentric band of variable width surrounding the trachyandesite core, the contacts between these units being steeply dipping. The central syenite is, in turn, completely surrounded by the gabbros which the syenite clearly intrudes. Within the southern part of the complex, four types of syenite are recognised:

(a) Marginal peralkaline syenite, consisting of a relatively mafic phase which intrudes and interfingers with the normal syenite, the latter becoming locally relatively coarse grained in proximity to the marginal phase. Petrographically, the peralkaline syenite contains alkali feldspar (microperthitic), sodic pyroxene (with cores of calcic compositions), sodic amphibole, quartz, aenigmatite, fayalitic olivine pseudomorphs, and Fe-Ti oxides.

(b) Normal syenite, a medium to coarse grained, somewhat porphyritic rock, which forms the main mass of the syenite intrusion. Petrographically, it contains subhedral phenocrysts of alkali feldspar and minor plagioclase (rimmed by alkali feldspar), up to 1.5 cm in length, in a coarse matrix of alkali feldspar, clinopyroxene, olivine, Fe-Ti oxides, and uralitic alteration products.

(c) and (d) Non-peralkaline and peralkaline dykes, both of which cut the normal syenite in the southern part of the syenite massif. In addition, post-syenite dykes are recognised in this same region, consisting of agglomerate, trachyandesites (resembling those of the summit region), and alkali trachyte.

No lineation or foliation has been recognised in the central syenite intrusion. In the eastern part of the complex, the syenite-gabbro contact is either subhorizontal, or has a shallow inward dip with the syenite overlying the gabbro. In the southern region, the contact is inwardly steeply dipping. The overall structure of the syenite is thus interpreted as essentially resembling an inverted cone, with steeper contacts occurring at the more deeply exposed levels.

Central Trachyandesite: The porphyritic trachyandesite forms the highest parts of the central complex and has generally been assumed to represent the core of the volcano. In structure, it is interpreted to represent a steep sided central plug with numerous radiating dykes and other minor plugs. The intrusion appears to have a multi-stage injection history, with trachyandesite xenoliths occurring within the trachyandesite, and the occurrence of internal finer grained contacts.

On the well-exposed northern and eastern slopes, the contact with the syenite dips inwards sharply, but irregularly at 65-83°. Nevertheless, the contact relations between the trachyandesite and surrounding syenite are, overall, rather ambiguous. For example: veins of syenite occur in trachyandesite; pegmatitic syenite is found in the syenite close to the trachyandesite contact; two small syenite outcrops are recorded within the trachyandesite, although these could be intrusive or xenolithic; trachyandesite in contact with the syenite is finer grained; trachyandesite dykes intrude the central syenite; glomeroporphyritic aggregates of potash feldspar occur in fine grained trachyandesite near the contact, and are identified as xenocrysts derived from a syenite. Jointing in the trachyandesite is strongly developed, and these joints are oriented parallel to the contact in the north and east, and appear to be circumferentially arranged about the summit. The preferred interpretation is that the trachyandesite represents a composite dyke with radial dykes. According to Solomon (1959) the trachyandesite was intruded through the syenite during an early stage of the latter's cooling, whereas Smart (1970) interpreted the trachyandesite as predating the syenite. Evidence from xenoliths is indefinite but Solomon's interpretation is preferred, with resulting recrystallisation and some plastic behaviour of the syenite along the contact zones.

Petrographically, the trachyandesites are characterised by prominent phenocrysts of labradorite and alkali feldspar (microperthitic to cryptoperthitic), together with sporadic clinopyroxene, hornblende and olivine, set in a holocrystalline, often relatively coarse groundmass of alkali feldspar, clinopyroxene, olivine, titanomagnetite, ilmenite, hornblende, quartz, traces of biotite, and apatite. Of particular significance is the common corrosion of the plagioclase phenocrysts, usually enclosed by sharply defined rims of alkali feldspar, and of mixed pyroxene compositions.

Syenite-Trachyte Ring Dyke: The ring dyke stands out as an almost complete elliptical, narrow, steep-sided ridge which encircles the present summit region. The dyke outcrop has been mapped as over 100 m in average width, but is usually less than 30 m at the ridge top. Where exposure permits examination, a steep inward-dipping inner contact is found. Solomon (1959) recorded a variation in rock type along the dyke; basalt along the southwestern sector, trachyte along the northwestern and southern sectors, and alkali syenite along the eastern parts. No compositional variation across the dyke has been found. Field and petrographic data indicate that dyke injection along the ring-fracture must have occurred in several distinct episodes. The following discrete phases are recognised in the northern and eastern sectors of the ring dyke; fine grained syenite (earliest); porphyritic syenite; trachyte; porphyritic peralkaline syenite. Moreover, lateral traverses along the ring dyke clearly show that it has been injected to varying heights, giving a step-like profile in longitudinal section. The top of the northern and eastern sectors of the ring dyke is frequently heterogeneous due to the abundance of gabbro xenoliths up to 30 m across; some of these outcrops are best described as breccias. They afford evidence of dyke intrusion along a zone of fracture (and subsidence?), together with stoping. Petrographically identical radial dykes are associated with the porphyritic syenite phase.

Mineralogically, these ring dyke syenites are characterised by phenocrysts of potash feldspars (microperthitic) and much less commonly plagioclase (as oligoclase cores in alkali feldspar phenocrysts). The coarse groundmass is holocrystalline and consists mainly of microperthite, quartz, arfvedsonite, aenigmatite, and sodic pyroxenes. In the eastern segment the ring dyke consists of an almost aphanitic quartz trachyte at the southern end; northwards, the ring dykes become dominated by blocks of layered gabbro, intermixed in a matrix of fine to medium grained syenite.

Basalt-Dolerite-Tholeiitic Andesite Dyke-Sill and Ring Dyke Phase: Numerous dykes and sills pervade much of the southern and eastern parts of the complex, with the exception of the central syenite and trachytic ring dyke. A major 'basaltic' phase forms the western segment of the ring dyke. The southwestern segment of this dyke northwards to, but excluding Brummies Lookout, consists of tholeiitic andesite containing common xenoliths of sandstone and conglomerate, but no gabbros. In the area of Brummies Lookout, there is a break in the elevation of the ring dyke, from 520 m to 570 m, and this is associated with a change in rock type from tholeiitic andesite to an aphanitic vesicular basaltic rock; it represents a separate intrusive phase.

Late Stage Felsic Dykes: These represent the youngest recognised intrusive phase, composed of comendites and trachytes, the former being predominant. They are found intruding all rock types in the complex, including the youngest ring dyke phase. Although the distribution of these dykes tends to be random, some show a tendency to be radially disposed about the trachyandesite core, and few are concentric. The dykes very from 0.3 m - 10 m in width. One very prominent dyke (or plug?) occurs as the northern cliff of the summit.

Mount Nullum Igneous Complex

This is dominated by microgranite, forming a high level intrusive mass about 3 km by 1.8 km in plan. It is interpreted as a Tertiary intrusive. Within the microgranite occurs a relict lenticular body of monzonite, some 900 m by 300 m. As xenoliths of this monzonite are locally abundant in the enclosing microgranite, it is interpreted as an earlier phase of the complex. The mineralogy of this monzonite varies across the body from augite monzonite (oligoclase-andesine, potash feldspar, augite, hornblende, Fe-Ti oxides, biotite, and minor apatite) to augite hypersthene monzonite (less quartz, more plagioclase, and exsolution lamellae in hypersthene, and possibly inverted pigeonite).

The dominant feature of interest within the microgranite is the essentially inward change of mineralogy from an outer fayalite-augite-hornblende microgranite through augite-hornblende granite, to an inner zone of hornblende-biotite granite. This change of mineralogy and chemistry is also accompanied by an inward increase in grain size. Considerable development of secondary epidote and chlorite has occurred. Miarolitic cavities are common in the micro-granite, ranging in size from 1-15 cm. These cavities typically contain euhedral quartz, and less common feldspar.

Intrusives on the Flanks of the Tweed Volcano

Most of these can be considered as possible sources for some of the lavas and tuffs and some may have built up parasitic (adventive) cones, now removed partly or completely be erosion. The most obvious vents are rhyolitic, especially those intrusive into rocks less resistant to erosion, which stand out from their surroundings as conical peaks, e.g. Egg Rock and Pages Pinnacle on the northern flanks, Dinseys Rock to the east of Mount Warning, and Nimbin Rocks and Doughboy Mountain to the south.

Pages Pinnacle is a vertical linear intrusion, with columnar jointing dipping steeply, outwards from the axis. Extrusive rhyolite occurs to the southeast, with a glassy base and poorly developed columnar jointing (Watt, 1971).

Surprise Rock, south of Binna Burra, is a dyke of alkali rhyolite, of a type not represented amongst the lavas, which appears to intrude the Binna Burra Rhyolite. It stands out as a narrow ridge with vertical walls, and shows well marked horizontal columns about 1 m in diameter.

Other rhyolitic intrusions which are less obvious as vents, but which may well have been vents, include Charraboomba Rock, a dyke at the base of Ballanjui Falls, at Kweebani Cave near Binna Burra, and on the Beechmont-Binna Burra Road (Stevens, 1984).

ROUTE GUIDE

The excursion will travel north through central New South Wales from Canberra via Cowra, Wellington, Dubbo and Gilgandra to Coonabarabran which will be the base for study of the Warrumbungle volcano. The party then moves north to Narrabri to visit the Nandewar volcano. From Narrabri, the route takes us east across the New England tableland to the Tweed volcano on the east coast near the New South Wales - Queensland border (Fig. 6).

Brief stops also will be made en route between the major volcanic centres to inspect some features of *lava field* volcanism and to view Mount Canobolas, another (smaller) example of a *central volcano* about 150 km north of Canberra.

DAY 1 - CANBERRA - COONABARABRAN

From Canberra, we will travel initially northwest to Yass and then north through Boorowa to Cowra. Immediately north of Cowra, exposures may be seen of Palaeozoic S-type granitoids of the Lachlan Fold Belt.

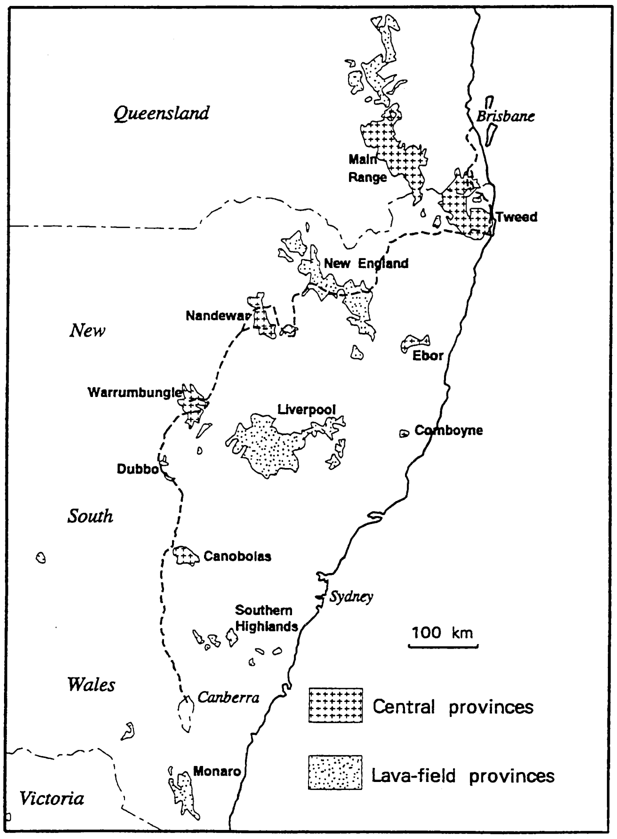

Figure 6. Map showing excursion route, Canberra to Brisbane, and the main central and lava-field volcanic provinces in New South Wales and southern Queensland.

