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CANBERRA 1993

EXCURSION GUIDE

NEWER VOLCANICS PROVINCE - BASALTS, XENOLITHS AND MEGACRYSTS

I. A. Nicholls, A.G. Greig, C.M. Gray and R.C. Price

GENERAL ASSEMBLY
SEPTEMBER 1993 - CANBERRA AUSTRALIA

ANCIENT VOLCANISM
MODERN ANALOGUES

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CANBERRA, AUSTRALIA, SEPTEMBER 1993

PRE-CONFERENCE FIELD TRIP A-4

Newer Volcanics Province - Basalts, Xenoliths and Megacrysts

Monday 20 - Friday 24 September, 1993

FIELD TRIP GUIDE

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August 1993

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INTRODUCTION

The Geological Setting of Victoria

The two main formative episodes in the geological history of Victoria were the Cambrian to Carboniferous evolution of the eastern Australian continental margin, and the Jurassic to present day opening of the Southern Ocean by the rifting of Australia from Antarctica.

Rocks associated with these episodes are geographically separate: Palaeozoic units are preserved in the Great Dividing Range which extends east-west centrally across the state; the Mesozoic-Cainozoic component occurs in an east-west coastal strip (Fig. I-1).
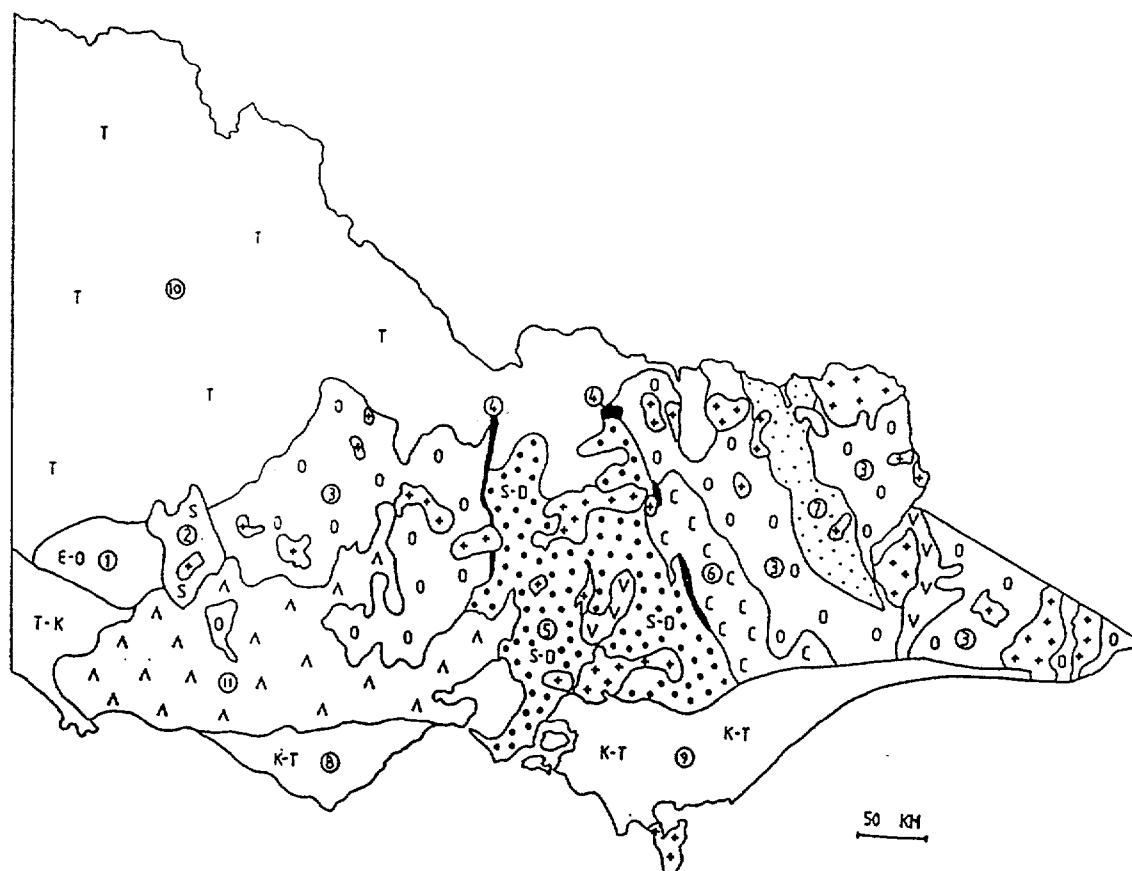
Fig. I-1: Victorian tectonic zones and geological units: 1 - Glenelg zone; 2 - Grampians subzone; 3 - Ararat-Bendigo zone; 4 - Heathcote greenstone belt; 8 - Otway Basin; 11 - Newer Volcanics province.

The Palaeozoic basement is subdivided into numerous tectonic zones of north-south strike and those of western Victoria which are pertinent to the field trip can be taken as typical. From west to east these zones are (numbers in *italics* refer to Fig. I-1):

(a) Glenelg zone *(1)* : sedimentary rocks of probable Cambrian age are metamorphosed from very low to migmatite grade and intruded by Cambro-Ordovician granites.

(b) Grampians subzone *(2)* : basalt-andesite-dacite volcanics and poorly exposed detrital sedimentary rocks of possible Cambrian age are tectonically disrupted into narrow strips. A rift valley developed on the site of the older units at the Silurian-Devonian boundary and filled with fluviatile sandstone (now exposed as the Grampians Range); this sequence was intruded by high level granites at ~400 Ma.

(c) Ararat-Bendigo zone *(3)* : extensive sandstone-siltstone-slate turbidites are unfossiliferous and are presumed to be of Cambrian age in the west, but are definitely Early to Middle Ordovician in the east. The zone was intruded by two groups of granites at 400 Ma (west) and 370 Ma (east). The eastern boundary of the zone is a narrow fault-bounded strip of Cambrian greenstones with ophiolitic character *(4)*.

The Palaeozoic tectonic setting envisaged for the development of these rocks is much debated, but in its broadest terms is considered an orogenic continental margin extending along the entire seaboard of eastern Australia and into Antarctica. For at least part of its history it was probably a convergent plate boundary, as suggested by the volcanism in the Grampians subzone.

During the Mesozoic, a new extensional tectonic regime was initiated across southern Victoria which led ultimately to the breakup of eastern Gondwana in this area and the initiation of sea-floor spreading between

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Australia and Antarctica. The earliest direct evidence for this extensional phase is seen in bimodal basalt-trachyte volcanics of Late Jurassic age in far western Victoria. This early volcanism was followed by thick sedimentation in the broad east-west Bassian Rift system which was firmly established across southern Australia in the Early Cretaceous. The initial rift valley phase in the Early Cretaceous was followed by a period of limited sea-floor spreading from about 90 Ma allowing the establishment of marginal and intermittently marine conditions during the Late Cretaceous. Rapid spreading on the south-Indian Rise began during the Eocene and allowed the establishment of fully marine conditions and continued shelf subsidence to the present day.

Cenozoic Volcanism in eastern Australia

The eastern margin of the Australian continent contains at least 16 major Mesozoic, and over 50 Cenozoic, volcanic-intrusive provinces. Cenozoic occurrences extend over 3500km in a belt up to 300km wide along and adjacent to the Eastern Highlands (Wellman and McDougall, 1974a). Three types of Mesozoic and Cenozoic volcanic provinces have been recognised in Eastern Australia (Wellman and McDougall, 1974a; Wellman, 1983), which in the order of their volumetric importance are basaltic lava fields, basaltic/felsic central volcano complexes and minor K-rich basalt-leucitite lava fields.

The areal extent and long duration of the three types of provinces have led many authors to propose models relating magmatism to large-scale tectonic activity. Wellman and McDougall (1974a) suggested that southward decrease in the age of central volcanic activity reflected northward movement of the Australian lithosphere at an average rate of 66 mm/yr, and models of this type have been elaborated and refined by e.g. Sutherland (1978, 1981, 1983), Smith (1982) and Wellman (1983). Sutherland (1981, 1983) related both central volcano and lava field provinces to movement of the Australian plate over multiple 'thermotectonic anomalies' originally associated with southeast Papua-Coral Sea-Tasman Sea spreading systems. Wellman (1983) discounted Sutherland's age-position relationships for lava field provinces, and re-interpreted the age relationships of central volcano and K-rich lava field provinces in terms of distance from the pole of rotation of the Australian plate relative to the fixed hotspot reference frame (Duncan, 1981). Wellman also demonstrated age-position relationships for Mesozoic igneous occurrences in southeast Australia. Relationships between plate motions, heat flow, magmatism and uplift of the Eastern Highlands have been discussed by e.g. Wellman (1979), Smith (1982), Karner and Weissel (1984) and Lister and Etheridge (1989).

The nature and origin of the 'hotspots', 'hot lines' or 'thermo-tectonic anomalies' within the asthenosphere required by the various models are problematical. They may involve:

(a) convective plumes from the deep mantle in the original sense of Morgan (e.g. Duncan, 1981),

(b) material rising from partially melted megaliths of subducted oceanic crust (Hofmann and White, 1982; Ringwood, 1982),

(c) former sites of oceanic spreading centres (Sutherland, 1981, 1983) or

(d) sites of tensional stress within the lithosphere leading to upwelling of the asthenosphere (Frey et al., 1978; Pilger, 1982).

Whichever model applies, there is already some plate tectonic and petrologic evidence that central volcano mafic-felsic provinces may represent magmas from deeper, fixed asthenospheric sources, while more extensive lava field provinces lacking clear cut age-position relationships represent melting events in the shallow asthenosphere or deep lithosphere in response to more local tectonic processes. Hence the two types of province may represent mantle magma sources with distinctive evolutionary histories and geochemical characteristics.

Volcanism in the Victorian portion of the Eastern Australian province over the past 160 million years has occurred essentially in three stages, although magmatic activity has been almost continuous (Wellman, 1974; Price et al., 1988):

(1) Early to Late Jurassic volcanism associated with the onset of rifting between the Australian and Antarctic continental plates. The basalt-trachyte association produced is confined to far western Victoria e.g. Dundas Tableland.

(2) Palaeocene to Early Miocene volcanism associated with formation of marine basins near the rifted margin of the Australian plate (The Older Volcanics). The remnants of extensive lava fields and valley flows of alkaline basalts are found as hilltop cappings in eastern Victoria. Similar rocks occur within marine sedimentary successions in western Victoria and offshore from eastern Victoria.

(3) Pliocene to Recent Volcanism associated with minor internal adjustment of the Australian plate margins (mainly faulting and uplift). The main resulting features are very extensive young lava fields ($\sim$20000km^2) in western and central Victoria (The Newer Volcanics province, consisting of the Western Plains and Central Highlands sub-provinces - Nicholls and Joyce, 1989).

The 'Newer Volcanics' basaltic province of Victoria

The Newer Volcanics provinces includes both an area of restricted lava fields and very numerous volcanic cones in the uplands northwest of Melbourne (the Central Highlands sub-province) and a much larger area of lava plains and cones within the southwestern part (The 'Western District') of the state of Victoria and the southeastern corner of South Australia (the Western Plains sub-province). The products of Central Highlands activity fill valleys in a heavily dissected area of mainly Ordovician sedimentary rocks of the Lachlan Fold Belt succession (part of the Ararat-Bendigo Zone). The western plains of Victoria were in existence before the commencement of Western Plains sub-province volcanism, and volcanic rocks form only a thin veneer (normally < 60m) on a late Tertiary erosion surface. Large areas of the southern half of the plain are underlain by shelf carbonates and sands of Miocene-Pliocene age, and the northern half is underlain by folded Palaeozoic rocks (Fig. I-2).
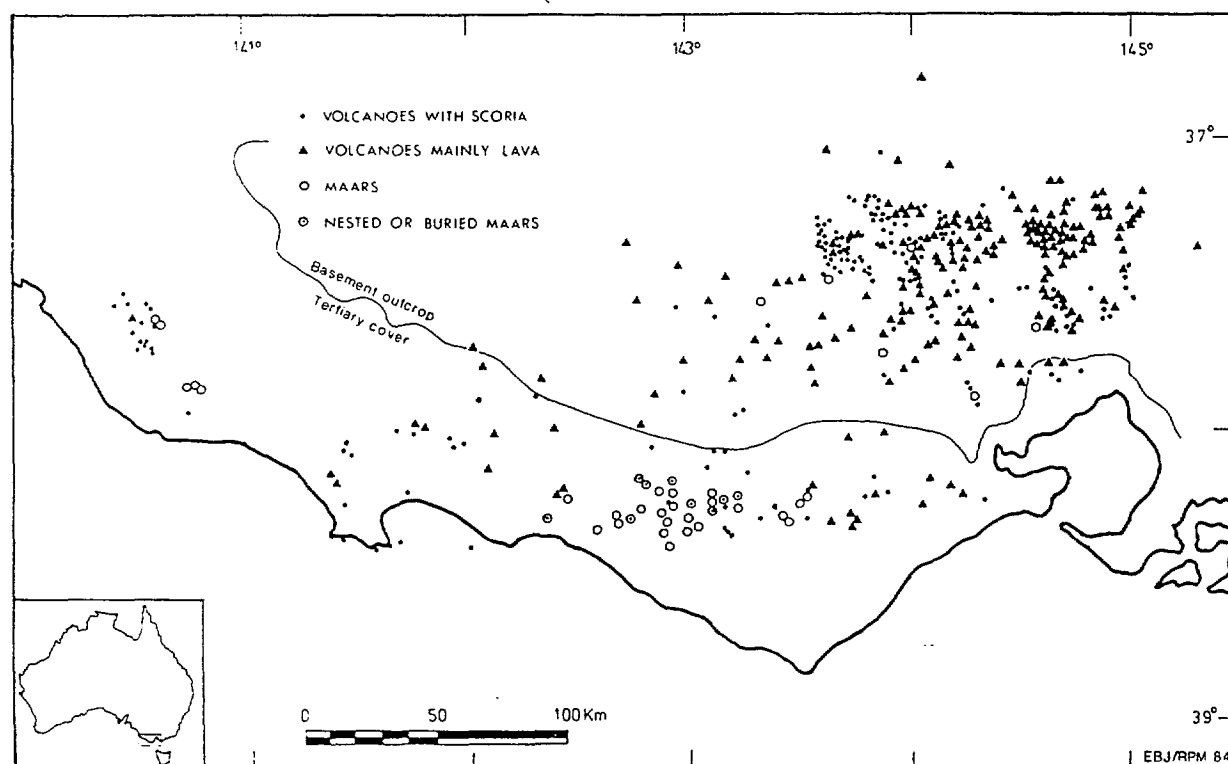
Fig. I-2: Distribution by type of 'Newer Volcanics' eruption points within southeastern Australia (from Joyce, 1975) showing the trace of the boundary between basement outcrop and Cenozoic cover sequences .

The earliest exposed lavas of the plains-forming activity date from around 4.5 Ma (McDougall et al., 1966) and they include large volumes of tholeiitic as well as alkaline basalts (see below). This early activity may have involved fissures which are now covered. However, slightly younger volcanic centres, including lava flows and pyroclastic fall and surge deposits, are well preserved in the far southwest of the Western Plains sub-province (Portland district). Lavas of some of these complexes have been dated at 3.0-2.7 Ma (Aziz-ur-Rahman and McDougall, 1972). Similar dates have been obtained for some of the older lava fields and volcanic cones in the Central Highlands sub-province. By contrast, most of the more prominent volcanic features (scoria cones, maars and major lava flows) of the Western Plains sub-province belong to much younger phases of activity (25000-5000 years BP), involving mainly strongly alkalic magmas (basanite-hawaiite).

The total number of Newer Volcanics scoria cones and maars is large (about 400 - Joyce, 1975), but even the largest of the cones (Mt. Elephant and Smeaton Hill) stand only ~250m above the surrounding lava plains and they are little more than 1 km in diameter. This is reflected in the small proportion of pyroclastic material (around 1%) estimated for the Newer Volcanics province (Ollier and Joyce, 1973). The youth of the volcanic centres is clear from the minor erosion they have suffered. Hence there is virtually no exposure of internal structures unless the cones are quarried (as they often are in the Western Plains). From the external form and features of quarry exposures, it is usually possible to classify them into a smaller number of types.

Types of Volcanic Centres

Lava Cones: Low-angle hills of moderate relief, formed by the repeated eruption of basalt lava flows (Singleton

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and Joyce, 1968). Examples are common west and north of Melbourne.

Scoria Cones: Conical hills formed by the accumulation of strongly vesiculated basaltic ejecta (scoria). The steepness of the slopes may differ widely depending on the coarseness of the ejecta, the height of the eruption, wind velocity, the geometry of the conduit and other factors, but slopes steeper than 10° are typical (Wood 1980a). They are the result mainly of Strombolian explosive volcanic activity, with the tephra deposited by air fall.

The cones are composed of variable sized basaltic ejecta, ranging from ash to blocks and bombs. The variable nature of the pyroclasts indicates that the cones accumulated by explosive activity of variable strength, erupting magma with variable properties. Scoriaceous clasts are angular, lapilli sized (2-64 mm) fragments of moderate to highly vesicular basalt, and they have stringy to breadcrust surface textures. Basaltic blocks and bombs (> 64mm) make up the coarse fraction of the cones. Blocks are irregularly shaped (normally angular) and are generally dense to semi-vesicular. Bombs display the greatest range of morphologies (e.g. cow-pat, spindle, fusiform and ribbon shaped) which are the result of changes in shape of the fluidal lava as it travels through the air or when it hits the ground. Bombs commonly display a zonation in vesicularity, with large vesicles in the core and dense micro-vesicular rinds. Some bombs and blocks contain cores of country rock or mantle-derived xenoliths (e.g. Mts. Leura, Shadwell).

The deposits forming scoria cones tend to be thick and massive. Bedding is poorly defined with some crude grading. Beds vary from agglomerates of discrete pyroclasts or spatter to agglutinates of flattened and welded fragments (e.g. Mts. Elephant, Eccles).

Maars and Tuff Rings: Maars are volcanoes which have craters cut into the surrounding bedrock. They generally lack preserved inward-dipping tuff beds and frequently exhibit vertical scarps below the crater rim, due to collapse of rim beds into the crater (Wood, 1980b). Tuff rings have relatively steep rims with both inwardly and outwardly-dipping beds preserved, with approximately equal slopes (Wood, 1980b). Typical crater diameters of the Newer Volcanic volcanoes of these types range from a few hundred metres to 3 km.

Maars and tuff rings result dominantly from phreatomagmatic volcanic activity. Phreatomagmatic eruptions occur when rising magma comes in contact with groundwater in an aquifer or surface water in a lake or sea. The disruption of the magma occurs first by the exsolution of magmatic gases to produce a coarse mode (as in Strombolian magmatic eruptions) and subsequently by explosive interaction between magma and water (Self and Sparks, 1978) (e.g. Lakes Bullenmerri, Gnotuk and Purrumbete).

Basaltic phreatomagmatic eruptions typically produce deposits with wide grainsize variations. The lapilli-sized clasts tend to be rounded, with cauliflower surface textures, and they are dense to microvesicular. The

ejecta are deposited by pyroclastic air-fall and pyroclastic (base) surge mechanisms. Surges are generated either as toroidal clouds expanding radially in all directions from vent (or, in some cases, as restricted, directed blasts) or by the collapse of an eruption column. Surges involve the lateral movement of pyroclasts as expanded, turbulent, low concentration gas/solid dispersions (Wright et al., 1980) and they form deposits which display unidirectional sedimentary structures, especially cross bedding.

In Western Victoria, the maars and tuff rings are closely associated with the deepest parts of the Tertiary sedimentary basins underlying the plains (Fig. I-3). The country rock fragments which occur within the deposits are dominantly limestone or sandstone, ripped up by the phreatomagmatic eruptions and the passage of magma through the strata.

Cross-bedded units, commonly with 'climbing dune' structures (dune crests migrate upward and away from source) and constant dune wavelengths (especially at Lake Purrumbete) are unambiguously identified as surge deposits. Antidune structures (prograding toward source) are rare, indicating that higher velocities of surge transport were rarely reached. Nearer source, large lava blocks, with associated 'bomb sags' are common. Accretionary lapilli occur, especially at Tower Hill. In several cases, slumping or faulting of layers and even large parts of the crater rim have occurred during eruption, and structural complexities arise (especially at Lake Purrumbete, where major unconformities occur).

Composite Centres: The composite volcanoes of the Newer Volcanics province are composed of deposits resulting from both phreatomagmatic and magmatic eruption mechanisms, which in some cases come from multiple eruption points. As an example the Tower Hill volcanic centre is composed of a maar with a scoria cone complex within its lake. The maar rim deposits were built up by irregularly alternating magmatic and phreatomagmatic eruptions, the latter producing deposits of dominantly base surge origin. The scoria cones present within the crater lake formed along two fissures in the last stages of eruptive activity. They showered the rim with scoria and basaltic bombs and produced lava flows of limited areal extent.

By contrast, Mt. Leura is composed of a group of scoria cones built up in the centre of a tuff ring or maar. The cones extended to cover almost the entire succession of underlying phreatomagmatic deposits. The scoria sequence contains an interbedded lava flow. The observed changes in style of activity reflect either decrease in the availability of water from aquifers, increase in magma discharge rate, or both.

Features of Lava Flows

The features of lava flows are very well illustrated by the 5000-7000 year old occurrences in the Portland-Hamilton-Port Fairy area, particularly the large flows originating from Mt. Rouse, Mt. Napier and Mt. Eccles (see Fig. 3). Ollier and Joyce (1964) distinguish two main types of lava flows in Western Victoria:

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NORTH   SOUTH

←—HIGHLANDS—→—◄————————— VOLCANIC PLAINS —————————►◄————►

                                                    OTWAY RANGES   BASS STRAIT

                              ←— MAARS —→

🐚	NEWER VOLCANICS	Ku	UPPER CRETACEOUS SEDIMENTS
Tm	MIOCENE SEDIMENTS	Kl	LOWER CRETACEOUS SEDIMENTS
Te	PRE-MIOCENE SEDIMENTS	+ +	GRANITE
		Pz	PALAEOZOIC SEDIMENTS
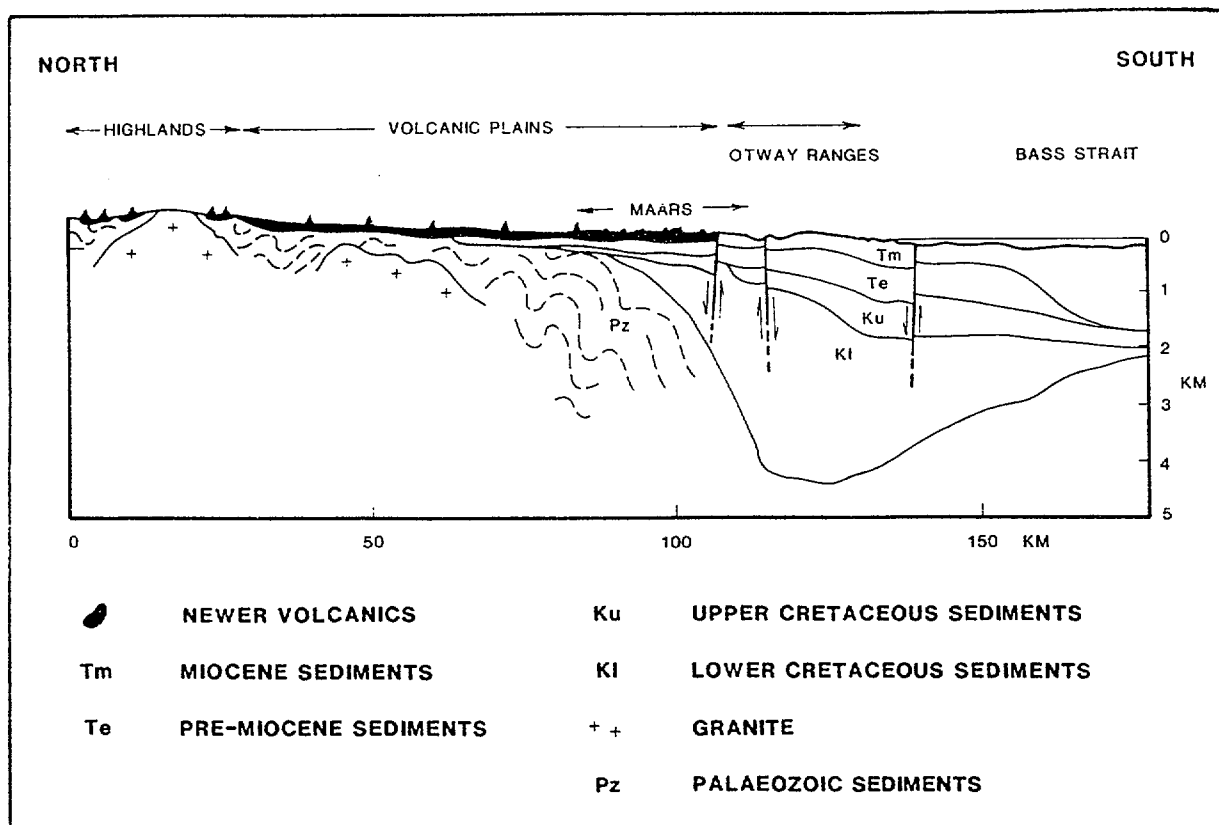
Fig. 1-3: Diagrammatic north-south cross-section across the Western Plains sub-province along longitude 143°E (from Joyce, 1975).

Sheet Flows - formed by the unconstricted spread of very liquid lava. Most flows are relatively thin, averaging around 5-7 m. Where exposures exist, the lava plains are seen to consist of repeated thin flow sheets.

Constricted Flows - follow pre-existing stream valleys, and are of much greater thickness but narrower than sheet flows. The youngest flows of this type are readily distinguished, e.g. the Harman Valley flow from Mt. Napier as seen from the Macarthur-Hamilton road near Byaduk (Locality 10). Some constricted flows travelled very long distances. e.g. the Tyrendarra flow from Mt. Eccles extends almost 60 km, including 15km now submerged beneath the sea (Fig. 7).

When hot basaltic lava flows on the land surface, it quickly cools to form a 'skin' of more rigid material, enclosing hot highly fluid interior lava. Many of the surface features of flows result from processes affecting this skin. The larger-scale features of this type which may be seen in the Newer Volcanics field include:

(1) Lateral Ridges: These occur when slow-flowing material along valley flow edges solidifies to form ridges or benches parallel to the flow edge. The more fluid central portion of the flow commonly subsides, leaving these raised features behind. Good examples are seen in the Tyrendarra flow of Mt. Eccles where it crosses the Princes Highway east of Portland and in the Harman Valley (Localities 10. 11).

(2) Lava Tunnels: When a rigid skin forms on a constricted lava flow, the interior fluid lava may drain away leaving extensive systems of lava tunnels up to 5 m high. Lava tunnels tend to form in constricted parts of flows (e.g. at Mt. Eccles and the Harman Valley flow from Mt. Napier at Byaduk - Localities 10-12).

(3) Stony Rises: In several areas of young basaltic flows seen during this trip, hummocks and depressions, channels and ridges make a completely confused topography with relief of 5-10m or less. The most common type (best seen near Pirron Yallock, on the Princes Highway east of Camperdown - Locality 18), appears to have arisen by sagging of the surface 'skins' of an extensive series of lava sheets.

(4) Lava Tumuli: Best seen near Wallacedale, northwest of Mt. Eccles, where the Harman Valley flow from Mt. Napier passes through the Condah swamp, these are domelike features. They are considered to have arisen by upwards pressure of liquid lava on the jointed surface crust of the flow, causing doming (Figs. 5, 6).