Stop 1.1 - Canobolas volcano - panoramic view

The Canobolas Volcano, dated at 11-12 Ma (Wellman & McDougall, 1974b), is much smaller than most of the older central-type volcanoes farther north, and may be a product of the waning stages of the hot spot activity. Canobolas volcano had an estimated initial volume of ca. 50 km^3 which is an order of magnitude smaller than the Warrumbungle and Nandewar volcanoes.

A central complex of felsic domes, plugs and lava flows is surrounded by an apron of mafic lavas dominated by feldspar-phyric hawaiites and mugearites (Middlemost, 1981,1989). A thin veneer of these mafic lava flows covers Palaeozoic basement rocks around Cudal. The flat-lying volcanics overlie Ordovician Limestones, volcanics, and clastic and volcaniclastic sediments of the Lachlan Fold Belt. From this vantage point, the geomorphic outline of the Canobolas volcano is well displayed. Note the elevated central area composed predominantly of felsic intrusives and extrusives surrounded on all sides by the thin low-angle apron of mafic lavas.

We will stop for lunch in in a park, adjacent to the Macquarie River, in the rural town of Wellington. Wellington is the centre of a wealthy agricultural area, based primarily on sheep and cattle.

The route continues north across Palaeozoic sediments and volcanics of the Lachlan Fold Belt. Mesozoic sediments of the Gunnedah Basin are encountered near Dubbo.

Stop 1.2 - Talbragar River

A volumetrically small lava-field province of mafic and minor felsic volcanics is dispersed over a wide area around Dubbo, midway between the Canobolas and Warrumbungle centres. The mafic rocks usually form thin valley-filling flows; the felsic rocks occur mostly as small plugs and domes. At this point, a small flow of basalt flowed down the valleys of the Talbragar and Macquarie Rivers. The flow, which has been dated at 12.0 Ma (Wellman & McDougall, 1974b), is perched only a few metres above the present river base. Some 150 km to the east, flows of a similar age followed the channel of the east-flowing Goulburn River for many kilometres. Remnants of these long flows are now preserved some 50 to 100 metres above the deeply incised meanders of the present river bed. The relatively insignificant downcutting of the Talbragar in the same time period indicates the much lower erosive power of the west-flowing Talbragar River, compared with deeply incised Goulburn River.

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Just north of Gilgandra we will have the first sight of the Warrumbungle volcano forming a distant, but still spectacular, jagged profile on the horizon to the north. We cross onto its volcanic products about 60 km southwest of Coonabarabran.

Stop 1.3 - Oxley Highway hawaiite

The flow here is one of a sequence of mildly undersaturated (*ne*-normative) hawaiites which overlie thick flows of trachyte and a felsic pyroclastic horizon. The hawaiites (Table 2, No. 2), consist of phenocrysts of glassy plagioclase and microphenocrysts of olivine in a groundmass of titaniferous augite (sub-ophitically enclosing plagioclase), alkali feldspar, olivine, titanomagnetite and minor apatite. Some flows contain small pyroxenite xenoliths and megacrysts of pyroxene and ilmenite.

Stop 1.4 - Hickey Falls

At Hickey Falls, Binnaway Creek cuts through a thick metaluminous trachyte flow at the base of the volcanic sequence. The trachyte contains sodic ferroaugite moulded on felted laths of anorthoclase, with minor fayalite, ilmenite and apatite. Overlying the trachyte is an aerially extensive pyroclastic unit consisting of bedded tuffs and breccias. The pyroclastics are well exposed immediately west of Binnaway Creek. The low stratigraphic position of the pyroclastic unit is consistent with it being contemporaneous with the complex of domes, plugs and pyroclastics comprising the central core of the Warrumbungle complex.

This is the last scheduled stop of the day. After leaving Hickey Falls the road passes up through a thick sequence of mainly hawaiite flows, with some interbedded and underlying pyroclastics, and proceeds on to Coonabarabran, another 40 km to the northeast. On the way you will see evidence of multiple thin lava flows, both the right and left of the road, as well as an overall view of the Warrumbungle volcano, showing the central area with abundant felsic domes and plugs, and the mafic lavas forming the shield dipping gently away to the south.

DAY 2 - WARRUMBUNGLE VOLCANO

This day commences with an overview of the Warrumbungle volcano from Siding Spring Mountain, but most of the day will involve a traverse through the eroded core of the volcano along one of the most popular walking tracks in the park. Siding Spring Mountain is the site of the one of the largest optical astronomical observatories in the southern hemisphere, including the 3.9 metre Anglo-Australian Telescope.

Stop 2.1 Mount Woorut, Siding Spring Mountain

Mount Woorut, the highest point on Siding Spring Mountain, provides a panoramic view of the eroded central portion of the Warrumbungle volcano. Siding Spring Mountain is one of the more substantial remnants of the shield-building lava and pyroclastic sequence. The rock at this point is a trachyte consists of phenocrysts of anorthoclase, sodic hedenbergite, opaque oxide and a brown phyllosilicate replacing olivine in a groundmass of anorthoclase, sodic hedenbergite, aenigmatite and a trace of arfvedsonite. This flow caps a sequence of mafic and felsic lava flows (hawaiites, mugearites and trachytes) and pyroclastics. This sequence will be examined more closely on Day 3.

From here, you can look to the southwest across the central portion of the volcano, where deep erosion has exposed numerous plugs, dykes and domes of trachyte and the underlying Jurassic Pilliga Sandstone. Around to the west is another erosional remnant of the lava shield, Mount Exmouth, and farther beyond are the flat western plains of the Murray-Darling drainage basin.

From Mount Woorut, we travel to Camp Pincham, the starting point for the Grand High Tops circuit and the most spectacular and most popular walk in the Park system (Fig. 7). From Camp Pincham, the track initially follows Spirey Creek for almost 4 km, mostly through Pilliga Sandstone. At about 1 km, the eastern margin of a trachyte dome (Mathgan Cone) is exposed in the creek bed to the right of the track.

Stop 2.2 - Bridget Peak - Bress Peak

A side spur off the main track from Camp Pincham to the Grand High Tops leads to the summit of Bridget and Bress Peaks. Initially, the steep track follows a ridge, the spine of which is a peralkaline trachyte dyke several metres wide and traceable for about 1 km. The trachyte (Table 2, No. 9) contains grains of quartz, blue arfvedsonite, green aegirine and minor brown aenigmatite enclosing laths of anorthoclase. The rock exhibits pronounced flow-banding. After passing the top of the ridge, the track veers to the left, off the trachyte dyke and onto an alkali dolerite plug which forms Bridget Peak. The medium-grained dolerite consists of olivine, augite, titanomagnetite, plagioclase and minor alkali feldspar. A trace of banding is seen in the dolerite at some points.

Adjacent to Bridget Peak, Bress Peak is composed of highly altered trachyte. Bleached and altered trachytes are common in the central part of the volcano but the degree of alteration at this locality is exceptional.

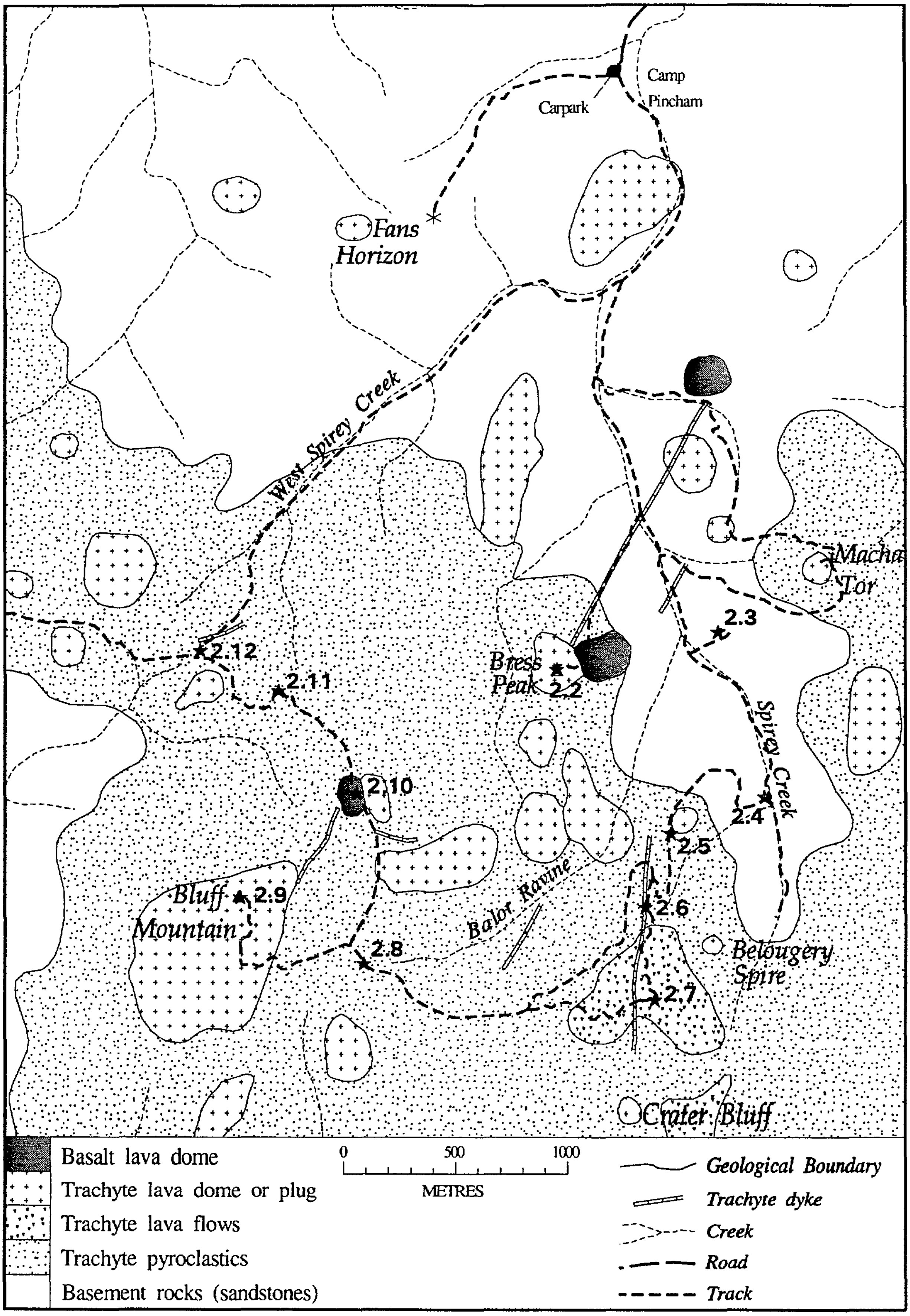

Figure 7.. Map showing walking tracks and generalised geology of the Grand High Tops area. Excursion stops shown as numbered stars.