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Geochemistry

Most of the more recent published petrological-geochemical studies of the Newer Volcanics have considered in detail only the volcanic centres of the Western Plains sub-province (Irving and Green, 1976; Frey et al., 1978; McDonough et al., 1985), with an emphasis on those that carry mantle-derived xenoliths and megacrysts. Within the province as a whole, the basalt types present span the full range from strongly tholeiitic to strongly alkaline. Representative chemical analyses are presented in Tables 1 and 2. The relative proportions of the various basalt types in both the lava plains and the volcanic cones are indicated in Fig. I-4, which shows that the cones are composed largely of alkalic types. The basanites are considered to be partial melts from a garnet peridotite source with the liquids unmodified by crystal fractionation on the basis of their high Mg-numbers and Ni contents. The remainder of the basalts, hawaiites to tholeiites, are interpreted as the products of a range of degrees of melting of mantle sources, followed by crystal fractionation dominated by olivine removal (Irving and Green, 1976). This view has been supported by REE modelling (Frey et al., 1978), but with the additional ingredient that some basalt types require sources which have undergone enrichment in light REE and other incompatible elements prior to melting to account for the relatively high abundances of these elements in the basalts. Primary basanite and nephelinite magmas formed by approximately 5% melting, and tholeiitic basalt magmas by up to 25% melting, of mantle sources.

Sr and Nd isotopic ratios of tholeiitic and alkaline types (McDonough et al., 1985) form a continuum of compositions within the range $^{87}Sr/^{86}Sr = 0.7038-0.7049$.
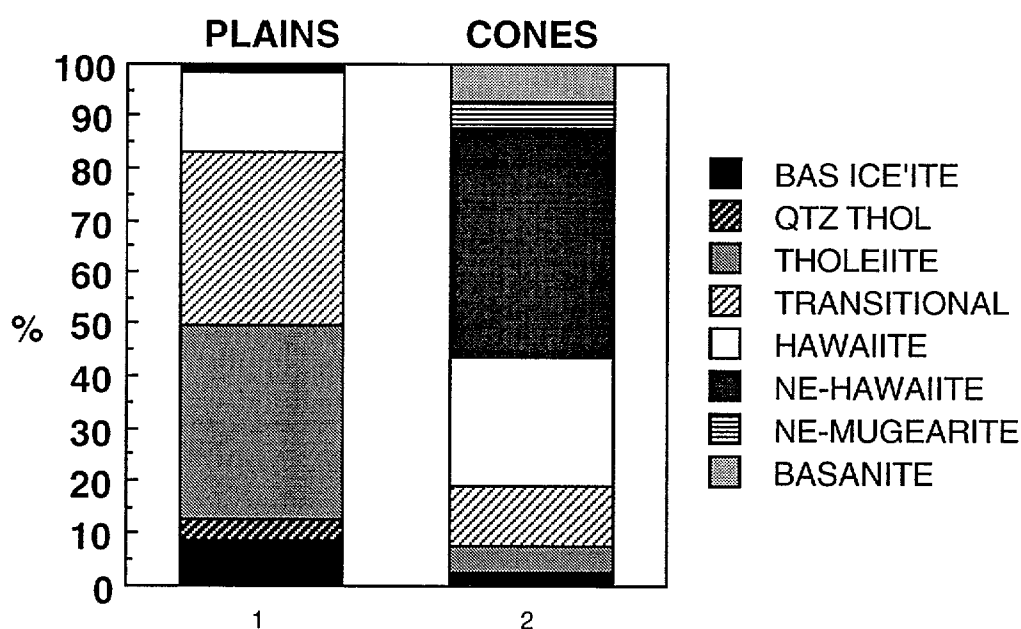
Fig. I-4 : Proportions of basalt lithologies in plains lava flows and volcanic centres in the plains subprovince. The following lithological classification is used throughout this guide. CIPW norms are calculated on an anhydrous basis assuming Fe_2O_3/FeO is 0.2. Rocks with >10% normative hypersthene are classified as tholeiitic and are further subdivided on the basis of SiO_2 content (tholeiite <52%; quartz tholeiite <52%, but with normative quartz; basaltic icelandite 52-55%). Rocks with 0-10% normative hypersthene and normative plagioclase An_{30-50} are labelled transitional hawaiites. Rocks with normative nepheline are classified following Coombs and Wilkinson (1969) with 5% nepheline taken as the boundary between moderately and strongly alkalic types.

The plains basalts have been the subject of recent intensive study (RCP and CMG) and over 500 analyses for major elements, trace elements and Sr-isotopes are now available. Price et al. (1991) demonstrated that for some incipiently weathered or altered samples, abundances of certain trace elements (Y, REE, and Ba) can be significantly modified from original magmatic values. These effects can be identified using specific trace element ratios (e.g. Ba/Rb). Exclusion of affected samples reduces the available data set to around 300, which still provides an excellent data base with which to examine the geochemistry of the province. Points that can be made immediately from consideration of these data are that the proportions of basalt types differs greatly between the plains sequences and the volcanic centres (Fig. I-4) and the province as a whole is not alkaline as previously believed, but tholeiitic to transitional. (It is likely that the data set for the volcanic centres is biased toward xenolith-bearing alkalic types and that the contrast between cones and plains is not as stark as in Figure I-2; however, it is important to note that the overall character of the province has been misrepresented in the literature).
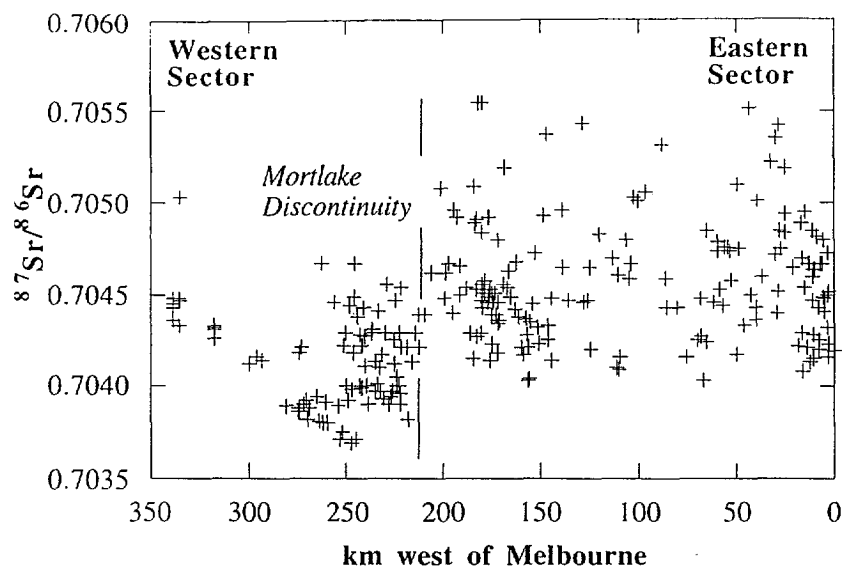
Fig. 1-5: *East-west section across western Victoria showing the variation in* $^{87}Sr/^{86}Sr$ *isotopic composition of plains basalts. There is a marked change in the range of isotopic compositions on either side of a line running through the town of Mortlake (The Mortlake Discontinuity). This divides the province into Eastern and Western sectors.*
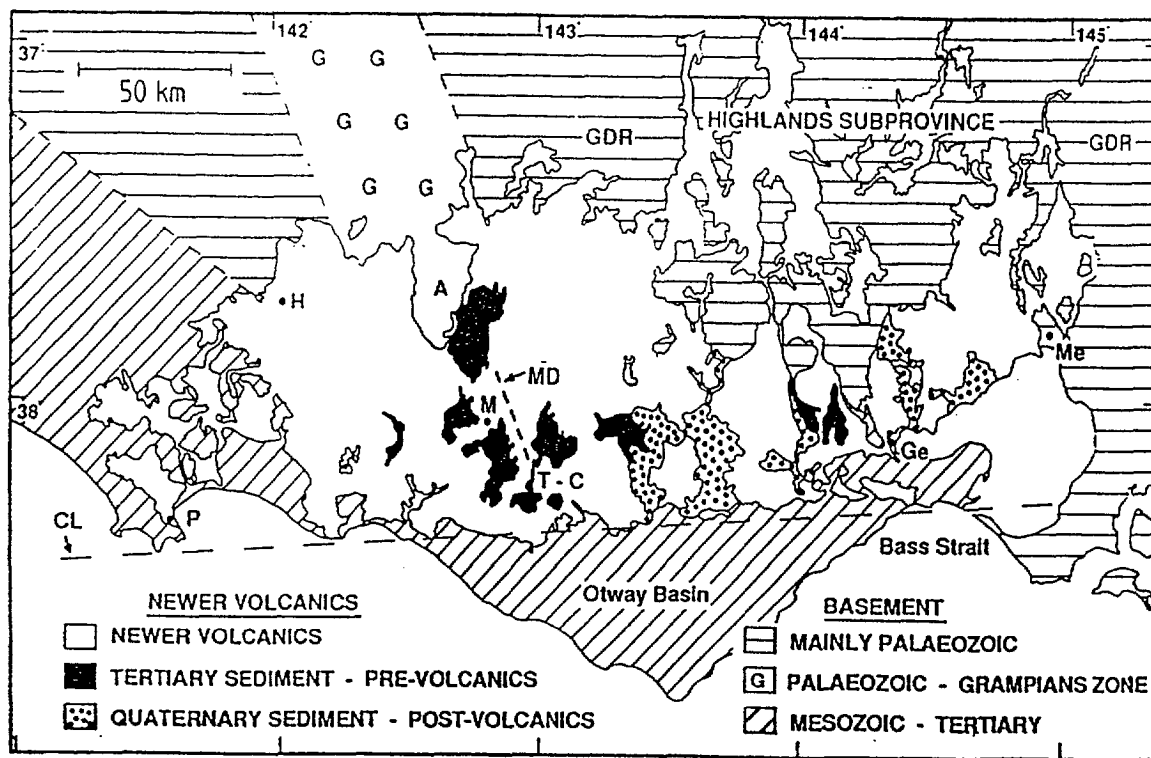
Fig. 1-6: *The Newer Volcanics Province of Victoria. GDR=Great Dividing Range; Ge=Geelong; H=Hamilton; M=Mortlake; Me=Melbourne; P=Portland; T-C=Terang-Camperdown area; CL=Colac Lineament; MD=Mortlake discontinuity.*

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Given that the majority of cones studied are alkaline, a derivative issue is the location of the sites of eruption of the tholeiitic rocks, because in tholeiitic areas the obvious volcanic peaks are commonly demonstrably alkaline. In many plains areas primary volcanic morphology has been destroyed by erosion, the dominant tholeiitic basalts have very similar chemical compositions, and geological mapping is virtually impossible. At the beginning of the plains geochemical survey the only available subdivision of these rocks involved relative age derived from the intensity of weathering profiles found in the far west of the subprovince (Gibbons and Gill, 1964). However, Sr isotopic compositions often vary sufficiently to allow distinctive domains of isotopically uniform basalts to be outlined and taken as primary mapping units. These domains are interpreted as representing individual flows or groups of flows from a single volcanic centre (Price et al., 1988; Gray and Price, 1989).

The Sr-isotopic data also permit the subdivision of the Western Plains sub-province into distinct eastern and western sectors. If the available data are projected on to an east-west section line (Fig. I-5), a clear discontinuity is expressed near the town of Mortlake (Fig. I-6) with both maximum and minimum initial ratios differing between the eastern (0.7040-0.7058) and western (0.7037-0.7050) sectors. In spite of this distinction, the overall geochemistry and eruptive histories of the eastern and western sectors are very similar and the sub-province may still be considered as a geological entity. The Mortlake discontinuity coincides with the projection across the sub-province of the Grampians tectonic subzone, which is a major basement structure interpreted herein as a Palaeozoic convergent plate boundary. Thus a significant lithospheric structure is expressed in a fundamental aspect of the basalt geochemistry, which therefore appears to be strongly influenced by the nature of the lithosphere beneath the Newer Volcanics province.

Using geochemical data alone, the petrological constraints on the plains basalts are as stated for the volcanic centres; the most significant aspect is that the abundant tholeiites would not be considered primary melts because their Mg numbers are mainly in the range 58-64. However, the addition of Sr, Nd and Pb isotopic data suggests a quite different assessment (Nd and Pb from Gray, Tatsumoto, and Price, unpublished results). The large number of Sr isotopic data allow the recognition of three broad lineages of basalts within a continuum of compositions (Fig. I-7). The eastern sector has two trends: the tholeiite trend from low-Rb tholeiites to basaltic icelandites has relatively low concentrations of Sr and Rb, with $^{87}Sr/^{86}Sr$ from 0.7040 to 0.7058; the alkalic (hawaiite) trend extends from low to high Sr and Rb concentrations within a narrow band of $^{87}Sr/^{86}Sr$ from 0.7035 to 0.7045. The western sector overlaps with the eastern data along the hawaiite trend, but includes a unique component, the Rouse trend, in which hawaiites have distinctive low values for both Rb and Sr concentrations and $^{87}Sr/^{86}Sr$ ratios.

There is a general decline in $^{87}Sr/^{86}Sr$ ratios through the history of the sub-province, punctuated in the eastern sector by a distinct spike of the most radiogenic tholeiites in the 3-2 Ma interval. The Sr-Nd isotopic correlation diagram (Gray, Tatsumoto, Ludwig, and Price, unpublished data) has discrete eastern and western alignments of data which converge to a common hawaiitic point at an $^{87}Sr/^{86}Sr$ of 0.7040. The Pb
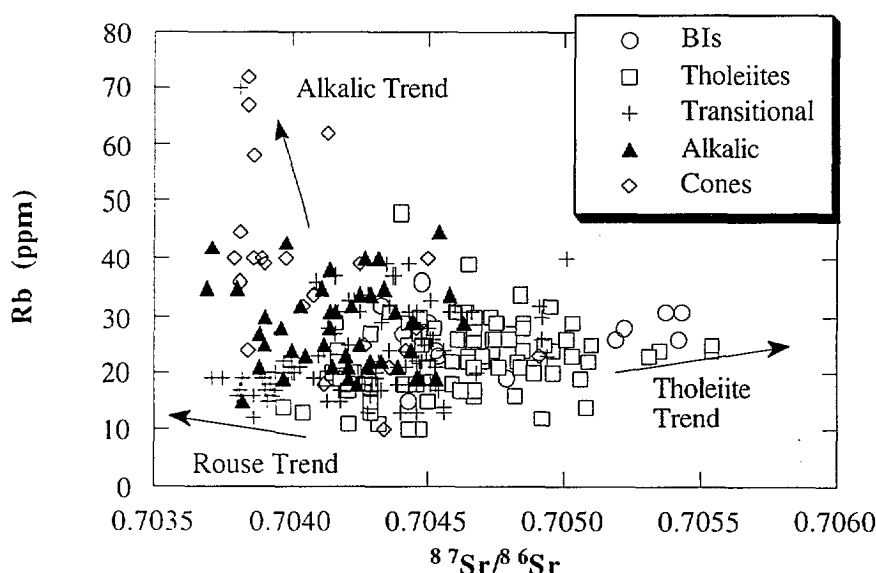

Fig. I-7: Rb concentration (ppm) versus $^{87}Sr/^{86}Sr$ ratio for basalts from the eastern and western sectors of the plains subprovince outlining the tholeiite, alkalic (hawaiite) and Rouse compositional trends. 'BI' (basaltic icelandite). 'tholeiites', 'transitional', and 'alkalic' are the compositional basalt types of the plains. 'cones' are the younger cone-building eruptives.

isotopic measurements form a continuum on a $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram with adjoining areas for eastern and western data, and a change to higher $^{206}Pb/^{204}Pb$ with decreasing age. The details of the isotopic data are inconsistent with formation of the basalts by varying degrees of partial melting of a single mantle source or by fractional crystallisation, and exclude significant amounts of crustal contamination. The coherence of the data suggests that the basalt geochemistry is the result of mixing between several asthenospheric and lithospheric mantle components. The mixing process is most readily explained by mixing of magmatic components during ascent, but might have occurred in the mantle source material well before melting.

Geochronology

The chronology of the Newer Volcanics is based upon conventional total rock K-Ar ages, mainly on plains lava flows and predominantly determined in the Research School of Earth Sciences, Australian National University laboratory. The early K-Ar ages had the dual purpose of establishing the volcanic history and the magnetic reversal timescale (McDougall et al., 1966; Aziz-ur-Rahman and McDougall, 1972). Subsequent work has emphasised geological objectives (McDougall and Gill, 1975; Singleton et al., 1976) including

defining the Pliocene-Pleistocene boundary. Approximately 50 K-Ar ages are available from these sources. The data base is virtually doubled by determinations that form part of the regional study of the plains basalts outlined above (Gray, McDougall and Price, unpublished data); the new ages are intended to constrain geochemical evolution, to date specific basalt domains, and to provide a more comprehensive geographic coverage of the sub-province.

Volcanism commenced at 4.6 Ma, and until 3.0 Ma involved the eruption of compositions mainly in the olivine and quartz tholeiite to transitional hawaiite range. The volumetric peak of activity occurred between 3.0 and 2.0 Ma, and in the eastern sector of the subprovince was marked by the development of strongly tholeiitic rocks with unusually radiogenic Sr ($^{87}Sr/^{86}Sr$ = 0.7050-0.7058 - Fig. I-5). Subsequent to 2 Ma, basalt compositions have become more hawaiitic with the alkaline influence stronger in the western sector. There are insufficient data to permit a full chronology of volcanic centres to be determined. The timing of the youngest eruptions has been constrained by ^{14}C dating of organic material such as peat, collected stratigraphically above and below lava flows (Gill, 1978). Activity as young as 6000 years BP is recorded in Victoria and 5000-4000 years BP in south-eastern South Australia.

Xenoliths of Mantle and Crustal Origin in the 'Newer Volcanics' Field

There are at least 30 known localities within the Newer Volcanics province at which abundant xenoliths and/or megacrysts of mantle or crustal origin are found in lava flows or fragmental deposits (see XENMEG - Wass and Irving, 1976). Some of these are amongst the classic xenolith/inclusion localities worldwide, and they have been the subject of intensive petrological/geochemical study (e.g. Irving, 1980).

The best known localities are those at which ultramafic rock types are found as rounded to angular fragments up to 15cm in diameter, within basaltic air-fall deposits of scoria cones. More rarely, abundant xenoliths are found associated with surge deposits of maars or tuff rings (e.g. Lake Bullenmerri). Fine crystal fragments from the disaggregation of xenoliths are common in both pyroclastic fall and surge deposits. These may be concentrated by water action on beaches or lake shores to form crystal-rich deposits.

Xenolith localities within the Newer Volcanics province are concentrated mainly in the Colac-Camperdown-Mortlake area of the Western Plains sub-province, the best known being scoria cones such as Mts. Leura, Noorat and Shadwell. There are several localities in the area north and west of Melbourne, including the well-known Mt. Franklin scoria cone occurrence near Daylesford. In the far west of Victoria, xenoliths and megacrysts are almost unknown, in both the older ($\approx$3 Ma) group of tholeiitic to weakly alkaline basaltic centres (Mts. Clay, Eckersley, etc.), and the very young (5000-10000 year) alkaline lava-scoria cone complexes such as Mts. Eccles and Napier.

Xenoliths

Almost all Newer Volcanics xenolith localities are dominated by peridotitic types. Of these, spinel lherzolites with characteristic apple-green Cr-diopside are by far the most common, occurring at 28 localities (e.g. Mts. Porndon, Leura, Noorat, etc.). Together with rare Cr-diopside-bearing harzburgites, dunites and wehrlites, these constitute a 'Cr-diopside series' (Wilshire and Shervais, 1975). Amphibole (Ti-pargasite) and phlogopite are common minor or accessory phases, and there is sometimes evidence from relics that amphibole was originally more abundant (Nicholls and Greig, 1989). Apatite is relatively rare. Glass, formed mainly by melting of hydrous phases and clinopyroxene, can be abundant. CO_2-rich fluid inclusions are common. Individual localities may have distinctive mineralogies. For example, lherzolites with amphibole$\pm$apatite$\pm$phlogopite are very common at Lake Bullenmerri, while anhydrous clinopyroxene-rich lherzolites predominate at the Anakies.

By contrast wehrlites, websterites and clinopyroxenites which contain black Al-Ti augite as a major constituent and Al-rich spinel as the aluminous minor phase, are often grouped as an 'Al-Ti augite series'. Xenoliths of this group occur at 10 Newer Basalt localities (e.g. Mts. Porndon, Leura, Shadwell). Garnet websterites and garnet or garnet-spinel clinopyroxenites form a third, 'garnet pyroxenite series', represented by rare xenoliths at 6 localities (e.g. The Anakies, Mts. Leura, Noorat,

etc.). Garnet pyroxenite series xenoliths are common at only one locality - Lake Bullenmerri/Lake Gnotuk.

Available evidence indicates that most of these xenoliths originated in the upper mantle or a mantle-crust transition zone. At a few localities (especially Lake Bullenmerri and the Anakies), granulite-facies xenoliths with plagioclase as a major phase are present. These may have been derived from mid- to deep crustal depths.

Most studies of Victorian xenoliths have concentrated upon optical characterization of mineral assemblages, the chemistry and isotopic compositions of major mineral phases and bulk rocks, and geothermometry and geobarometry. Relatively little emphasis has been placed on textures and deformation histories. Studies of Cr-diopside series xenoliths include those of Frey and Green (1974), McDonough and McCulloch (1987), O'Reilly and Griffin (1988), Griffin et al. (1988) and Yaxley et al. (1991), while Irving (1974a), Ellis (1976), Nickel and Green (1984) and Griffin et al. (1988) have presented data for Al-Ti augite series xenoliths. Irving (1980) has concentrated on the features and origin of composite xenoliths (see below). The most comprehensive studies of Victorian garnet pyroxenite series xenoliths are those of Hollis (1981) and Griffin et al. (1984, 1988) on Lake Bullenmerri/Lake Gnotuk material. Wass and Hollis (1983) have studied eclogite and granulite xenoliths from The Anakies in some detail.

Textural Types in Xenoliths

Xenoliths of the Cr-diopside series are characterized by dominantly equigranular metamorphic textures with grainsizes in the 2-10mm range. These are best classified as *coarse equant* according to the scheme proposed by Harte (1977). Rare examples are classified as *coarse tabular* on the basis of the dominant olivine habit. Olivine in these xenolith types commonly develops broad deformation lamellae, but pyroxenes show almost no evidence of deformation.

Much less abundant lherzolite xenoliths at several localities (e.g. The Anakies, Mt. Leura, Lake Bullenmerri) show pronounced grainsize reduction, often accompanied by development of weak planar fabric, due to deformation and recrystallization to granoblastic aggregates of neoblast crystals. Olivine is most strongly affected, with an average grainsize around 1-2mm. These types are classified according to Harte as *granuloblastic*.

Pyroxenes are rarely recrystallized, but they show deformation features and also exsolution features due to re-equilibration to lower temperatures. Xenoliths which retain coarse olivine and pyroxene crystals in a matrix of finer olivine are described as *porphyroclastic* or with more extensive development of neoblast aggregates as *mosaic porphyroclastic* (Harte, 1977).

Al-Ti augite and garnet pyroxenite series xenoliths show a wide range of grainsize (1-10 mm) and textures. Some contain clinopyroxene megacrysts up to 20-30mm in diameter which contain oriented exsolution

patches of garnet or Al-spinel (Lake Bullenmerri - Griffin et al, 1984). Granulite xenoliths are generally of finer grainsize (0.5-2mm), with well-developed metamorphic textures.

Composite Xenoliths

At a few Newer Volcanics localities, notably Mt. Shadwell (Irving, 1980) and Lake Bullenmerri (Griffin et al., 1984), composite xenoliths are found in which host Cr-diopside lherzolite is veined by pyroxene-rich material (usually wehrlite of the Al-Ti-augite series). At Lake Bullenmerri, amphibole-bearing lherzolites may also contain veins consisting largely of pargasitic amphibole. At the same locality, complex intrusive relationships are also observed between various rock types belonging to the garnet pyroxenite series.

Origin of Xenoliths

The dominant Cr-diopside lherzolites are normally interpreted as derived from typical shallow mantle wall rocks through which the alkaline basaltic magmas which carry xenoliths to the surface pass after leaving source depths in the 80-100km range (Irving and Green, 1976; Frey et al., 1978). Geothermometry carried out on typical assemblages indicates equilibration temperatures in the 800-1100°C range, but no precise estimates of depths of equilibration are available for these spinel-bearing xenoliths.

The detailed geochemical work on Cr-diopside lherzolites carried out by Frey and Green (1974), O'Reilly and Griffin (1988) and others indicates that most xenoliths have undergone complex histories involving both basaltic melt extraction and variable addition of an incompatible element-rich fluid or melt phase. O'Reilly and Griffin (1988) suggested that metasomatism was caused by CO_2/H_2O-rich fluids, derived from crystallizing basaltic veins, infiltrating adjacent wallrock peridotites. The fluids evolve in composition with distance from the vein due to reaction with the wallrock, producing a variety of metasomatic mineral assemblages with distinct trace element enrichment patterns. However, Frey and Green (1974) and McDonough and McCulloch (1987) suggested that metasomatism was caused by silicate liquids derived from small degrees of melting in equilibrium with garnet.

Yaxley et al (1991) studied the geochemistry of Cr-diopside wehrlites which carried amphibole and apatite and suggested that they represent harzburgites which have reacted with a sodic-dolomitic carbonatite melt to produce Ca-rich decarbonated assemblages. Ortho-pyroxene reacts to produce clinopyroxene, resulting in wehrlites with extreme enrichment in incompatible elements, but trace element patterns with negative Ti anomalies. They also suggested that residual CO_2/H_2O fluids rich in incompatible elements may have caused the metasomatism found in peridotitic xenoliths. Lherzolite and harzburgite xenoliths span a wide range of isotopic compositions, from depleted ($\varepsilon_{Nd} = +12$, $^{87}Sr/^{86}Sr = 0.7025$) to enriched ($\varepsilon_{Nd} = -8$, $^{87}Sr/^{86}Sr = 0.7105$) and this range can be present at a single locality

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(McDonough and McCulloch, 1987; Griffin et al., 1988). Cr-diopside wehrlites are isotopically similar to bulk earth compositions (Yaxley et al., 1991) as are amphibole+apatite lherzolites (Griffin et al., 1988).

The pyroxene-rich vein or dyke phases found in composite xenoliths are interpreted by Irving (1980) as cumulates of near-liquidus phases of basaltic magmas flowing in restricted conduits before forming a discrete magma body. Similar processes or perhaps high pressure cumulate formation in small magma chambers at upper mantle depths, are believed to be responsible for the formation of discrete Al-Ti-augite xenoliths (Irving 1974a; Ellis, 1976). Isotopically, these xenoliths are similar to their host basalts (ϵ_{Nd} = ~+3.6, $^{87}Sr/^{86}Sr$ = ~0.7039) and are thus probably related to Newer Volcanics magmas (Griffin et al., 1988). Garnet metapyroxenites probably represent older cumulates which have been reequilibrated due to cooling, exsolution and recrystallization. Geochemically they are distinct from Al-Ti-augite xenoliths and span a wide range of isotopic compositions from those similar to xenolith host magmas to significantly enriched (ϵ_{Nd} = -9, $^{87}Sr/^{86}Sr$ = 0.7158 - Griffin et al., 1988).