Stop 2.3 - Spirey View

Spirey View is a small sandstone bluff only a short detour off the main track. It provides excellent views of Belougery Spire and the Breadknife.

Stop 2.4 - Wilson's Ramp

The track begins to climb steeply after leaving Spirey Creek at Wilsons Ramp. Adjacent to the track at the beginning of the climb is a basalt flow of unknown affinities. The rock is a plagioclase-phyric basalt petrographically and geochemically distinct from any other analysed rock from the volcano. While its stratigraphic position is uncertain, it could conceivably lie within the Pilliga Sandstone and be related to the Jurassic Garawilla Volcanics centred some 70 km to the east. If instead it is an early flow from the Warrumbungle centre, it is the only mafic flow known to precede the trachytic volcanism in the central part of the shield.

Stop 2.5 - Sreng Saddle

The lookout at Sreng Saddle offers an imposing view through the trees to Belougery Spire, just across the valley to the southeast. Trachytic tuff/breccias exposed along the path and in large boulders at this point are typical of the pyroclastics which dominate the central part of the shield. They are usually massive, uniform, unbedded or nearly so, and dominated by fragments of fine-grained grey-green trachyte. The trachyte is virtually identical in appearance to the finer grained marginal phase of the Belougery Spire trachyte. Across to the west from Sreng Saddle is Balor Ravine, where large exposures of bedded pyroclastics dip to the north.

From Sreng saddle, the track continues to climb over pyroclastic rocks to the base of the Breadknife and then follows close to the rock face toward the Grand High Tops. Another branch of the track passes around the northern end of The Breadknife.

Stop 2.6 - The Breadknife

The Breadknife is undoubtedly the most spectacular feature in the Warrumbungles. For approximately 600 metres of its length, the Breadknife is a prominent, upstanding wall of rock up to 60 metres high but mostly no more than 2 metres wide. The rock is a peralkaline aegirine trachyte (Table 2, No. 8) consisting of occasional equant phenocrysts of anorthoclase in a felted groundmass of anorthoclase, aegirine, wilkinsonite, minor arfvedsonite and, in some samples, sodalite. The wilkinsonite is titaniferous, trending towards aenigmatite. The dyke, which intrudes pyroclastics and and overlying arfvedsonite trachyte flow, appears to be a radial offshoot from Crater Bluff. The margins of the dyke and the contact relationships are very clearly exposed, with a narrow chilled margin and a plane of contact characterised by bulbous protrusions, suggesting that the intruded pyroclastics were largely unconsolidated. Elsewhere, the intruded arfvedsonite trachyte is extensively shattered. Just after the track leaves the Breadknife, it passes Lugh's Wall, a small offshoot from the Breadknife dyke.

From Lugh's Wall it is only a short climb to Lugh's Throne, the summit, and surely the most spectacular location, on the Grand High Tops circuit. We will stop here for lunch and the opportunity of a panoramic view of the volcano.

Stop 2.7 - Lugh's Throne

From here, close to the geographic centre and also the volcanic centre of the volcano, you have a virtually uninterrupted 360^{0} view of the whole volcano and the surrounding countryside. Close by are all the major plugs and domes including Belougery Spire, Crater Bluff, Bluff Mountain and Balor Peak. In the middle distance are several remnants of the lava shield such as Mount Exmouth, Mount Bullaway, Junction Mountain, Siding Spring Mountain and Needle Mountain. In the distance to the east are the remnants of the Jurassic Garrawilla Volcanics, interbedded with the sediments of the Gunnedah Basin. On a clear day, it is possible to pick out the profile of the Nandewar Volcano some 120 km to the north. The rock forming Lugh's Throne is a an arfvedsonite trachyte containing phenocrysts of anorthoclase in a felted groundmass of anorthoclase and arfvedsonite. It is thought to be a remnant of a thick trachyte flow, probably derived from activity centred on Crater Bluff.

From Lugh's Throne, the track continues in a westerly direction, passing over the southward continuation of the Breadknife and then descending to Dagda Saddle.

Stop 2.8 - Nuada Ramp

From Dagda Saddle, the track climbs steadily to Nuada Gap. For part of the climb, the track traverses bedded tuffs and breccias. These contain boulders up to 50 cm in diameter, at least some of which appear to have been ballistic blocks.

We continue on to a point where a side track leads to the summit of Bluff Mountain. The climb to the summit is optional, but it is highly recommended if you still feel sufficiently energetic. The walk is not as strenuous as it first appears and the scenic rewards are outstanding.

Stop 2.9 - Bluff Mountain

Bluff Mountain is composed of a rather uniform body of aegirine-arfvedsonite trachyte, believed to represent a single, large lava dome.

Along the climb to the summit, there is an excellent vantage point for a view of Crater Bluff. From here, a bowl-shaped depression surrounding Crater Bluff is clearly evident. The view from the summit of Bluff Mountain is magnificent. It provides a wonderful vista of some of the southern areas of the park such as the thick slab-like flow of arfvedsonite trachyte forming Mount Naman, and the conical plug of Tonduron Spire (mugearite; Table 2, No. 4). A sample of trachyte from the Mount Naman flow is noteworthy in containing traces of aegirine having the highest Zr content yet recorded in pyroxene (14.5 wt % ZrO_2; Duggan, 1988).

Return to Nuada Saddle.

Stop 2.10 - Dow's High Tops

After returning to Nuada Saddle, the track follows a narrow ridge to Point Wilderness. Several small knolls along the ridge are composed mainly of intensely weathered white trachyte and trachyte breccia. At one point, a flow of mugearite approaching benmoreite (Table 2, No. 5) crops out beside the track. This is the only example of a mafic lava among the felsic rocks in the central part of the volcano that is unquestionably part of the Warrumbungle sequence. Along this track you cannot but be impressed by the spectacular view of the north side of Bluff Mountain which rises some 250 metres as a near-vertical face. A complex pattern of joints is evident on the rock face.

Stop 2.11 - Point Wilderness

Point Wilderness offers outstanding views of the western part of the volcano. In particular, the gently westward-dipping lava/pyroclastic sequence on Mount Exmouth is clearly seen. One flow in particular, of metaluminous trachyte, forms a prominent scree slope and is overlain by a pyroclastic horizon. In front of Mount Exmouth are several small plugs or domes, mostly of arfvedsonite trachyte and comendite.

At this point we take the track to the right which descends West Spirey Ramp to West Spirey Creek, and then on to Camp Pincham and the carpark.

Stop 2.12 - West Spirey Ramp

The track down West Spirey Ramp traverses a sequence of very well-bedded tuffs and breccias in which the bedding is near-vertical. The origin of the steep dips is not certain. Near the bottom of the steepest descent, a trachyte dyke occurs adjacent to the track.

The return to Camp Pincham is a pleasant stroll along the banks of West Spirey Creek, mostly traversing Pillaga Sandstone. At one locality in the creek bed, the sandstone is silicified and cut by a network of fine quartz veins, probably related to the Warrumbungle volcanism.

DAY 3 - WARRUMBUNGLE VOLCANO; COONABARABRAN - NARRABRI

On Day 3 we will examine deposits on the eastern flanks of the volcano, including a section through the lava/pyroclastic sequence and some petrographically diverse lava domes.

We will initially drive up the road to Siding Spring, and then walk downhill to examining the section through the stratigraphic sequence. We rejoin the bus at the John Renshaw Parkway road junction at the bottom of the hill.

Stop 3.1 - Siding Spring Road section

The road to the Anglo-Australian Observatory on Siding Spring Mountain provides a typical section through the lava sequence. A geological sketch map of Siding Spring Mountain is shown in Figure 8. The traverse will commence at the hairpin bend and pass down through the sequence. The rock at the hairpin bend is a mugearite dated at 15.7 Ma by Wellman and McDougall (1974b). It contains glassy phenocrysts of plagioclase and microphenocrysts of augite, olivine and apatite in a groundmass of plagioclase, alkali feldspar, augite and opaques. Underlying the mugearite is a sequence of felsic and mafic trachyte flows, trachytic pyroclastics and debris flows. A trachyte dyke about 2 metres wide exposed in the road cutting is traceable on aerial photographs for about 2 km.

A shallow quarry near the road junction exposes the base of the volcanic sequence where a mafic lava flow (hawaiite) is separated from the underlying Pilliga Sandstone by a pyroclastic horizon containing silicified plant material.

Stop 3.2 - Shawns Creek

In Shawns Creek, just east of Tibuc homestead a bedded pyroclastic sequence appears to be predominantly air-fall in origin. Bedding is well developed on a centimetre to decimetre scale over a thickness of at least 40 metres, with neither the top nor the base exposed. Cross bedding and other depositional

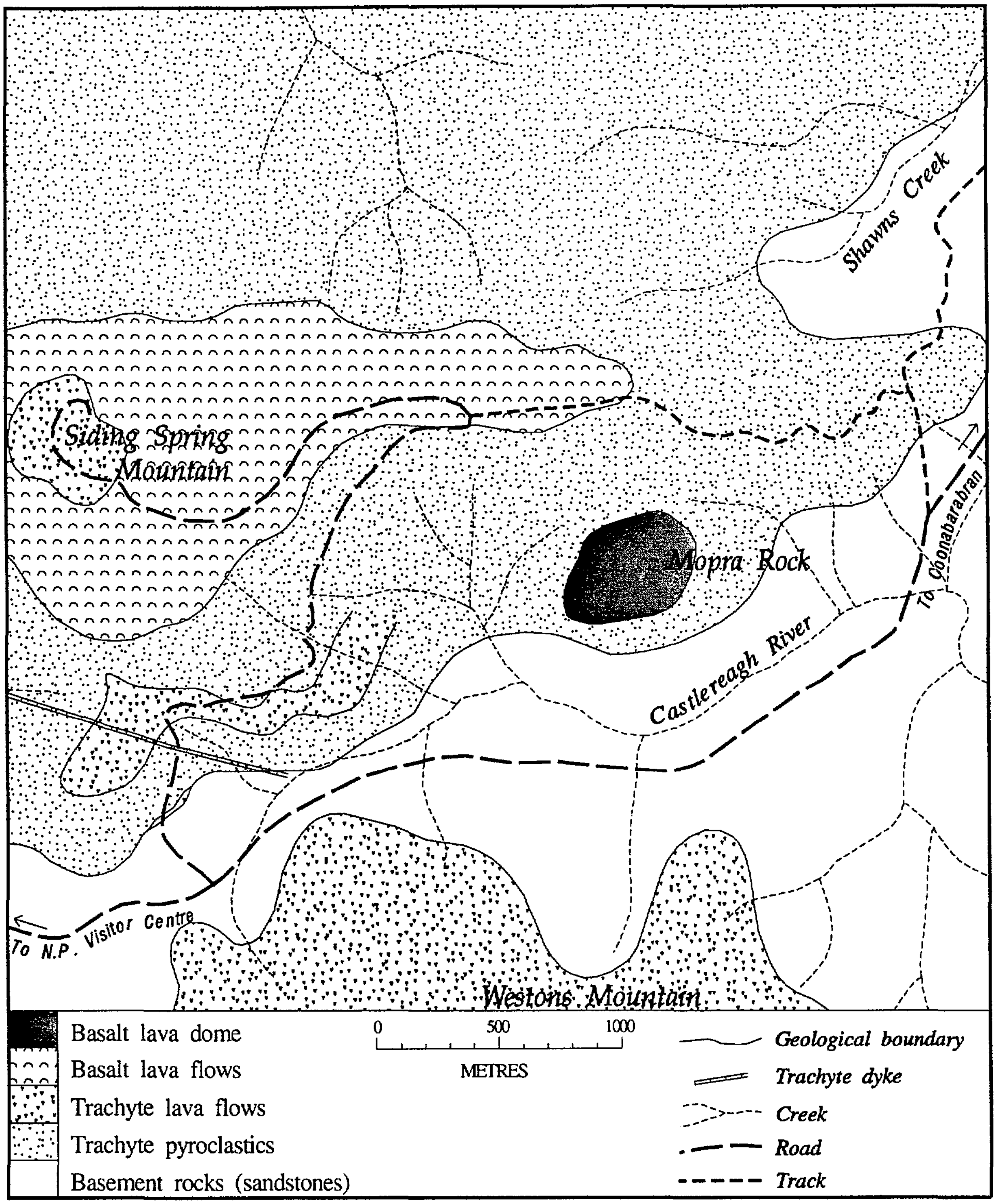

Figure 8. Sketch map of Siding Spring Mountain showing the generalised geology and location of the traverse A - B for excursion stop 3.1

structures are rare. The pyroclastics are overlain by metaluminous trachyte.

Stop 3.3 - Timor Road

This spectacular road cutting exposes a clastic sequence apparently deposited along a precursor to the present Shawns Creek. The lower unit, overlying a deeply weathered felsic rock (?trachyte) is a well-sorted boulder bed approximately 2 metres thick composed of clast-supported trachyte 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 a discontinuous, essentially clast-free muddy horizon about 0.5 metres thick. The upper unit is an unsorted deposit of matrixsupported boulders reaching 2 metres in diameter in a muddy matrix. This is believed to be a mass-flow (lahar) deposit.

Stop 3.4 - Timor Rock

Timor Rock is an elongate dome or plug of arfvedsonite trachyte. The rock consists of anorthoclase, arfvedsonite, aenigmatite and interstitial quartz.

Stop 3.5 - Bingie Grumble Mountain

We will walk a short distance from the bus to exposures of the Bingie Grumble trachyte on the northern slopes of the dome. There will be time to walk a few hundred metres along the track towards the summit to observe variations in the trachyte.

Bingie Grumble, believed to be a broad lava dome at least 100 metres thick and over one kilometre across, is the type locality for wilkinsonite, $Na_2Fe^{2+}{}_4Fe^{3+}{}_2Si_6O_{20}$, a Ti-free member of the aenigmatite group (Duggan, 1990). A track to a telecommunications antenna on the summit provides good exposures for sample collection. The outer 200 metres consists of relatively fine grained trachyte containing phenocrysts of anorthoclase and sodalite in a groundmass of anorthoclase, aegirine-hedenbergite, wilkinsonite, sodalite and traces of arfvedsonite, eudialyte and other complex Zr-silicates. An analysis of the rock is given in Duggan (1990). The grainsize increases markedly toward the interior of the body. An analysis of trachyte from the summit is given in Table 2, No. 7.

Mafic lava flows in the immediate vicinity of Mount Bingie Grumble do not appear to be disrupted by the dome, suggesting that they post-date its emplacement.

Stop 3.6 - Forked Mountain

This conical hill adjacent to the Oxley Highway is a small dome of metaluminous trachyte (Table 2, No. 6) intruding the Pillaga Sandstone and is one of the most easterly exposures of the Warrumbungle volcano. It is similar in composition to the mafic trachyte lava flows forming a large part of the shield. The rock contains microphenocrysts of Fe-rich olivine in an orthophyric groundmass of anorthoclase, augite, magnetite and apatite.

DAY 4 - NANDEWAR VOLCANO

The fourth day of the excursion is spent examining the volcanology and petrology of the Nandawar volcano. We will initially drive up through the volcanic sequence to the summit of Mount Kaputar for an overview of the volcano. We will look more closely at many of the outcrops as we drive down the same route later in the day (Fig. 9).

From road take a walking track which climbs gently to the summit of Mount Kaputar. This track starts in porphyritic K-hawaiite, but for most of its length passes over mafic trachyte. It is about a 10 minutes walk each way.

Stop 4.1 - Mount Kaputar summit

The summit of Mount Kaputar (1 510 m high) provides a splendid 360° view of the whole Nandewar volcano. It consists of a plug-like intrusion, about 17 Ma old or slightly younger, which was emplaced under very shallow cover. It is a fine-grained, blue-grey peralkaline trachyte, vesicular in part, with stumpy phenocrysts of K-feldspar. Typically the Nandewar peralkaline trachytes carry sparse phenocrysts of calcic anorthoclase and sanidine, clinopyroxene, $\pm$ titanomagnetite $\pm$ ilmenite $\pm$ olivine, in a groundmass of sanidine laths, alkali amphibole and acmitic pyroxene. Titanomagnetite and ilmenite microphenocrysts commonly exhibit a narrow rim of aenigmatite. The prominent knob to west of tower is Sinclair Peak, the hill to NE is Mount Capel (1464 m). Mount Yulludunida, the rounded hill to the east, and the prominent ring dyke which encircles it, are also peralkaline trachyte. We will be looking more closely at Mount Yulludunida later in the day. The older peraluminous rhyolites, namely the Killarney Gap sequence, apparently preceded the main shield-building episode, and form the prominent range to the northwest, which includes Pound Mountain (rising up from trachyte cliffs, with Mount Lindesay behind), Little Peak, Mount Grattai and Doyles Peak. In the distance to the south are the Garrawilla Volcanics, and the Warrumbungle volcano may possibly be visible west of these. The New England Tablelands, forming part of the Great Dividing Range which runs the full length of eastern Australia, can be seen to the east.

Return to bus along the same track and walk down road for about 100 metres where there is a good exposure of porphyritic K-hawaiite in a road cutting (right side of road as you descend).

Stop 4.2 - Porphyritic K-hawaiite

Hawaiite and K-hawaiite are generally aphyric or slightly porphyritic with phenocrysts of olivine, plagioclase (some strongly zoned), and clinopyroxene. Some flows, however, are strongly porphyritic with up to 50 volume percent phenocrysts. Megacrysts of aluminous augite and bronzite rimmed with low-pressure reaction products (olivine and clinopyroxene)

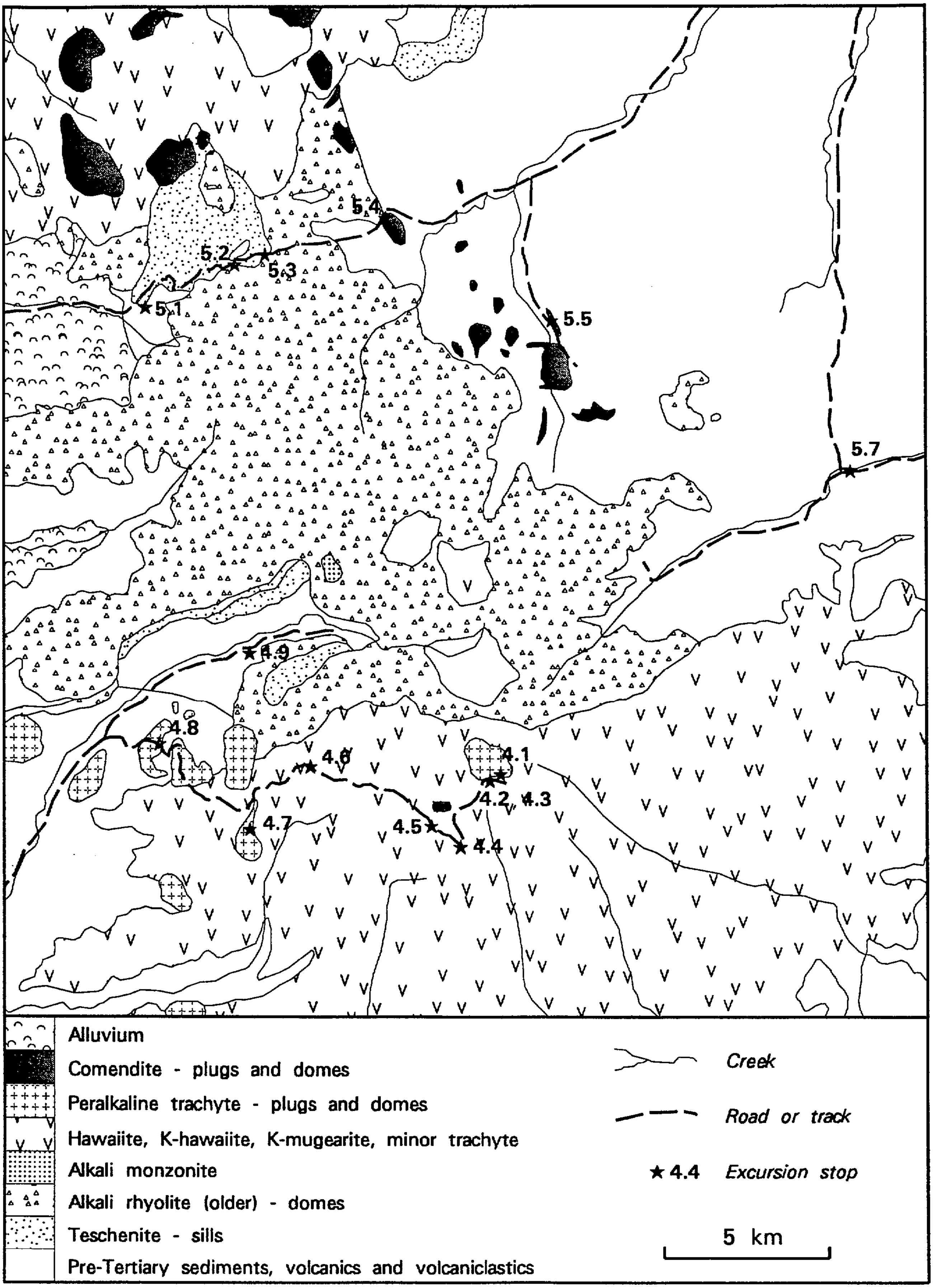

Figure 9. Generalised geology and excursion stops for the Nandewar volcano. Geology after Stolz (1983).

are present in some K-hawaiites. The porphyritic K-hawaiite seen here has abundant phenocrysts of plagioclase (labradorite - but andesine in other similar rocks) to 2 mm, augite to 0.5 mm, titanomagnetite and apatite to 0.2 mm, in a fine-grained trachytoid groundmass of plagioclase, alkali feldspar, augite and opaques (thin section 49037). Hawaiite and K-hawaiite have SiO_2 contents of 47-51%, and range from being slightly *ne*-normative to *hy*-normative. 100Mg/(Mg + Fe^{2+}) values vary between 65.2 and 40.3. The hawaiites are the most sodic of the Nandewar rocks with Na_2O/K_2O ratios ranging from 1.80 to 2.97.