Interpretations of the available isotopic data vary widely. Griffin et al. (1988) consider the peridotites and metapyroxenites to fall on a mixing trend at about 300-500 Ma. They therefore suggest that the peridotites were metasomatised around this time by fluids derived from the melts that ultimately yielded metapyroxenites. At this time the metapyroxenites have very unradiogenic Nd and unsupported radiogenic Sr, suggesting a large component of older crustal material recycled by subduction processes. Apatite-bearing lherzolites, however, do not plot on this trend, suggesting metasomatism by different fluids with present-day bulk earth isotopic characteristics. Cr-diopside wehrlites also have bulk earth isotopic compositions, similar to the compositions of some Newer Volcanics basalts, and Yaxley et al. (1991) suggest that the carbonatite magmas which metasomatised these xenoliths were related to Newer Volcanics magmatism. On the basis of Nd model ages, McDonough and McCulloch (1987) suggested that most peridotites were metasomatised no later than 600-970 Ma and their low Sr/Nd ratios (~15) ruled out any fluid associated with subduction zone magmatism. Evidence that some metasomatism is directly related to Newer Volcanics basaltic magmatism is provided by the preservation of Ti, Zr and Sr zoning in lherzolite clinopyroxenes from some discrete and composite xenoliths (Greig et al., 1993).

The complex and highly varied xenolith population at Lake Bullenmerri, belonging to all of the major xenolith suites, has been interpreted by Griffin et al (1984) and O'Reilly and Griffin (1985) as sampling a complex upper mantle/deep crustal section. Geothermometry and geobarometry carried out on garnet-bearing xenoliths indicates that most assemblages last equilibrated at 900-1100°C, 11-16 Kbar (i.e. 30-55km depth), while rare examples indicate conditions near 1200°C, 20 Kbar (70km). The implied high geothermal gradient at shallow depths is inconsistent with thermal conduction models for heat

flow and may be due to heat input from basaltic intrusions forming a 4 km thick layer at around 28 km depth (Cull et al., 1991). A feature of the Griffin et al., interpretation is the presence of a broad mantle-crust transition in which a zone consisting mainly of spinel hornblende lherzolite contains lenses and pods of metamorphic pyroxenite, intrusive wehrlite cumulates and pockets of gabbroic rocks, the latter metamorphosed to eclogite or granulite facies assemblages (Anakies xenoliths - Wass and Hollis, 1983).

Megacrysts

Megacrysts occur in at least 18 Victorian localities. By far the dominant types are black to dark green glassy clinopyroxene (Al-Ti-augite) and alkali feldspar (anorthoclase), which are both present at 14 localities. Dark brown amphiboles (kaersutite or Ti-pargasite) are present at 5 localities, orthopyroxene (Al-bronzite) and phlogopite-biotite at 2 each. Megacrysts of apatite and magnetite are present only at The Anakies.

All these megacryst species except anorthoclase are possible near-liquidus phases of basaltic magmas. However, discrepancies in e.g. Mg-number of mafic megacrysts with respect to host basalts often indicate an accidental origin (Irving, 1974b). Anorthoclase has been produced in experimentally crystallized basanites, alkali olivine basalts and hawaiites only as a near-solidus phase. Most lines of evidence therefore indicate that major megacryst phases represent disaggregated material from mantle or deep crustal intrusive bodies.

Xenolith and megacryst-bearing magma types

Of the 30 Newer Volcanics xenolith and/or megacryst localities described in the XENMEG catalogue, 12 are associated with lavas or fragmental deposits described by Irving and Green (1976) and Wass and Irving (1976) as of nepheline basanite composition. However, these rocks have relatively sodic normative and modal plagioclase, and they are better described as mafic ne-normative hawaiites. They are associated with the major group of very rich localities in the Colac-Camperdown-Mortlake district. The next most important xenolith- and megacryst-bearing magma groups are asociated with less mafic and ne-rich hawaiites (9 localities). Other localities are associated with alkali olivine basalts (3 localities), nepheline mugearites (2) and hy-normative hawaiites (1).

That the occurrence of xenoliths and megacrysts is not simply related to magma type is shown by their almost complete absence from volcanic centres in the Portland-Hamilton area, e.g. Mts. Eccles, Napier and Rouse. These volcanic centres consist dominantly of ne- or hy-normative hawaiites not obviously different from those of the xenolith- and megacryst-bearing scoria cones of the Camperdown area. The apparent lack of a relationship to specific basalt magma types implies that factors such as rate of magma ascent and eruption are dominant in preserving xenolith and megacryst populations (O'Reilly, et al, 1989).

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TABLE 1:   Representative chemical analyses of rocks of the Newer Volcanics province and Macedon-Gisborne area - Field Trip Days 1 and 2

Number	1	2	3	4	5	6	7	8	9	10	11	12	13
					DAY 1						DAY 2		
Locality	Plains domains near Melbourne			Deer Park	Mt. Gisborne	Camel's Hump	Mt. Franklin	Mt. Warrenheip	Mt. Elephant	Mt. Shadwell	Plains domain	Plains domain	Mt. Rouse
Type	tholeiitic basalts			hawaiite	trachy-andesite	qz-trachyte	ne-mugearite	alkali ol-basalt	ne-hawaiite	basanite	ol-tholeiite	hawaiite	hawaiite
SiO_2	51.80	50.96	51.77	48.60	56.73	65.08	47.96	46.39	46.53	44.74	50.34	49.41	49.36
TiO_2	1.63	1.84	1.69	2.10	0.75	0.24	2.22	2.09	2.14	2.75	1.65	1.84	2.11
Al_2O_3	14.17	14.46	13.78	13.82	15.24	15.62	15.51	14.49	11.32	12.61	14.42	13.37	13.74
Fe_2O_3	2.52	3.98	3.14	2.82	2.80	4.93	3.60	1.79	4.44	2.95	5.23	3.04	4.72
FeO	7.74	6.48	7.24	7.98	6.11		7.20	8.94	6.81	8.95	5.99	7.58	6.45
MnO	0.16	0.16	0.16	0.17	0.21	0.10	0.16	0.17	0.18	0.16	0.18	0.17	0.16
MgO	7.74	6.61	8.30	8.79	3.91	0.20	6.44	9.26	12.44	12.47	8.13	9.60	8.62
CaO	8.43	8.68	8.25	8.49	6.53	0.71	6.72	8.29	8.17	8.70	8.33	8.94	8.77
Na_2O	3.25	3.57	3.10	3.62	3.39	6.50	4.81	3.47	2.89	3.46	3.61	3.63	3.41
K_2O	0.81	1.02	0.79	1.53	2.97	4.97	2.82	1.84	1.65	1.78	0.91	1.10	1.12
P_2O_5	0.28	0.34	0.29	0.46	0.32	0.23	0.87	0.66	0.73	0.88	0.33	0.42	0.43
H_2Otot	0.96	1.37	1.02	1.02	1.68	1.04	1.59	1.99	2.44	0.74	1.01	0.66	0.92
CO_2	0.28	0.48	0.06	0.55			0.08	0.08	0.03	0.13	0.04	0.15	0.02
S	0.00	0.00	0.01	0.00		0.02			0.01		0.00	0.01	0.00
Total	99.77	99.95	99.60	99.95	100.64	99.63	100.00	100.00	99.78	100.42	100.17	99.92	99.83
Mg-No.	61.9	58	63.4	63.7	53.3	11.4	61.4	64.9	70.8	69.3	61.5	66	62.9
Rb	23	32	26	32		298	64	40	34	36	16	21	19
Sr	333	450	377	598		4	1141	890	718	830	453	504	527
Zr	148	173	148	199		1218	361	287	297	281	99	159	142
Ni	141	85	154	162		5	92	189	370	342	170	174	179

Analyses of R.C. Price, or from data of Edwards and Crawford (1940), Irving and Green (1976), McDonough, et al (1985) and Smakman (1992).

TABLE 2:   Representative chemical analyses of rocks of the Newer Volcanics province - Days 3-5

Number	1	2	3	4	5	6	7	8	9	10
	DAY 3			DAY 4				DAY 5		
Locality	Mt. Napier - Harman flow	Mt. Eccles	Tower Hill	Mt. Leura	Mt. Noorat	Mt. Porndon	Warrion Hill	Red Rock	Anakies (W)	Anakies (E)
Type	ne-hawaiite	ne-hawaiite	basanite	ne-hawaiite	basanite	ne-hawaiite	hawaiite	ne-hawaiite	hawaiite	ne-mugearite
SiO_2	48.99	47.54	46.81	45.03	45.29	46.21	49.40	48.22	48.14	48.78
TiO_2	2.03	2.22	2.41	3.24	2.43	2.51	2.23	2.20	2.33	2.19
Al_2O_3	13.73	13.79	14.02	12.97	12.00	12.38	13.97	13.20	14.41	15.40
Fe_2O_3	2.87	1.97	1.89	3.28	1.94	2.00	1.87	1.88	1.27	3.45
FeO	8.30	9.83	9.79	9.32	9.70	9.98	9.34	9.41	9.32	6.90
MnO	0.16	0.17	0.17	0.17	0.17	0.18	0.16	0.18	0.18	0.16
MgO	9.44	9.72	8.95	9.88	13.76	11.71	8.94	9.32	8.21	7.20
CaO	8.65	8.77	8.99	8.51	7.96	8.56	8.45	9.34	7.97	6.52
Na_2O	3.58	3.83	4.04	4.06	3.95	3.54	3.65	3.72	4.44	5.72
K_2O	1.12	1.50	2.14	2.22	1.95	2.01	1.44	1.77	1.18	2.87
P_2O_5	0.45	0.66	0.80	1.14	0.85	0.90	0.55	0.66	0.71	0.64
H_2Otot	0.43			0.16	0.20				1.17	0.08
CO_2	0.06			0.07	0.07				0.06	0.04
S	0.00									
Total	99.81	100.00	100.00	100.15	100.27	100.00	100.00	100.00	100.00	100.00
Mg-No.	64.6	63.8	62.0	62.9	71.7	67.6	63.0	63.8	61.1	65.1
Rb	21			45	40				58	72
Sr	498			950	835				775	825
Zr	144			327	319				294	493
Ni	180			263	439				313	149

Analyses of R.C. Price, or from Irving and Green (1976) and McDonough, et al (1985).

FIELD TRIP ITINERARY

DAYS 1-5, MONDAY 20 - FRIDAY 24 SEPTEMBER 1993

DAY 1: MELBOURNE TO BALLARAT

**Lava plains and eruptive complexes near Melbourne; Trachytic domes of the Macedon area;
Scoria cones of the Daylesford-Creswick-Ballarat area**

The route for Day 1 of the field trip traverses the young (<3 Ma) lava plains to the west of Melbourne, visiting several localities at which plains lavas and their source eruptive complexes may be studied. Stops at the Camel's Hump (one of a group of ~6 Ma trachytic domes in the Macedon-Trentham area) and Mt. Macedon (the highest point of a range composed of Late Devonian dacitic ignimbrites) allow overviews of the lava plains. The route then proceeds westward through Trentham into the Daylesford-Ballarat-Maryborough area, part of the Central Highlands sub-province of the Newer Volcanics province. This area contains about two-thirds (~250) of all Newer Volcanics eruption points (Nicholls and Joyce, 1989). The field trip will visit Mt. Franklin, a scoria cone noted for both peridotitic xenoliths and alkali feldspar megacrysts, then proceed to Ballarat *via* Creswick. The Creswick-Ballarat area contains about twenty closely-spaced large volcanic cones, which unlike equivalents in the Western Plains sub-province (Days 2-5) have not been intensively quarried. Localities at which internal structures may be seen are rare, and they will not be visited.

Carlton to Deer Park (22 km)

The route from Carlton is past Flemington Racecourse (home of the Melbourne Cup horserace) and through the western suburbs of Melbourne to the Western Highway, the main road to Adelaide *via* Ballarat.

Locality 1: Deer Park quarry
(Melbourne BU997160 - permission required for entry)

Stop 1-1: Hawaiite flow in quarry

The volcanic plains to the north and west of Melbourne contain at least six domains which may be distinguished on the basis of the dominant lava type and Sr-isotope compositions (Fig. 1). At Deer Park, on the western outskirts of Melbourne, a hawaiite lava flow belonging to Domain 1 is exposed in a quarry, and a short stop will enable sample collection. Hawaiites are one of three dominant rock types of the lava plains, the others being tholeiitic basalts (Analyses 1-3, Table 1) and basaltic icelandites). Analysis 4 of Table 1 is of a hawaiite sample from 8 km south-east of the quarry. K-Ar ages of Domain 1 lavas group around 1.43 Ma. The analysed rock is typical of the most alkalic plains basalts of the 2-0 Ma interval.

The three major basalt types of the Melbourne area lava plains are closely similar in hand specimen; all have comparable olivine phenocrysts and the only distinguishing feature is slightly finer grainsize in hawaiites. In thin section, the rocks are texturally distinct: the tholeiitic basalts and many basaltic icelandites contain abundant interstitial glass, usually partly devitrified, whereas hawaiites are typically finer-grained and holocrystalline.

Deer Park to Mt. Kororoit (25 km)

The route from Deer Park quarry is westward along the Western Highway (Ballarat Road) then northward across lava plains to Mt. Kororoit. Isotopic Domain 2, dominated by basaltic icelandites, is entered about 5 km north of the Western Highway.

Locality 2: Mt. Kororoit
(Melbourne BU936298 - permission required for entry)

Stop 2-1: Mt. Kororoit composite cone - summit area

Mt Kororoit is an eroded composite volcano, consisting of tholeiitic basalts. Its constructional features include: (a) a broad lava apron, several kilometres in diameter, which merges with the regional plains; (b) a cone-building sequence of lava flows and pyroclastic layers, the highest of which dip inward to a presumed central crater; and (c) a feeder dyke system which can be seen to bifurcate on the north-eastern slope. The summit lava flows and dyke are distinguished by abundant phenocrysts of plagioclase and clinopyroxene.

A climb to the summit presents a clear view of the surrounding volcanic plains and allows the abundance of small eruption points in this part of the Newer Volcanics province to be appreciated. The topographic expression of three neighbouring volcanoes is of note. Sheoak Hill to the north is a composite alkaline basaltic volcano with the remnants of a crater, dominated by pyroclastics with thin intercalated lava flows. The low ridge to the east is a basaltic icelandite lava shield with eruptive centres on its two highest points. Due south, the hawaiite volcano Mt. Cottrill has the characteristic subdued profile of a lava shield, which rises to a steeper crest produced by its final lava flows. The surrounding plains are a patchwork of basaltic lava flow domains derived from these centres.