Walk another 200 metres down the road to look at K-mugearite in road cutting (right side of road) before rejoining bus.

Stop 4.3 - Porphyritic K-Mugearite

Porphyritic K-mugearites typically contain up to 5% microphenocrysts of olivine, clinopyroxene, plagioclase, titanomagnetite and apatite, in a fine-grained groundmass of plagioclase, clinopyroxene, titanomagnetite, apatite and alkali feldspar. Some, as seen here, are glassy and strongly porphyritic with plagioclase phenocrysts up to 1 cm across. K-mugearites have SiO_2 contents from 55.8 to 59.6% and all are *hy*- ± *qz*-normative. They have Na_2O/K_2O values between 1.09 and 1.68.

Drive to Kaputar Plateau carpark. Walk down road to Doug Sky Lookout (about 1 km) passing through a series of K-hawaiite (fine-grained, porphyritic, phenocrysts of plagioclase up to 1.5 cm in length, and olivine, augite and occasional magnetite to 1 mm diameter, in a groundmass of plagioclase, alkali feldspar, augite and opaques - thin section 49059), and fine-grained sparsely porphyritic K-mugearite (phenocrysts of plagioclase and augite) flows with rubbly flow tops and bases and massive cores.

Stop 4.4 - Doug Sky Lookout

From Doug Sky Lookout there are extensive views outwards towards the flanks of the volcano where the most common rock types are hawaiite, K-hawaiite and mafic trachyte. The prominent plug is Mount Deriah, composed of peralkaline trachyte. Euglah Rock has well-developed columnar jointing, suggesting it may be a flow remnant. The rock cropping out at Doug Sky Lookout is a crystal-rich agglomerate which at this point has considerable thickness suggesting it may represent a breccia pipe. Note that rock fragments similar to this agglomerate can be seen near the top of the 20 cm thick oxidised ash layer in the road cutting immediately behind the lookout. This road cutting has a variety of volcanic products including a fine-grained K-mugearite flow with aligned laths of plagioclase. This flow has a massive core and brecciated flow bottom, and overlies a crystal lithic pyroclastic deposit which is topped by oxidised ash. The pyroclastic unit in turn overlies another massive sparsely porphyritic K-mugearite flow.

Return to the bus and continue downhill for 1 km (to about 400 m past Bark Hut Camp). Alight from bus and walk down section for about 300 metres observing strongly feldspar-phyric basaltic rock, and the overlying fine-grained hawaiite.

Stop 4.5 - Feldspar-phyric rock section

This road cutting is dominated by a massive outcrop of strongly feldspar-phyric basalt. Phenocrysts include abundant plagioclase up to 5 cm long, less commonly olivine and clinopyroxene, in a fine basaltic groundmass. The rock is mostly strongly weathered and is at least partly fragmental, which most likely represents rubbly flow material. Within the rubbly material, however, are lenses up to several metres long and 1-2 metres thick of fresh massive rock. There is a highly irregular contact between this unit and the overlying flow of fine grained, mainly aphyric hawaiite, which has a chilled base and amygdales up to 4-5 cm infilled with zeolites. The hawaiite in turn is overlain by more of the strongly feldspar-phyric basaltic rock which forms the massive cliffs above.

Rejoin bus and descend 4.5 km to a spectacular cutting exposing massive flows of sparsely porphyritic K-hawaiite overlying a strongly porphyritic breccia unit.

Stop 4.6 - Porphyritic K-hawaiite

The basal unit is a strongly plagioclase-phyric basaltic breccia which is overlain by a 30 cm thick horizon of red crystal-rich tuff. This grades upwards into ash containing abundant feldspar fragments, which in turn is overlain by a mostly massive flow of fine-grained hawaiite containing acicular laths of glassy plagioclase. It has a chilled base and, in places, highly irregular gas cavities up to 10 cm across are prominent.

Return to bus and continue to Green Camp carpark for lunch. After lunch, we will walk into the Mount Yulludunida peralkaline trachyte ring dyke (a good 3 hour return trip).

Stop 4.7 - Mount Yulludunida

Mount Yulludunida is a spectacular east-dipping dyke structure about 200 to 300 metres wide and 1 km long, convex to the southwest. It consists of peralkaline trachyte with phenocrysts of anorthoclase to 5 mm in length, in a trachytic groundmass of alkali feldspar, aegirine, titanomagnetite, minor arfvedsonite and quartz (thin section 49104). The peralkaline trachytes have SiO_2 contents of 62.8% to 67.1% and all are a *qz*-normative (as are the mafic trachytes which have SiO_2 values from 59.9% to 63.1%). Na_2O/K_2O values for the mafic and peralkaline trachytes are 0.99 to 1.25 and 1.17 to 1.29, respectively. Another massive east-west trending dyke can be seen to the east, beyond the Yulludunida 'crater', where it intrudes a sequence of thick flows gently dipping to the east-southeast. The peralkaline trachyte dykes and plugs are largely confined to the southern part of the volcano and were intruded into the volcanic pile and adjacent basement at about 17 Ma, following or possibly during the waning stages of the main shield-forming volcanism (Stolz, 1985).

Return to Green Camp car park to rejoin bus, which will proceed down the volcanic sequence for another 6 km to carpark at the National Park information display. Walk down road for about 200 metres.

Stop 4.8 - Peralkaline trachyte

The peralkaline trachyte at this stop is a light blue-grey, sparsely porphyritic rock with anorthoclase phenocrysts in a groundmass of more sodic anorthoclase and minor arfvedsonite, aegirine, aenigmatite, quartz and some secondary carbonate (thin section 49098). A massive Triassic sandstone unit separates the peralkaline trachyte from a more mafic porphyritic trachyte uphill from this point.

Rejoin bus at outcrop and proceed to Lawlers Creek to look at an inclusion- and megacryst-rich nephelinite. Walk about 250 metres upstream.

Stop 4.9 - Lawlers Creek nephelinite

The nephelinite crops out as a sill in the west bank of Lawlers Creek. It intrudes Permian sedimentary rocks and has a maximum thickness of about 1 metre. Utramafic inclusions and megacrysts are concentrated in the lower part of the sill (totalling up to 70%), although the upper part also has abundant smaller megacrysts and fragmented inclusions. The inclusions fall into a Cr-diopside group and a Ti-augite group. The former are dominated by Cr-spinel lherzolites of restricted modal composition, and the latter by olivine and titaniferous Al-rich clinopyroxene assemblages which vary widely in their modal proportions (Wilkinson, 1975a). The two main megacryst minerals are olivine and black titaniferous Al-rich clinopyroxene. Megacrysts of titanphlogopite, kaersutitic amphibole, and deep green, relatively Fe-rich clinopyroxene are comparatively rare. The host nephelinite is generally altered. Slightly coarser grained 'micro-pegmatitic' areas consist of pinkish-brown clinopyroxene (sometimes zoned to green acmitic rims), nepheline, analcime and other zeolites, opaque oxide, biotite and apatite. Alkali feldspar may also be present but has not been positively identified. Amygdales of carbonate ± quartz are common, and carbonate is an ubiquitous groundmass phase. The average SiO_2 value for the nephelinite groundmass is 42.4%. and $100Mg/(Mg+Fe^{2+})$ is 66.2. It has 3.6% TiO_2, 8.95% MgO and 12.6% CaO. Normative *ne* is 17.0%. Wilkinson (1975b) concluded, on the basis of compositional relationships between megacrysts and analogous phases in Ti-augite inclusions, plus evidence afforded by experimental data, that the Ti-augite inclusions are cognate cumulates, derived from olivine nephelinite at pressures in the vicinity of 15-20 kb, and that the cryptic variation in the suite results primarily from fractionation of olivine and clinopyroxene at elevated pressures.

Walk back downstream to bus and return to Narrabri for evening.

DAY 5 NANDEWAR VOLCANO TO GLEN INNES

Today will be spent traversing the northern segment of the Nandewar volcano through Killarney Gap, then on across its distal eastern flanks to Barraba, and finally through the New England* *lava-field* type province to Inverell and Glen Innes.

Leave Narrabri and drive 35 km to Sawn Rocks carpark. Walk about 900 metres along track to Sawn Rocks.

Stop 5.1 - Sawn Rocks

Sawn Rocks form a 40 metre cliff and creek bed sequence of columnar jointed alkali rhyolite representing the older, and more voluminous, episode of rhyolitic volcanism. The columns of Sawn Rocks have a diameter of 50-80 cm and are 4-7 sided (mostly 5 or 6). There are some excellent exposures of the columns in cross section in the creek pavement. These older alkali rhyolites are commonly vesicular and carry up to 15 volume percent phenocrysts of anorthoclase and sanidine in a groundmass of feldspar, quartz and titanomagnetite (now largely converted to hematite). They have SiO_2 values of 65.76% to 68.37% and Na_2O/K_2O values of 0.90 to 1.07. Compared to the comendites, they mostly have lower Zr (680-785 ppm versus 693-1245 ppm, respectively), significantly lower Rb (130-151 ppm versus 141-294 ppm), and Li (5-13

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* Historically this *lava-field* province has been called the Central Province, however, to avoid confusion with the *central-type* provinces, we will refer to it as the New England *lava-field* province.

ppm versus 20-53 ppm), and higher Sr (8-10 ppm versus 1-5 ppm) and Ba (165-298 versus 4-10 ppm).

Return along track to bus and drive up hill to Killarney Gap passing over teschenite and minor rhyolite. Most of rhyolites and comendites. Mount Grattai is mainly basaltic in composition and Castle Top Mountain is mapped as older rhyolite. Leave bus at top of hill (Killarney Gap), walk across cattle grid and down road to left-trending curve where teschenite crops out on the left side of the road.

Stop 5.2 - Teschenite

The teschenite is a dark-grey, medium-grained rock, variably porphyritic with euhedral phenocrysts of olivine in a groundmass of plagioclase laths, stumpy titaniferous augite prisms, skeletal magnetite and interstitial analcime (thin section NDW22). In this area the teschenite has coarse pegmatoidal patches with amphibole phenocrysts up to 1.5 cm long. The age of the teschenite sills is not known. However, they are petrographically very similar to the Mesozoic teschenites of the Gunnedah and Mullaley areas to the south and are probably related to these. The oldest rocks dated from the Nandewar volcano include a trachyte flow, dated at 21 Ma, which overlies this teschenite sill to the north.

Return to bus and proceed for 3 km to road cutting through rhyolite. Walk about 100 metres eastward to cutting.

Stop 5.3 - Older alkali rhyolite

This older alkali rhyolite appears to be one of several small flows or dykes in the immediate area. It is intercalated with a rhyolite breccia bed mostly composed of angular, less commonly rounded, clasts up to 10 cm across in a muddy matrix. There also appears to be a sedimentary unit. The rhyolite is typical of the massive flows along the range to the south and southwest (thin section 49122).

Return to bus for short drive to Nobbys Hill.

Stop 5.4 - Younger alkali rhyolite, Nobbys Hill

Nobby's Hill is a small plug of the younger alkali rhyolite which intrudes the Permo-Carboniferous Rocky Creek Conglomerate (large boulders of which can be seen near the road on the eastern side of the hill). Cropping out at the base of the hill is a vuggy blue-grey porphyritic alkali rhyolite with microphenocrysts of anorthoclase in a fine-grained felted groundmass of anorthoclase, quartz and arfvedsonite (thin section 49128). Slightly up hill the rhyolite is a pinkish-grey colour and only sparsely porphyritic. With 74.5% SiO_2, the younger alkali rhyolites are more silica-rich than the older alkali rhyolites. They also have lower Ba (4 ppm) and Sr (not detected), and higher Rb (190 ppm) than the younger alkali rhyolites.

Return to bus. Depending on how time is going we will either go on to look at a comendite dyke (which involves a 9 km drive plus a 1 km return walk). Otherwise we will drive directly to Rocky Creek Gorge for lunch.

Stop 5.5 - Comendite dyke

There are a series of dykes in this area associated with the Pound Rock comendite plug. Some are spectacular, particularly on the eastern side of the plug, but unfortunately the track is unsuitable for bus access and it is a long walk in. These dykes are variably porphyritic with anorthoclase phenocrysts up to 5 mm long set in a felted groundmass of quartz, alkali feldspar, and arfvedsonite $\pm$ acmitic pyroxene. The SiO_2 content of the Nandewar volcano comendites varies from 68.9% to 72.8% and their Na_2O/K_2O values range from 1.11 to 1.34. The A.I. (agpaitic index = molecular $(Na_2O + K_2O)/Al_2O_3$) varies from 1.01 to 1.07.

Return to bus and continue on to Rocky Creek for lunch where, for a change of pace, we will have an opportunity to look at some sedimentary rocks.

Stop 5.6 - Rocky Creek

This is the type section for the Late Carboniferous Rocky Creek Conglomerate which provides a traverse from fluvially reworked glacial deposits with large-scale scour and fill features, through tillites, to varved sediments (Percival, 1985). Upstream, towards the top of the formation, there is a massive sequence of paraconglomeratic tillites and interbedded varves about 40 metres thick. The sub-rounded to faceted angular tillite clasts consist mainly of biotite granite (in boulders up to 1.3 metres in diameter) and rhyolite, together with quartz-amphibole-biotite-cordierite hornfels and quartz-biotite-amphibole schist. With a decrease in clast size and bedding thickness, these rocks grade into coarse varves with contain abundant dropped clasts and slump structures.

This afternoon we have an optional stop to look at an inclusion- and megacryst-rich analcimite; this is followed by a brief look at the distal eastern deposits of the Nandewar volcano (including a diatomite quarry), before we leave the Nandewar *central-type* volcanic province and enter the New England *lava- field* province. On our way eastward to Glen Innes, where we will spend the night, we will be passing over a series of thin flows ranging in composition from nephelinite and alkali basalt to tholeiitic basalt.

Stop 5.7 - Boomi Creek analcimite.

The Boomi Creek analcimite sill is about 2 metres thick and intrudes Carboniferous tuffaceous sedimentary rocks. Unfortunately, most of the former outcrops of the sill in the creek bed are now buried by boulders and gravel. The analcimite is very rich in mafic and ultramafic inclusions and has a varied megacryst assemblage, both being concentrated in the lower part of the sill. The host analcimite is extremely fine grained and invariably altered to some degree. Olivine (altered to 'bowlingite' and carbonate), pinkish clinopyroxene and sometimes plagioclase are set in a structureless analcime-rich groundmass which also contains alkali feldspar, biotite and titanomagnetite (Wilkinson, 1975b). The majority of inclusions belong to an ultramafic-mafic granulite suite whose members generally contain a Cr-poor green spinel. Ultramafic granulites of the Al-spinel suite are mainly pyroxenites, with rarer lherzolites, and the mafic granulites are usually composed of the assemblage plagioclase-aluminous pyroxene-spinel. Other inclusion types include Cr-spinel lherzolites - more Fe-rich than Cr-diopside lherzolite inclusions in alkaline volcanics - and rare wehrlite heter-adcumulates, probably cognate with the host analcimite. The megacryst assemblage is dominated by anorthoclase, accompanied in order of decreasing abundance by tschermakitic clinopyroxene, titanbiotite, kaersutite, and aluminous titanomagnetite. An analysis of the host rock, less inclusions and megacrysts, gives 40.63% SiO_2, 2.90% TiO_2, 7.71% MgO and 10.60% CaO. It is slightly *ne*-normative (3.7%) and has an $100Mg/(Mg + Fe^{2+})$ ratio of 63.0.

Wilkinson (1975a) suggested that the Al-spinel ultamafic-mafic inclusions were remnants of a layered 'pluton' which initially crystallised at pressures in the vicinity of 10 kb, and subsequently re-equilibrated at subsolidus temperatures (ca 950°C) and comparable pressures. The pressure regime of megacryst formation apparently was greater than 10-12 kb - i.e. the megacrysts precipitated before acquisition of xenoliths of the Al-spinel granulite suite by the analcimite host.

Rejoin bus and drive to Nandewar Range, 25 km to the southeast where distal products of the Nandewar volcano are exposed in road cuttings.

Stop 5.8 - Nandewar Range

The road passes up through the stratigraphic sequence from thinly bedded Permian basement sedimentary rocks, through tuffaceous sediment - which in one area contains rounded clasts suggesting some reworking - to a sparsely porphyritic hawaiite with fresh phenocrysts of olivine and clinopyroxene. The tuffaceous material forms a conspicuous marker bed, which can be seen near the top of the range and extending northwards.

Rejoin bus and proceed through Barraba and on to a diatomite quarry (35 km) where we will examine diatomite deposits associated with the Nandewar volcano.

Stop 5.9 - Diatomite Quarry

This quarry provides a 5 metre exposure of diatomite which overlies and is interbedded with tuffaceous sediments and clays, and is capped by basaltic flows. The basal tuff rests unconformably on shallow dipping Early Carboniferous-Late Devonian mudstone, sandstone, and conglomerate. *Melosira granulata* is the dominant diatom species (Towner, 1988). This quarry produces about Aust$1.5 million worth of diatomite per year which is calcined on-site. Its industrial usage is primarily as a filter medium, but also as a filler and extender in paint, paper, rubber, and plastics, and as an anti-caking agent, a thermal insulating material, industry absorbent, catalyst carrier, and mildly abrasive polishing medium. Flat-lying diatomite beds extend over many hectares and formed in the distal areas of the Nandewar volcano. Beds rich in plant fossils are present in some areas. Similar, but less extensive diatomite beds are also associated with the Tweed and Warrumbungle volcanoes and some of the latter contain well-preserved fish fossils.

Return to bus and drive 190 km to Glen Innes. On the way, if time allows, there will be a brief stop between Bingara and Inverell to look at a tholeiitic basalt of the New England *lava-field* province.

Stop 5.10 - *Lava-field* type tholeiitic basalt

The country we have been driving through is typical of the older *lava-field* type volcanic provinces of eastern Australia which generally consist of thin flows on a largely featureless landscape. This vesicular tholeiitic basalt is fine grained and aphyric and is cut by a series of volatile release pipes. The basalts of the New England *lava-field* province are mostly mildly to strongly undersaturated, but in the Inverell area tholeiitic basalts form a minor but important component and appear to form the lowermost flows (Duggan, 1972). Basalts of the New England Tableland fall into an Older and Newer series. The rocks in the central area of the province and southwards are dated at about 35 Ma, whereas in the southern and northwestern areas they are about 21 Ma. It is likely that this tholeiitic basalt belongs to the latter episode of volcanic activity.

DAY 6 - GLEN INNES TO MURWILLUMBAH

The first part of the day is spent driving north and east across the New England Tableland, then on down the Great Escarpment to the coastal plain and the Tweed volcano on the New South Wales-Queensland border (Fig. 10). Initially we will be passing over a series of Permian to earliest Triassic granites and volcanic rocks which are a major component of the New England Tableland. We will stop briefly at a quarry to look at the Dundee Rhyodacite (the rock used for the IAVCEI 1993 General Assembly commemorative paperweight) located just to the west of the Great Dividing Range.

The **Dundee Rhyodacite** is a unit of the Late Permian Coombadjha Volcanic Complex, a remnant of an extensive cauldron sequence of silicic calc-alkaline volcanics (McPhie, 1986). The Complex is elliptical, measures 15 x 24 km, and consists of an older group of ignimbrites, lavas, breccias and volcaniclastic rocks at least 1500 m thick, overlain by 500 m of texturally homogeneous, crystal-rich, dacitic ignimbrite - the Dundee Rhyodacite. The Dundee Rhyodacite covers an area of 180 km^2 in the centre of the Coombadjha Volcanic Complex and consists of four lithologies: ignimbrite, porphyritic dacite lava, bedded tuff and breccia. Ignimbrite, which forms this quarry, is the dominant phase and the matrix is totally devitrified and typically completely recrystallised to a microcrystalline mosaic of quartz and feldspar. Fresh crystal fragments (plagioclase + biotite + quartz + hornblende + pyroxene + magnetite $\pm$ K-feldspar) comprise more than 50 modal percent, and relic aligned welded shards appear as paler lenses on weathered surfaces. On fresh surfaces the pumice fragments are difficult to distinguish from the matrix of the host rock, although phenocrysts in the pumice are euhedral, sparser and larger. The continuous eruption of large quantities of the Dundee Rhyodacite ignimbrite led to sagging, then wholesale collapse intact of a fault-bounded, oval-shaped plug, to form the Coombadjha cauldron (McPhie, 1986).

Travel north to Tenterfield and then east along the Bruxner Highway towards Lismore.

Stop 6.1- Mallanganee Lookout

This stop provides a distant view of some of the outlying parts of the Tweed volcano and of other Miocene volcanic structures including the Tweed Range and the Mount Barney Complex. The latter, consisting mainly of granophyre bordered by an encircling ring fault (Stephenson, 1959, Ewart et al., 1987), is considered to be part of the Focal Peak Volcano, a large, deeply eroded central-type volcano predating the Tweed Volcano. Lava flows from the Focal Peak Volcano (the Albert and Kyogle Basalts) extend eastward to be overlapped by the basal flows from the Tweed volcano (Fig. 9).

Continue east through Casino, Lismore and Ballina to the coast at Lennox Head. From Casino to Ballana, the road traverses thin sequences of mafic lavas on the southern flanks of the Tweed volcano.

Stop 6.2- Lennox Head

This locality provides excellent coastal exposures of some of the distal mafic shield-building lavas of the Tweed volcano. The flows are typically thin, sometimes porphyritic, with vesicular tops and bases. On the northern side of the small headland, horizons of coal occur interbedded with the lava flows and produce interesting pipe-like structures of vesicles which appear to result from gas streaming from the wet coal beds.