Mt. Kororoit to Mt. Gisborne (28 km)

After leaving Mt. Kororoit, the field trip route follows the Digger's Rest-Coimadai road to Toolern Vale, then . turns northward toward Gisborne. North of Toolern Vale, low hills to both sides of the road consist of Late Ordovician sandstones and shales of the Lachlan Fold Belt succession. Further east, close to the Calder Highway between the towns of Sunbury and Gisborne, are several prominent volcanic cones - Mt. Holden and Burke's Hill near Sunbury and the steep-sided Mt.

Aitken further north. Gisborne township stands on the northern slope of a larger but poorly exposed volcanic complex - Mt. Gisborne - the summit of which rises to

643 m above sea level and offers a splendid view of the lava plains and the city of Melbourne to the south.
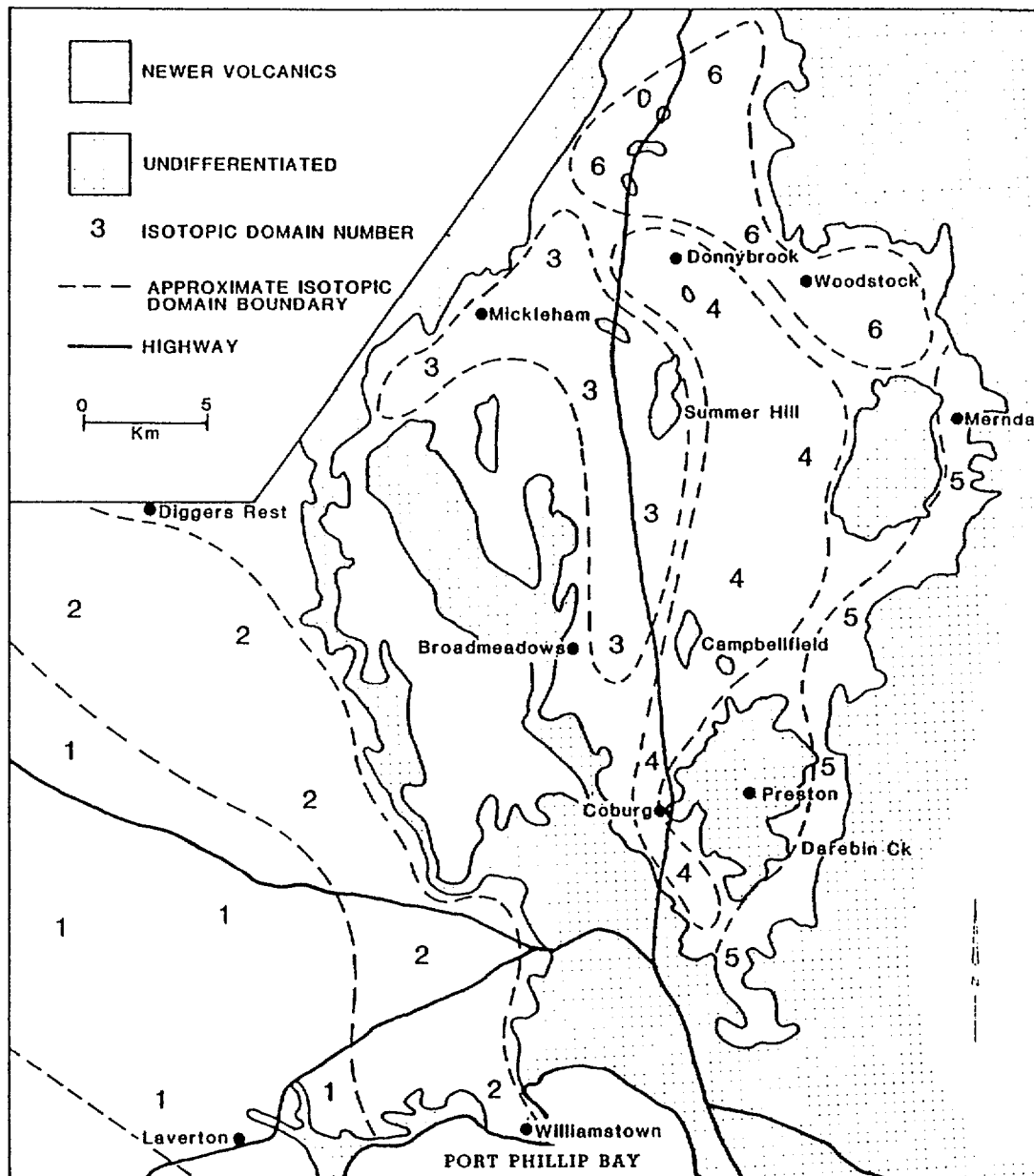
Fig. 1: Sr-isotope domains within the basaltic lava fields of the Melbourne area (from Price, et al, 1988).
Domains: 1 - Hawaiite (Laverton); 2 - Basaltic icelandite (Williamstown/Digger's Rest); 3 - Tholeiite (Mickleham/Broadmeadows); 4 - Tholeiite (Donnybrook/Coburg); 5 - Tholeiite (Mernda/Darebin Creek); 6 - Tholeiite (Woodstock).

Locality 3: Mt. Gisborne summit area (Melbourne BU864445)

Stop 3-1: Road cuttings near summit

Mt. Gisborne, 3 km west of the Calder Highway, is a complex lava dome with three eruption points, rising 160 m above the surrounding lava plain (Fig. 2). According to Singleton (1973) (after Edwards and Crawford, 1940) the complex was the source of up to nine lava flows, ranging from glassy mafic types originally termed limburgites (K-rich basanites or mafic hawaiites) through potassic hawaiites and mugearites to

orthopyroxene-bearing rock types which are sufficiently potassic to be termed basaltic trachyandesites or trachyandesites (Analysis 5, Table 1) according to the total alkalies-silica scheme of La Bas, et al (1986). The main lava dome consists of trachyandesite lava flows and minor fragmental deposits. Lavas thought to derive from Mt. Gisborne have not been explicitly dated, and it is unclear whether they belong to the main Newer Volcanics association (<4.5 Ma) or to the ~6 Ma group of lava flow and dome complexes which includes the three trachytic domes in the Macedon area immediately to the north (including Camel's Hump - Locality 4).

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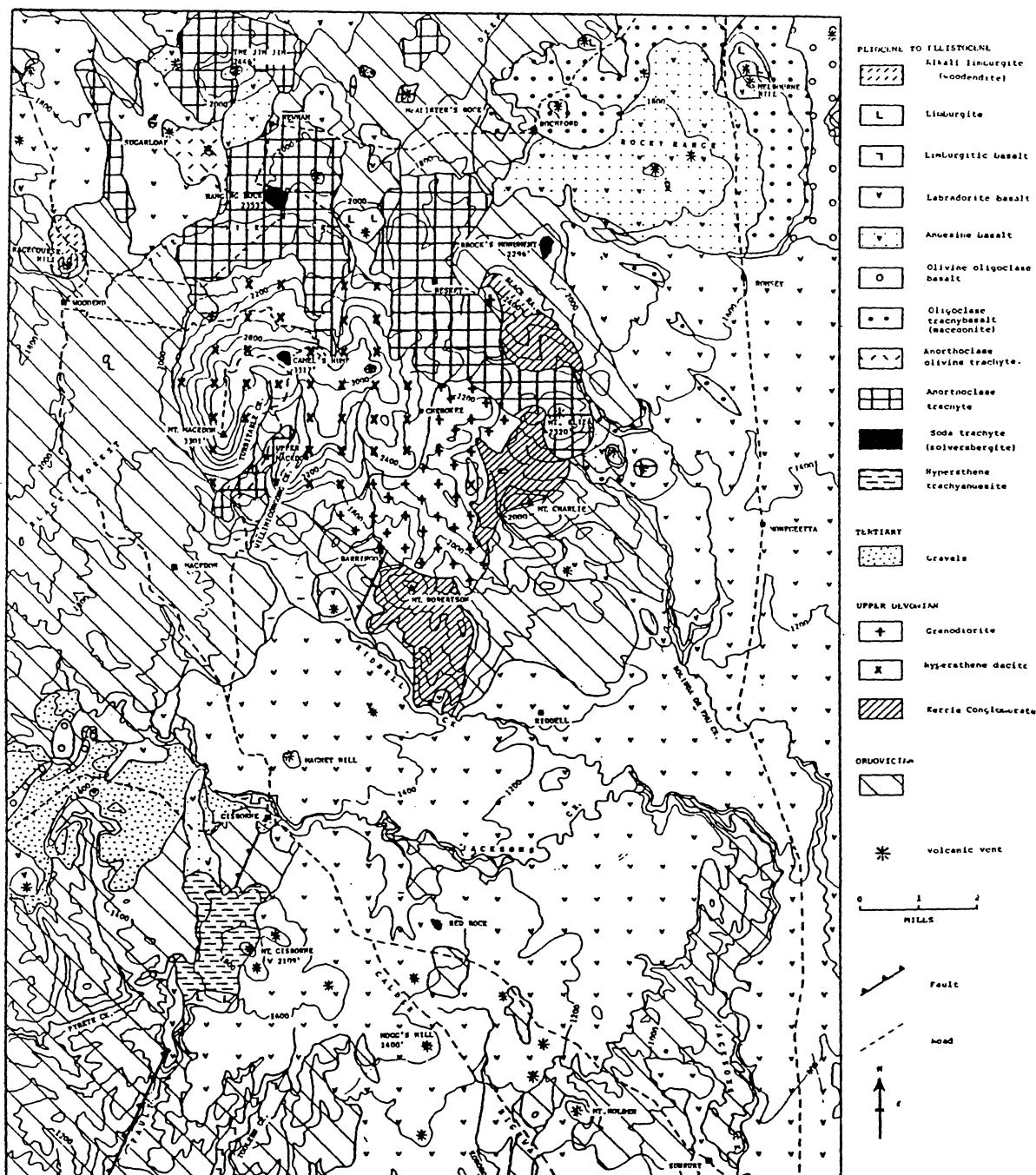
Fig. 2: Geological map of the Gisborne-Macedon district (from Singleton, 1973).

Three large trachyandesite flows originated from Mt. Gisborne. That which makes up the bulk of the dome is exposed in low cuttings on roads near the summit. It contains coarse phenocrysts of plagioclase (labradorite-andesine) and alkali feldspar (anorthoclase-sanidine) and finer augite, hypersthene and rare olivine phenocrysts set in a glassy groundmass consisting of oligoclase, sanidine and pyroxenes. All phenocryst species except augite show strong evidence for resorption. Rounded quartz crystals are common.

A feature of this rock is the presence of abundant small (2-10 cm diameter) enclaves with rounded outlines and scalloped margins, usually light green-brown in colour. The dominant type consists of a fine-grained aggregate of hypersthene and labradorite, but some enclaves are rich in olivine. These enclaves have previously been interpreted as fragments of crystal-rich material produced by accumulation of phenocrysts from the host trachyandesite magma. However, their rounded shapes, fine grainsize and the presence of olivine-rich types

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contrasting strongly with both the dominant hypersthene-plagioclase enclaves and the olivine-poor host rock, suggest that they may represent globules of magmas involved in mingling to produce a hybrid product.

Mt. Gisborne to Camel's Hump (17 km)

The route to Camel's Hump crosses the Calder Highway, the main road to the former goldfields region of Maldon-Castlemaine-Bendigo, about 100 km to the north, and climbs northward onto the Macedon ridge, the remnant of a thick sequence of phenocryst-poor dacitic ignimbrites of Late Devonian age. The road reaches the ridge top almost beside the Camel's Hump trachytic lava dome-flow complex. A road to the left leads past the Camel's Hump car park to Mt. Macedon (with its war memorial cross), the highest point at the western end of the ridge. From the cross lookout, many of the features of the lava plains between Melbourne, Macedon and Geelong (to the south, on the western side of Port Phillip Bay) and the Central Highlands sub-province (to the northwest and west) may be seen.

Locality 4: Camel's Hump trachytic lava dome and Mt. Macedon lookout

Stop 4-1: Summit of Camel's Hump dome
(Woodend BU871612)

The Camel's lava dome (1010 m ASL) has a maximum diameter of about 500 m and it rises almost 100 m above the Macedon ridge. It is composed of a number of flows, which extend south and east from the dome for several hundred metres and in some cases thin to less than 1 m. Internal flow banding is well developed, along with crude columnar jointing. Small xenoliths of the underlying dacitic ignimbrites are common.

An intermediate alkali feldspar (anorthoclase) is the main phenocryst mineral. The groundmass consists of a more potassic alkali feldspar, minor oligoclase, aegirine-augite, aenigmatite, arfvedsonitic clinoamphibole, Ti-magnetite and minor biotite. Analytical data for a typical slightly qz--normative sample (Smakman, 1992) are presented in Table 1 (Analysis 6). The trace element geochemistry is characterised by moderate to high light REE and HFSE levels, especially Zr (>1200 ppm) and Nb (>300 ppm).

Stop 4-2: Memorial cross lookout, Mt. Macedon
(Woodend BU854595)

Mt. Macedon (1000 m) lies approximately 5 km southwest of the Camel's Hump. The memorial cross lookout lies about 500 m west of the summit, and allows clear views southward to the Melbourne area, with the eruption points seen during the drive from the city prominent, and south-westward to the Geelong area. The latter view takes in the prominent Rowsley Fault scarp (with the upthrown Brisbane Ranges block to the west consisting of Ordovician marine sandstones and siltstones), the three Anakies scoria cones (to be visited on the final day of the field trip) and the Late Devonian granite peaks of the You Yangs (Fig. 23).

To the west and northwest lies the higher, more deeply dissected area of Palaeozoic rocks which forms the basement to the Central Highlands sub-province of the Newer Volcanics province. The prominent volcanic cones to the southwest are Mts. Bullengarook and Blackwood, the sources of large southward flowing valley lava flows in the hawaiite-mugearite range. The older of two discordant K/Ar ages available for Mt. Bullengarook is 3.64 Ma (McKenzie, et al, 1984).

Due west is the Trentham-Daylesford area, which contains a wide variety of basaltic to trachytic rocks belonging to both the ~6 Ma group (including *ne*-normative trachytes at Babbington Hill and Blue Mountain - Ewart, 1985) and the younger Newer Volcanics *sensu stricto*.

Mt. Macedon to Mt. Franklin (68 km)

From Mt. Macedon, the route returns past the Camel's Hump and descends from the Macedon ridge *via* its north face. As the road turns west toward the town of Woodend, the Hanging Rock (or Mt. Diogenes) trachytic dome (the setting for a well-known film and popular picnic race meetings) may be seen rising from the plain about 3 km north.

From Woodend, the route is through Trentham to Daylesford, a popular resort town with a number of mineral water springs and lakes which owe their origin to volcanic activity. The next stop, the Mt. Franklin scoria cone, lies 10 km north of Daylesford on the road to the former gold mining town of Castlemaine.

Locality 5: Mt. Franklin scoria cone

Stop 5-1: Mt. Franklin summit
(Castlemaine BU472720)

Mt. Franklin scoria cone is slightly less than 1 km in diameter, and rises to a height of about 180 m. It has a large crater, breached on the southern side, which extends down almost to the original ground surface. It is composed dominantly of a crudely bedded sequence of breccia, block and bomb and lapilli deposits, with minor lava flows, best exposed in low cuttings on the entrance track where it skirts the outer western slope of the cone. The dominant rock types present are potassic *ne*-hawaiite and *ne*-mugearite (Analysis 7, Table 1). A K/Ar date on a hawaiite sample has yielded an age of 470,000 years (Wallace, 1990).

Mt. Franklin is best known as a locality for megacrysts of pyroxene (to 9 cm) and anorthoclase., which may be found in the vicinity of the summit car park and on the track past the fire observation tower. However, small peridotite (dominantly lherzolite) xenoliths are also quite abundant.

The lookout allows a fine view westward over the Wombat State Forest to the field of large volcanic cones in the Maryborough-Creswick-Ballarat area. Coulson (1954) noted the strong topographic contrast between small, confined lava fields in the steep country to the east of Daylesford and more extensive fields in open country in the Creswick-Ballarat area further west.

Coulson recognised "100-odd" eruption points within the Daylesford-Creswick area, many of them small craterless scoria mounds 60-150 m high. The largest of the cones with craters is Smeaton Hill, which rises to nearly 700 m above sea level, is more than 2 km in diameter, and stands about 250 m above its base. The only other similarly sized Newer Volcanics cone is Mt. Elephant, in the Western Plains sub-province (Day 2).

Mt. Franklin to Ballarat (75 km)

The route into Ballarat is initially northwestward to Campelltown through an area of Ordovician sediment-ary rocks of the "Ballarat Trough", then almost due south over lava plains through Creswick. About 14 km south of Campbelltown, the road passes between the Mt. Moorookyle scoria cone (west) and Smeaton Hill composite scoria-lava cone (east). The Birch Hill scoria cone and Green Hill lava cone lie a further 7 km south, beyond the village of Smeaton. A K/Ar date of 2.2 Ma is available for basalts in a borehole near Birch Hill. The Forest Hill and Spring Hill scoria cones lie about 4 km northeast of Creswick, and 8-10 km southwest of Creswick is a further group of three large scoria or composite cones (Mts. Hollowback, Blowhard and Pisgah). K/Ar dates of 3.0-2.9 Ma are available for material from Mt. Rowan, a small lava cone which lies close to the route just north of Ballarat. Two further prominent scoria cones near Ballarat, Mt. Warrenheip to the southeast (composed of alkali olivine basalt - Analysis 8, Table 1) and Mt. Buninyong to the south, have yielded K/Ar dates (1.0 and 4.0 Ma respectively) which bracket the age range of volcanic activity in the Ballarat region of the Central Highlands sub-province.

The dominant rock types of the scoria, lava and composite cones in the Maryborough-Creswick-Ballarat area are *ne-* to weakly *hy*-normative hawaiites, typically more potassic than similar types within the Western Plains sub-province (Wallace, 1990). Some more potassic examples classify as trachybasalts using the total alkalies-silica (TAS) classification. As in other parts of the Newer Volcanics province, the cones and their aprons often consist of rock types significantly more alkaline than those of the underlying plains-forming lavas.

Much of the Ballarat area consists of a series of lava fields with diameters of tens of kilometres, producing relatively level plains related to the pre-volcanic drainage pattern (Yates. 1954; King, 1985). At least three major lava flow sequences underlie the area. These sequences cover "deep leads" - buried stream courses marked by gravel deposits - which were a rich source of gold during the early (1850-1870) history of the highly prolific Ballarat goldfield. K/Ar dates on lava samples taken from mines, quarries and boreholes in the area (especially quarries at Alfredton and Dunnstown) are mainly in the range 3.2-2.6 Ma. During and after the plains-forming interval dominated by lava flows, mildly explosive Strombolian or Hawaiian "fire-fountaining" styles of dominantly magmatic activity produced the prominent scoria cones which rest on the surface of the lava fields. In addition, a small number of eruptive complexes in the area involved highly explosive phreatomagmatic activity, driven by interaction between magmas and water. Probable maars or tuff rings include structures at Callender Bay, on the northwestern margin of the volcanically-dammed Lake Burrumbeet, close to the Western Highway 20 km west of Ballarat, and at Lake Learmonth, northwest of Ballarat. Much better developed structures of similar origin will be seen in the Western Plains sub-province.

DAY 2: BALLARAT TO HAMILTON

Scoria cones and lava aprons of the east-central Western Plains sub-province; xenoliths and megacrysts at Mts. Elephant and Shadwell; the Mt. Rouse cone complex and its long lava flows

The route for Day 2 heads southwest from Ballarat into the Western Plains sub-province, which stretches over 300 km into south-eastern South Australia. As the name suggests, much of it consists of extensive near-level plains, developed upon a veneer of lava flows rarely more than 60 m thick. In areas within the northern half of the sub-province to be visited on Day 2, this veneer rests mainly on Early Palaeozoic (Cambrian-Ordovician) metavolcanic and marine sedimentary rocks or Late Palaeozoic granitic rocks of the Lachlan Fold Belt succession. Xenoliths of these basement rocks and of the plains basalts veneer are found in deposits of the large scoria cones or composite scoria-lava cones which are characteristic of this part of the sub-province. On the way to the Western District regional centre of Hamilton, the field trip will visit two major scoria cones - Mts. Elephant and Shadwell - which have very rich suites of both mantle-derived xenoliths and megacrysts. The final stop for the day will be the scoria-lava cone of Mt. Rouse, which was the source for long lava flows which extend southward to the coastline near Port Fairy.

Ballarat to Mt. Elephant (85 km)

The route follows the Glenelg Highway from Ballarat southwestward through lightly wooded farming country to Smythesdale (home of the Yellowglen winery, maker of popular champagne-style wines) and Scarsdale, then turns south through open plains country to join the Hamilton Highway near Lismore. The first stop for the day, Mt. Elephant, lies 11 km west of Lismore, near the town of Derrinallum.

Locality 6: Mt. Elephant scoria cone

Stop 6-1: Panorama of Mt. Elephant
(Skipton XC977975 - Hamilton Highway roadside, 8 km west of Lismore)

Mt. Elephant is the largest volcanic cone of the Western Plains sub-province, and its name refers to both its size and profile as seen from a distance. It is a monogenetic cone, slightly elliptical in plan (approximately 1.4 km east-west by 1.2 km north-south) and 240 m in height, with a shallow crater, 650 m in maximum diameter, breached at a high level on the northern side. The cone consists almost entirely of pyroclastic fall deposits, including material ranging from lava blocks several metres in diameter to ash. It rests upon a broad apron of lava flows which slopes gently away from the base of the cone. The dominant rock type of both the cone and the lava apron is *ne*-hawaiite (Irving and Green, 1976).

Stop 6-2: Quarries on the western flank of Mt. Elephant (Skipton XC923960 - Mt. Elephant road, 2.9 km west of Derrinallum - permission required for entry)

The deposits of the cone are exposed in large operating quarries at the western foot. They are apparently entirely magmatic in origin, consisting of black, brown and red, poorly-sorted vesicular ejecta ranging from fine ash through angular to spindle-shaped lapilli (scoria) to blocks and spatter bombs 15-20 cm in diameter. The deposits are crudely bedded approximately parallel to the surface of the cone. The common large lava blocks on the quarry floor consist of very fine grained to glassy *ne*-hawaiite (Analysis 9, Table 1), rich in small ultramafic xenoliths and megacrysts. Blocks of partially-melted granite, derived from the underlying basement, are also common.

Ultramafic xenoliths are typically <5cm in diameter, and smaller disaggregated fragments are common. As is usual for Newer Volcanics centres, they are dominantly spinel lherzolites, but rare wehrlites are also present. Microstructures of lherzolites are typically of the coarse equant type (Harte, 1977), with little evidence for extensive deformation and recrystallization (Ellis, 1976). Megacryst assemblages are dominated by 1-2 cm crystals of glassy black Al-Ti augite and dark brown Al-bronzite. The two pyroxenes may be distinguished in hand-samples by the nature of reaction rims. Al-Ti augites develop broad cloudy rims of low-Al augite charged with glass inclusions, reflecting partial melting. Bronzites develop more sharply defined, light coloured reaction coronas of olivine and low-Al augite.

Granitic xenoliths are often large (>15 cm) and angular. They typically have a friable, spongy appearance due to partial melting, which preferentially affects the biotite (Le Maitre, 1974). Most quartz and feldspar crystals are also rimmed by glass. Rare quartzite xenoliths show similar features.

Stop 6-3: Lava apron of Mt. Elephant (Skipton XC890954 - Hamilton Highway roadside, 7 km west of Derrinallum)

After leaving the quarry, the route returns to the Hamilton Highway and continues westward over a relatively rough surface with abundant lava outcrops. This is a degraded form of a type of lava flow surface, known locally as "stony rises", which reflects partial collapse of the roofs of lava tunnels. A similar example will be seen on ~0.3 Ma lava flows from Mt. Rouse.

Younger (20000-5000 years B.P) and better preserved examples will be seen on lava flows from Mt. Napier (Day 3) and Mt. Porndon (Day 5).

The Mt. Elephant lava apron is roughly circular and ~8 km in diameter. The source vent, marked by the scoria cone, lies only 2 km from the northern margin of the apron, reflecting preferential southward flow of lava on a gently sloping plains basalts surface. The margin of the apron is marked by an abrupt ~5 m flow front. This apron serves as a model for the simplest geometry of older plains basalt domains, in which surface features have been destroyed by erosion or infilled by younger deposits. It is envisaged that much of the present-day plains surface is underlain by overlapping basalt sheets similar in form to these aprons.

Derrinallum to Mortlake (43 km)

Southwest of Mt. Elephant are the Mt. Kurweeton (transitional hawaiite with ultramafic xenoliths) and Mt. Koang cones. Midway to Mortlake, the Mt. Noorat tuff ring/scoria cone complex appears on the southwestern skyline. This will be visited on Day 4. Ahead, just north of Mortlake, is the group of overlapping scoria cones which makes up the Mt. Shadwell complex. In the vicinity of Darlington the plains are capped by 2 Ma tholeiitic basalts, and volcanism of this age dominates the plains for many kilometres around Mt. Shadwell. The basalt domains in this area, formed during the peak of volcanism in the sub-province, range in composition from olivine tholeiite to hawaiite. These domains tend to show south-southwest elongation, reflecting the regional land surface gradient at the time of emplacement. The plains hawaiites were the first voluminous products of more alkalic basaltic volcanism, which commenced during the peak of activity and gradually became predominant with time, especially in the younger cone complexes.

As outlined in the Introduction, Mortlake lies on the trace of a northwest-southeast trending discontinuity in the isotopic compositions of Western Plains basalts (the Mortlake Discontinuity). Most equivalent basalt types on either side of the discontinuity have similar major and trace element compositions, apart from small differences in Rb/Sr ratios. However, some distinctive basalt types are limited to one or other sector, e.g. radiogenic basaltic icelandites are found in the eastern sector and a young hawaiitic type is present in the west (Rouse component - Locality 8, Fig. I-7). The evolutionary histories of the eastern and western sectors are broadly similar, although complexes with products younger than 10000 years B.P. which include long lava flows (Mts. Napier and Eccles) occur only in the western sector. In addition, mantle-derived xenoliths are virtually unknown west of the "Mortlake line", reappearing only in the <5000 years BP volcanic centres of south-eastern South Australia (Mts. Gambier and Schank). Nonetheless, within 15 km there are significant changes in Sr, Nd and Pb isotopic compositions; both maximum and minimum $^{87}Sr/^{86}Sr$ ratios are higher in the eastern sector, although there is considerable overlap.

The isotopic discontinuity corresponds to the projection across the Western Plains of a Palaeozoic basement structure, the Grampians Subzone (see Introduction). The Late Silurian-Early Devonian fluviatile sandstones of the Subzone form the Grampians Range, one of the most scenic parts of Victoria. In the vicinity of Mortlake the basement structure is manifested only by a low tableland of Tertiary rocks, uncapped by basalts, visible as an escarpment northwest of Mt. Shadwell. On the basalt plains the only apparently related geological features are pockets of unusually extensive pre-basalt Tertiary sediments, which imply low intensity of volcanism; there is no geomorphic expression of a tectonic discontinuity within the basaltic sequences themselves.

Locality 7: Mt. Shadwell scoria cone complex

Mt. Shadwell, 1.5km north of Mortlake, is a complex of multiple scoria cones, with the largest rising 140m above the plains basalts surface. A limited lava apron is developed on the southern side of the complex. Several large quarries on the eastern and southern sides expose the lower levels of the crudely bedded black to red scoria sequence with interbedded block and bomb beds which make up the compex. Large ballistic lava blocks are found throughout the sequence. All exposed deposits reflect dominantly magmatic eruption. The main basaltic rock type is mafic basanite with normative and modal plagioclase more calcic than the much more abundant hawaiites of the Newer Volcanics province (Analysis 10, Table 1). Mt. Shadwell has not been studied in detail from the points of view of either eruptive history or petrology/geochemistry.