From Lennox Head we will travel north to Murwillumbah, visiting outcrops on the southeastern flanks of the volcano *en route*.

Stop 6.3- Lookout north of Bangalow

This stop provides good views of the southern part of the shield and illustrates the low-angle dip slopes characteristic of the outer slopes of the Tweed volcano. Cape Byron, immediately to the east and the most easterly point on the Australian continent, consists of Palaeozoic basement sediments.

Stop 6.4- Coorabell Road

A brief stop will be made to examine a fresh example of the more mafic lavas of the Tweed Volcano. The rocks have been exposed by recent road works and no petrographic details of the rock are available. However, it appears typical of many of the mafic lavas of the southern Tweed which consist of occasional plagioclase phenocrysts in a groundmass of plagioclase, augite, ilmenite, minor olivine and a turbid glassy mesostasis of rhyolitic composition.

Stop 6.5- Mixed magma lava flow

This rock is clearly of hybrid origin. In addition to the numerous fragments of intermediate composition, the rock contains crystals of Mg-rich olivine (Fo_{80}; usually pseudomorphed by phyllosilicates), plagioclase, sanidine, augite, ferroaugite and quartz, all set in a brown glassy base of rhyolitic composition containing abundant pyroxene and feldspar microlites.

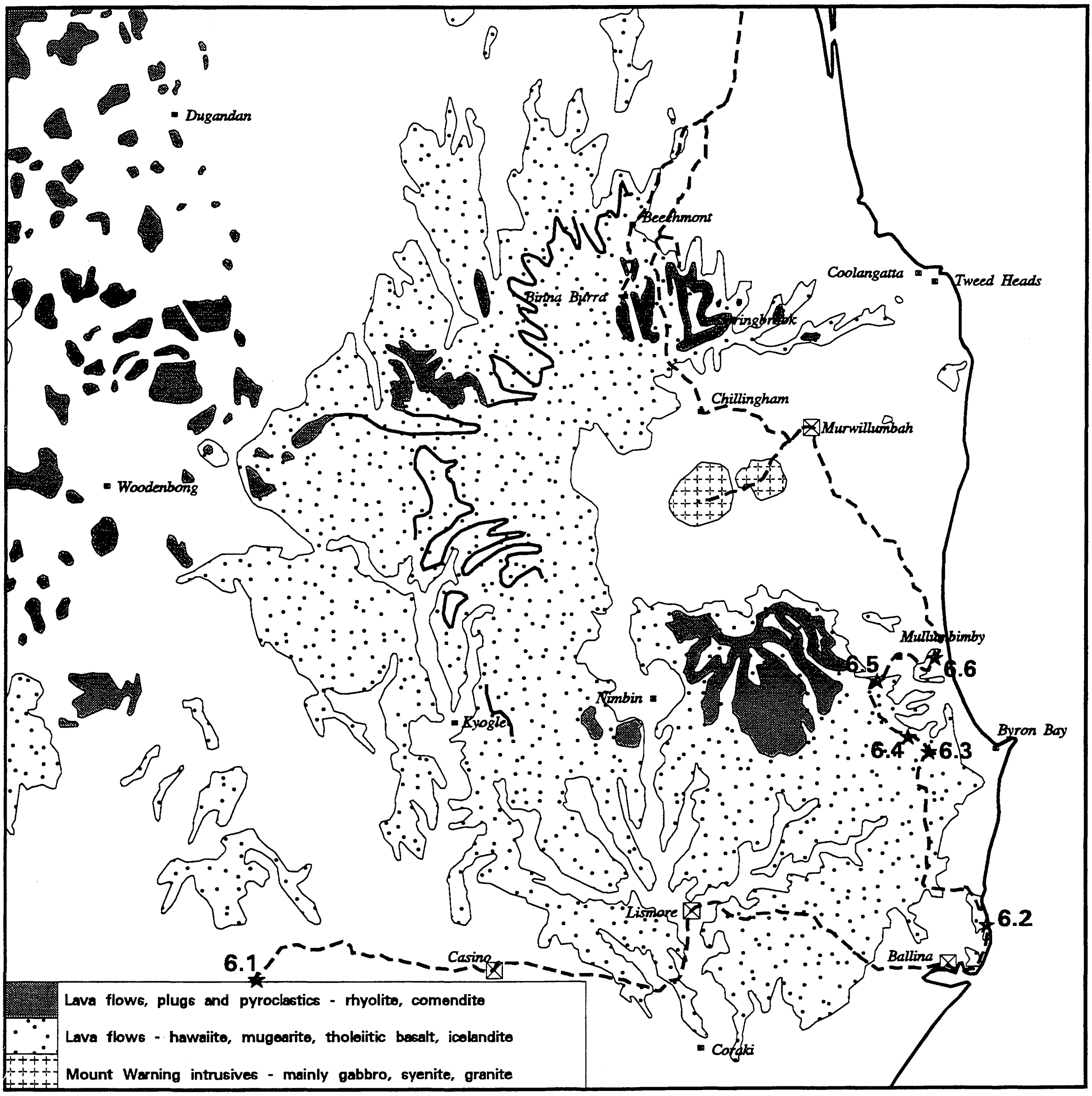

Figure 10. Generalised geological map of the Tweed Volcano showing the excursion route for Days 6 and 7.

Stop 6.7 - Brunswick Heads quarry

The plagioclase-phyric basaltic rock in this quarry (Table 3, No 3) has been described by Duggan & Wilkinson (1973). Crystals of aluminian enstatite ($Ca_4Mg_{71}Fe_{25}$; 4 wt % Al_2O_3) and sub-calcic augite ($Ca_{36}Mg_{44}Fe_{20}$; 5.2 wt % Al_2O_3) occur as inclusions in the very large plagioclase phenocrysts and in the groundmass (where they are mantled by a reaction rim of olivine and augite). The plagioclase phenocrysts are slightly more sodic than the groundmass plagioclase. The assemblage is believed to have crystallised near the crust-mantle boundary.

DAY 7 - MOUNT WARNING TO BINNA BURRA

Mount Warning: Ascent to the Summit (1156 m) is by graded track, leading from the parking area, a climb of nearly 770 m (in 4.5 km). At the Summit, an excellent series of lookouts has been constructed which allow 360° panoramic views of the surrounding caldera rim margins, and intervening Tweed Valley.

From Murwillumbah, the route is along the Uki Road, following the South Arm of the Tweed River. About 9.5 km from Murwillumbah, outcrops of micrographic rhyolite and microgranite are seen west and east of the road; a little farther on, a road to the west is followed up Korrumbyn Creek to a parking area

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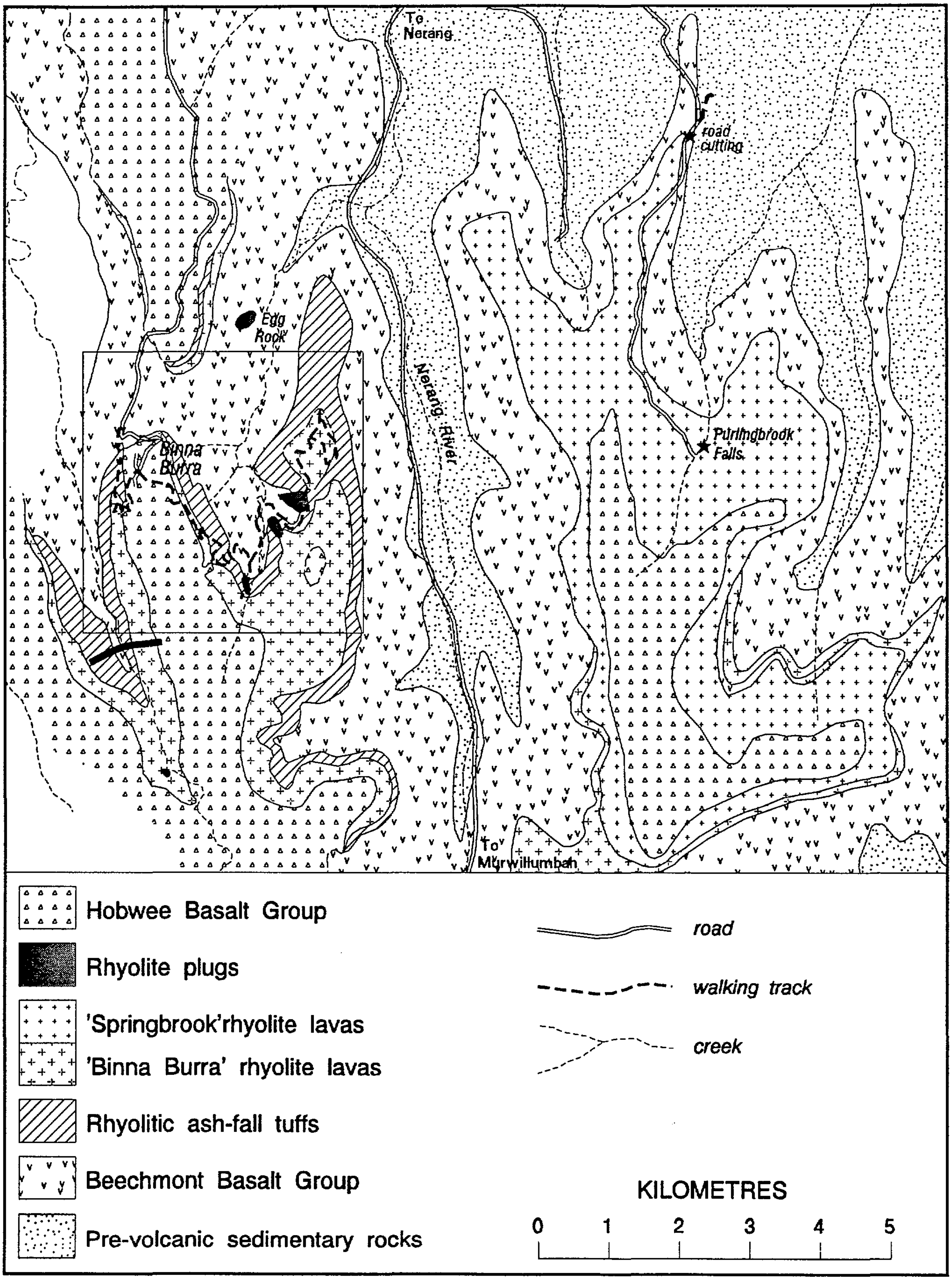

Figure 11. Geological map of the Binna Burra and Springbrook plateaus on the northern flanks of the Tweed volcano. The enclosed area is shown in more detail in Figure 12.

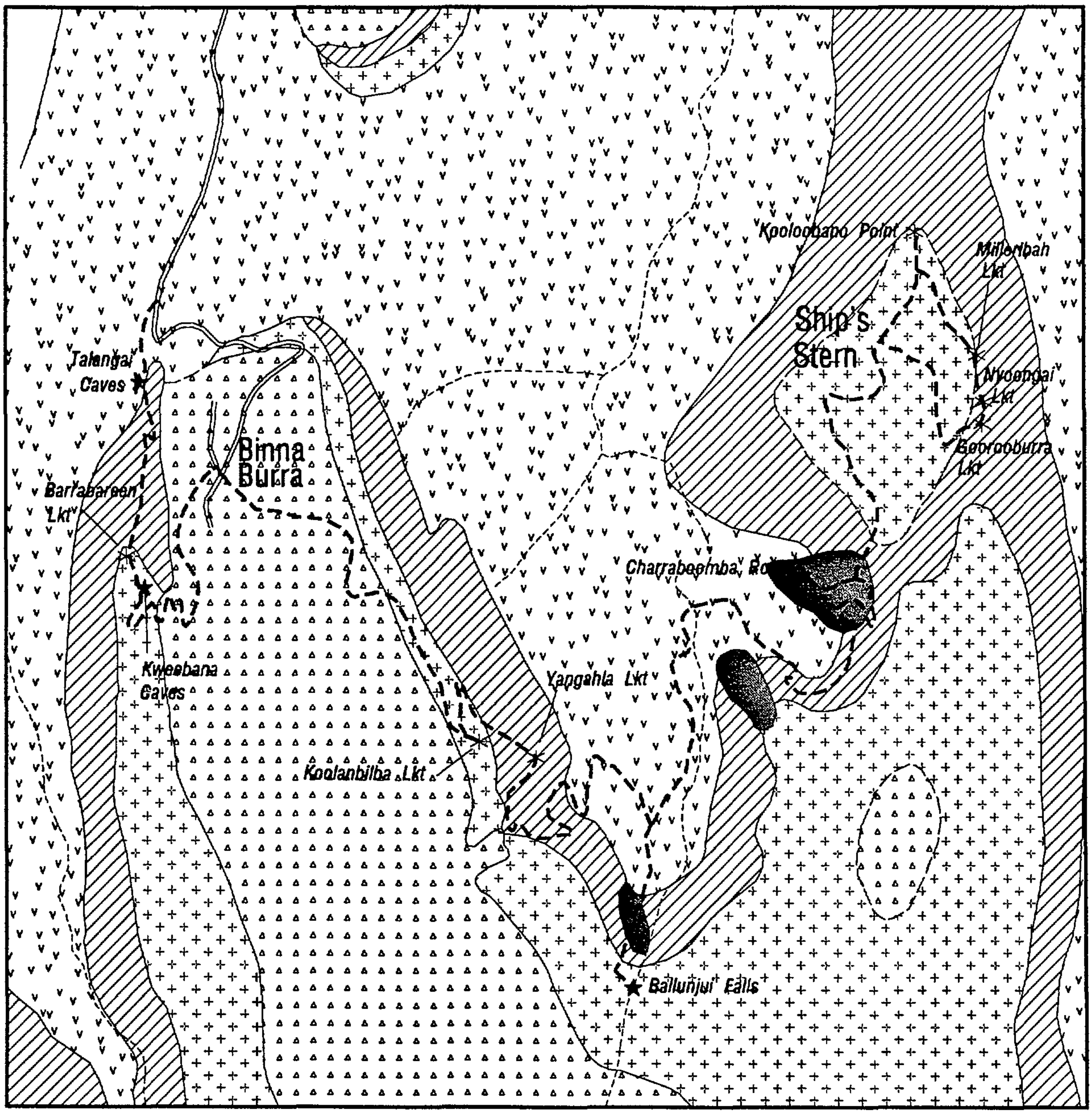

Figure 12. Detailed geology of part of Binna Burra National Park showing walking tracks to Talangai Caves and Ships Stern (inset area in Figure 11). Symbols as in Figure 11.

about 390 m above sea level. The foot track to the summit passes from the younger gabbro series on to syenite after about 1.6 km, then on to trachyandesite 0.8 km farther on. Good outcrops of jointed trachyandesite are traversed on the final steep climb to the summit.

On the return trip along the road from the parking area, recrystallised gabbros of the older series are seen along the roadside with andesine gabbro outcrops in the creek bed. At 1.7 km from the parking area, outcrops of gabbro occur below a small dam and for the next 320 m gabbro, in places cut by monzonite veins, outcrops sporadically in the area close to the road. From 2.1-2.5 km from the parking area, monzonite outcrops along the road and creek bed, with exposures present in the creek draining into the northern side of Korrumbyn Creek. The next rock type down the road is hornfels showing well-developed veining. It is derived from the Lower Palaeozoic metamorphics.

Murwillumbah to Binna Burra via Springbrook

From Murwillumbah, the route follows the Chillingham Road along the North Arm of the Tweed River. Close to Chillingham, the Palaeozoic-Mesozoic unconformity is crossed; the Triassic Chillingham volcanics (mostly rhyolites) form the conspicuous ridges. From Chillingham, the route is northerly, passing over sandstones and shale of the Bundamba Group, then Tertiary basalts, up to the State Border. Prominent cliffs to the right (east) are Springbrook rhyolite on the margin of the Springbrook Plateau. The road then runs down along the Numinbah Valley, following the Nerang River (Fig 11).

The route detours up to the Springbrook Plateau where two stops will be made. The first, at the summit of the ridge where the Numinbah and Gold Coast roads meet, is at a road cutting within the distal margin of the Springbrook rhyolite. This is vitreous, grading locally to pitchstone, and flow banded. The rhyolite is chemically and mineralogically distinct from those seen at Binna Burra; phenocrysts are plagioclase, sanidine, quartz, ilmenite, and Fe-rich orthopyroxene. The latter phase is highly susceptible to the hydration processes affecting the rhyolite.

The second stop is at Purlingbrook Falls. This provides an excellent lookout across the rhyolite unit (95 m thick) down to the underlying mafic lava flow belonging to the Beechmont Basalt. A vertical section through the volcanics at Purlingbrook Falls is shown in Figure 13.

DAY 8 - BINNA BURRA TO BRISBANE

A map showing detailed geology and walking tracks in the Binna Burra area is shown in Figure 12.

Talangai and Kweebani Caves via Barabareen Lookout: This is by foot along a graded track, a return distance of 2 km from the bitumen road. In this area, rhyolitic tuffs overlie, as well as underlie the rhyolite lava, the lava rapidly thinning out in a northerly direction. In the Talangai Cave, well bedded rhyolitic ash and lapilli are exposed, up to 60 m thick, interpreted to be lacustrine deposited at the caves, but passing upward into primary subareal tuffs.

The upper tuffs are immediately underlain by a coarse rhyolite boulder horizon, presumably the autobrecciated top of the underlying rhyolite lava. The Kweebani Cave provides an excellent exposure of the massive vitreous rhyolite and the breccia deposits. In fact, at this locality, there is some evidence for the upward protrusion of massive rhyolite into the breccia possibly indicative of a lava vent. The rhyolite is moderately phyric with quartz+plagioclase+sanidine and traces of ulvöspinel.

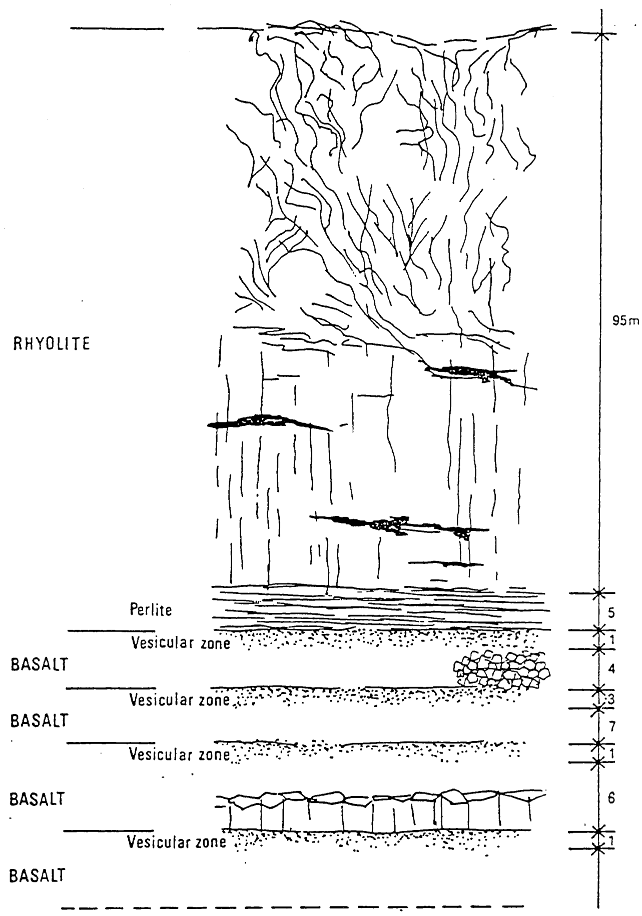

Figure 13. Vertical section exposed at Purlingbrook Falls, Springbrook Plateau. The track runs along the base of the rhyolite unit.

Swimming Pool Track: Graded track involving approximately a 3 km return trip to road. Exposed here is a very rare example of a Tertiary ash-flow deposit which forms the lower part of the main rhyolitic tuff sequence underlying the rhyolite lava. The deposit is 10 m thick, and passes up gradationally to bedded rhyolite ash fall deposits. The basal zone contains carbonized tree trunks and their casts, and overlies a baked and carbonised soil horizon.

Ships Stern: This is accessed by graded track, with a return distance of approximately 14 km. The track leaves Binna Burra, and descends some 360 m into the Kurraragin Valley, and then ascends 300 m to the summit of Ships Stern. Return to Binna Burra is via the same route.

The track passes through the Hobwee basalt to the Binna Burra rhyolite. An excellent panoramic view is obtained from Koolanbilba Lookout across to the Ships Stern with Charraboomba Rock and Egg Rock well

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Figure 14. Panoramic view looking north and northeast from Koolanbilba Lookout, Binna Burra, showing the Ships Stern Range (right), Turtle Rock (middle), Egg Rock, and northern part of Binna Burra (left). Sketch by Dr. E.J. Heidecker, Dept Earth Sciences, Univ. of Queensland.

seen (Fig. 14); these two spine-like features represent dyke-like intrusions. Charraboomba rock is petrographically similar to the Ships Stern rhyolite lava, and is a likely source of the rhyolite (a characteristic feature being the presence of biotite).

The track then descends through an apparent discontinuity in the rhyolite flow, well exposed at the Koolanbilla Cave where spectacular spheruloid structures occur. Below the cave the track passes by Yangahla Lookout, and the basal, perlitic breccia phase of the lava. Below this, and extending down toward the Kurraragin Valley, are the tuff horizons comprising phases of repeated explosion, interspersed with short erosion intervals (local unconformities). The tuffs contain fragments of basalt, rhyolite, and sandstone, locally to 1 m diameter. The tuffs are underlain by Beechmont Basalts at the bottom of the valley.

The track up to Ships Stern passes Charraboomba Rock, and passes up into the rhyolite lava. Excellent exposures of glassy rhyolite are common. The rhyolite contains phenocrysts of plagioclase, sanidine, quartz, biotite, ilmenite and rare allanite. From the northern and eastern sides of Ships Stern, spectacular views of the Numinbah Valley are obtained.

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