Mt. Shadwell is, however, one of the most extensively studied xenolith and megacryst localities of the Newer Volcanics province. Xenoliths are very abundant, particularly in the northern part of the main operating quarry, and they are often large (up to 20cm). As in most Newer Volcanics occurrences, Cr-diopside spinel lherzolites are dominant, but a range of wehrlites, dunites, websterites and clinopyroxenites is present, and very rare garnet-spinel lherzolites have been reported (Irving, 1974a; Wass and Irving, 1976). Lherzolites show a wide range of textures, from coarse equant to fine granuloblastic with planar foliation developed in tabular olivines. Some carry accessory phlogopite, amphibole and apatite. Pyroxene-rich xenoliths contain typical black Al-Ti augite. Composite xenoliths from this locality, with poikilitic-textured clinopyroxenite veins cutting lherzolite hosts, have been described in detail by Irving (1980) and Nicholls and Greig (1989). The main megacryst species present at Mt. Shadwell are black Al-Ti augite and anorthoclase, with rarer Al-bronzite (Ellis, 1976).

Stop 7-1: Quarry at eastern foot of Mt. Shadwell
(Mortlake XC593867. Access from Ararat road - permission required for entry)

This large operating quarry gives good exposures of the scoria cone sequences. Both xenoliths and megacrysts are abundant. Anorthoclase megacrysts are common in large lava blocks heaped in several parts of the quarry.

Stop 7-2: Lava apron of Mt. Shadwell
(Mortlake XC597843 - Hamilton Highway, road cutting 2 km east of the centre of Mortlake)

The basaltic apron on the southern side of Mt Shadwell has a level surface and terminates abruptly in an escarpment ~15 m high. The lithology in the cutting at Stop 7-2 is highly unusual, consisting of a jumble of large bodies of vesicular *ne*-hawaiite associated with finer fragmental material. The basalt contains abundant lherzolite xenoliths, up to 10 cm in diameter, and anorthoclase megacrysts. Its mode of occurrence varies from apparently *in situ* lava flow bodies up to 10 m long and 3 m thick with vertical columnar jointing, to dyke-like masses up to 50 cm across and an exposed vertical extent of up to 2 m. The associated fragmental material consists of angular basalt clasts (2 - 40 cm) in a fine orange-coloured weathered matrix.

Mortlake to Penshurst (59 km)

West of Mortlake, the Hamilton highway continues across a 2 Ma land surface composed of numerous basalt domains. The tholeiitic domain immediately to the southwest of the town (Analysis 11, Table 1) is one of the largest in the province and may consist of a single lava flow, 43 long and 12 km wide, which extends southward almost to the sea; the rocks which comprise it may be recognised by a distinctive texture of plagioclase laths and a characteristic $^{87}Sr/^{86}Sr$ ratio of ~0.7041. Further west, the plains remain almost featureless until the peak of Mt. Rouse appears on the horizon. The plains in this area were again formed from extensive lava flows near the 2 Ma peak of activity in this part of the Western Plains. Some 300, 000 years ago the Mt. Rouse scoria cone-lava flow complex developed on the plains surface.

The locations of Stops in the vicinity of Mt. Rouse (Locality 8) and at other Localities (9-12) to be visited during Day 3 are shown in Fig. 3.

Locality 8: Mt. Rouse

Stop 8-1: Panorama of Mt. Rouse
(Hamilton XD159082 - Hamilton Highway roadside, 6 km east of Penshurst)

The plains basalt occupying the low country at this site is a 1.95 Ma hawaiite (Analysis 12, Table 1). Lava flow domains in this area are elongated south-west, away from a basement high south of Glenthompson. There is a strong contrast between the almost featureless upper surface of the older hawaiite flow and the hummocky basalt apron of Mt. Rouse, with flows of the apron ending in fronts up to 7 m high. Mt. Rouse consists of two scoria cones, rising to a maximum height of 370 m ASL. Only the higher northern cone, 100 m above the plains and with slopes as steep as 20°, is visible from this point.

The Mt. Rouse complex is composed of hawaiites and *ne*-hawaiites (Analysis 13, Table 1).
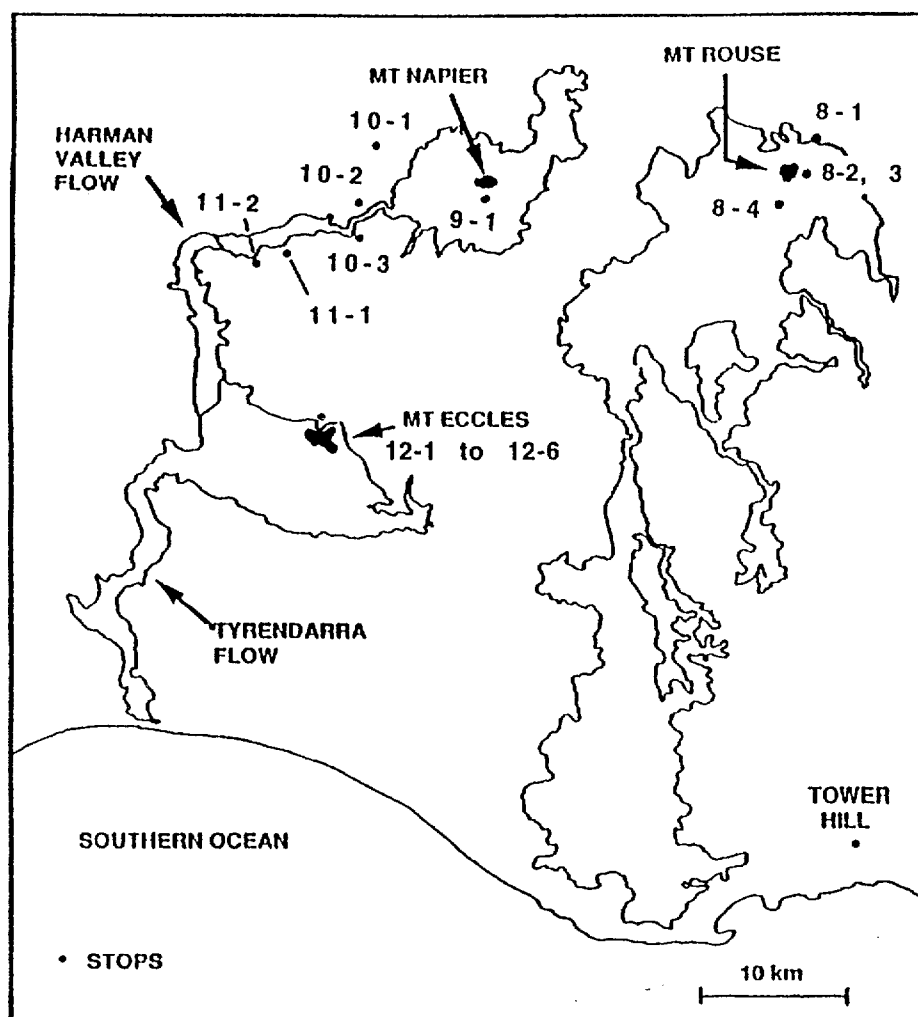
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Fig. 3: Lava flow aprons and major lava flows associated with the Mt. Rouse, Mt. Napier and Mt. Eccles volcanic complexes.

Stop 8-2: Mt. Rouse summit (Hamilton XD143063)

The road ascends from the lava apron along a sinuous route from the southern to the northern scoria cone, each of which has a well-preserved crater. A short climb to the summit from the car park provides an excellent view of the complex and its surroundings. Mt. Rouse has been intensively studied by Whitehead (1986) and the descriptions given are derived from that source. The summit is located above the northern flank of the higher cinder cone. The northern crater structure is elongated east-west, due its formation from two overlapping circular craters 150 and 250m in diameter. The southern crater has:

".......very steep sides, dropping about 30m to a permanent lake. The steepness of the sides of this crater, particularly around the northern rim, where a basalt flow creates a vertical drop of about 3m, indicates that it has been partly produced by collapse. A small lava channel can be traced to this crater, indicating that it was a volcanic vent and not a collapse structure." (Whitehead, 1986).

The small ridge near the lookout is a spatter rampart,

".......5m high and extending for about 35m. It is composed of small scoriaceous fragments approximately 1-5 cm across that have been welded together. Small white inclusions of granite are relatively common. A vertical section through the rock shows layering of the particles, and occasional larger fragments show impact structures such as bomb sags." (Whitehead, 1986).

Whitehead mapped four morphological units within the 8 x 16 km basalt apron around Mt. Rouse, each of which comprises numerous flows. The limits of the unit (4 x 8 km) nearest to the scoria cones may be clearly seen from the extent of irregular topography around the peak; the stony rises are examined in detail at Stop 8-4.

Whitehead goes on to say:

"Beyond the stony rises, individual lava flows can be traced for 6 km. The most prominent ridges are up to 7m high and have relatively abrupt edges but, as the flows approach the stony rises surrounding Mt

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Rouse, their relative relief diminishes, and they grade into the surrounding basalts. Parallel ridges occur in the larger flows, with the intervening depressions being due to the collapse of lava tunnels."

Individual valley flows emerge from the apron and extend up to 60 km to the south, reaching the sea at Port Fairy (Fig. 3). Parts of these flows which were confined by pre-existing stream channels are as narrow as 200 m, but together they cover areas up to 10 km across (Day 3, Mount Eccles to Port Fairy). The flows have been K-Ar dated at 0.45-0.31 Ma near Port Fairy (McDougall and Gill, 1975) and 15 km south of Mt Rouse (unpublished results). However, Ollier (1985) has published an older date (1.82 Ma) for flows of the cone complex. Due to their relative youth these flows are readily mapped, and they may be used as a further model for the likely geometry of plains basalt domains, namely a circular to elliptical apron at the head of a long lobe of relatively narrow valley flows infilling pre-existing drainage.

Stop 8-3: Quarry on the eastern flank of Mt. Rouse (Hamilton XD147055 - Access adjacent to reserve entrance)

This quarry contains an excellent section through the flank of the southern scoria cone of Mt. Rouse. At its northern end are pyroclastic deposits with centimetre to metre-scale planar bedding. The bulk of the material comprises vesicular lapilli (scoria) in the 5-20 mm range, with occasional bombs and blocks up to 10 cm in diameter. Individual lapilli are often exceptionally well-preserved, showing the sheen of original glassy surfaces. Some coarser horizons contain bombs with dimensions up to 1 m. Near the southern end of the quarry adjacent to the entrance, a columnar-jointed 2 m thick hawaiite flow overlies the pyroclastic deposits and dips off the flank of the cone. The lower ropy surface of this flow, which rapidly lenses out to the north over a distance of 200 m, is very well preserved.

Stop 8-4: Hawaiite lava flows from Mt. Rouse (Hamilton XD132037 - Penshurst-Hawkesdale road/ Stonefield Lane intersection, 4 km south of Penshurst).

This site is on typical stony rises terrain of the Mt Rouse apron. As described by Whitehead (1986):

"Within a radius of approximately 4 km of Mt Rouse, lava flows cannot be traced for more than 200m. This region consists of a very uneven surface of ridges, troughs and basins. It is thought that this topography is formed primarily by collapse of lava flows when molten lava is withdrawn through tunnels beneath a solid crust. The lack of continuity of most of these collapse features suggests that a complex arrangement of anastomosing tunnels was present within the lava flows."

The jumbled flow surface is still quite obvious, in spite of erosional modification during the last 300, 000 years. The effects of erosion and infilling of irregularities within the surface may be readily appreciated by comparing this example with much younger equivalents on flows from Mts. Napier and Eccles (Day 3). This comparison will allow you to further calibrate the 'eyeball' method of determining lava flow ages and rates of erosion.

The lavas at Stop 8-4 are transitional hawaiites with unexceptional major element compositions. However, hawaiitic rocks such as this from the young volcanoes west of the "Mortlake line" have distinctively low Rb/Sr ratios, which when combined with their relatively unradiogenic Sr-isotopic compositions (0.7037-0.7041) define a distinct geochemical component within the basaltic system of the Western Plains sub-province.

Penshurst to Hamilton (31 km)

The direct route to Hamilton crosses progressively older land surfaces (0.3 Ma hawaiite, 1.8 Ma transitional hawaiite, 4.5 Ma tholeiite) with corresponding loss of lava flow surface morphology and increasing depth of weathering profiles.

If time permits, a digression northward *via* Dunkeld to the southern end of the Grampians Range will provide scenic relief and an opportunity to reinforce the significance of the Mortlake discontinuity.

DAY 3: HAMILTON TO PORT FAIRY

Young volcanic complexes with long lava flows in the Hamilton-Port Fairy area

Hamilton to Mt. Napier (15 km)

The route south from Hamilton crosses one of the oldest segments of the regional basalt plain, a 4 Ma surface with little outcrop and a weathering profile up to 10 m thick. This surface is more dissected than those with younger basalt cover, with some broad and deep valleys. The landscape to the south is dominated by Mt. Napier (pronounced 'Napeer'), the summit of which is at the highest elevation (400 m ASL) of any volcano of the Western Plains sub-province. The height of the main cone above its base is about 200 m.

Plains basalts in this area often exhibit the anomalously high Ba and/or rare earth element

concentrations, reflecting weathering processes, which were noted in the Introduction.

Locality 9: Mt. Napier complex

The base of Mt. Napier is a lava shield of hawaiite flows, partly concealed by hawaiite scoria deposits which locally form small cones. Forest which originally covered the complex is preserved on rough terrain of the lava shield. Low flow fronts may be seen extending into the surrounding cleared areas. The steep-sided main mass of Mt. Napier consists of several large scoria cones. It is now bare due to the effects of bushfires, whose heat was concentrated on the slopes by combustion of the forest below.
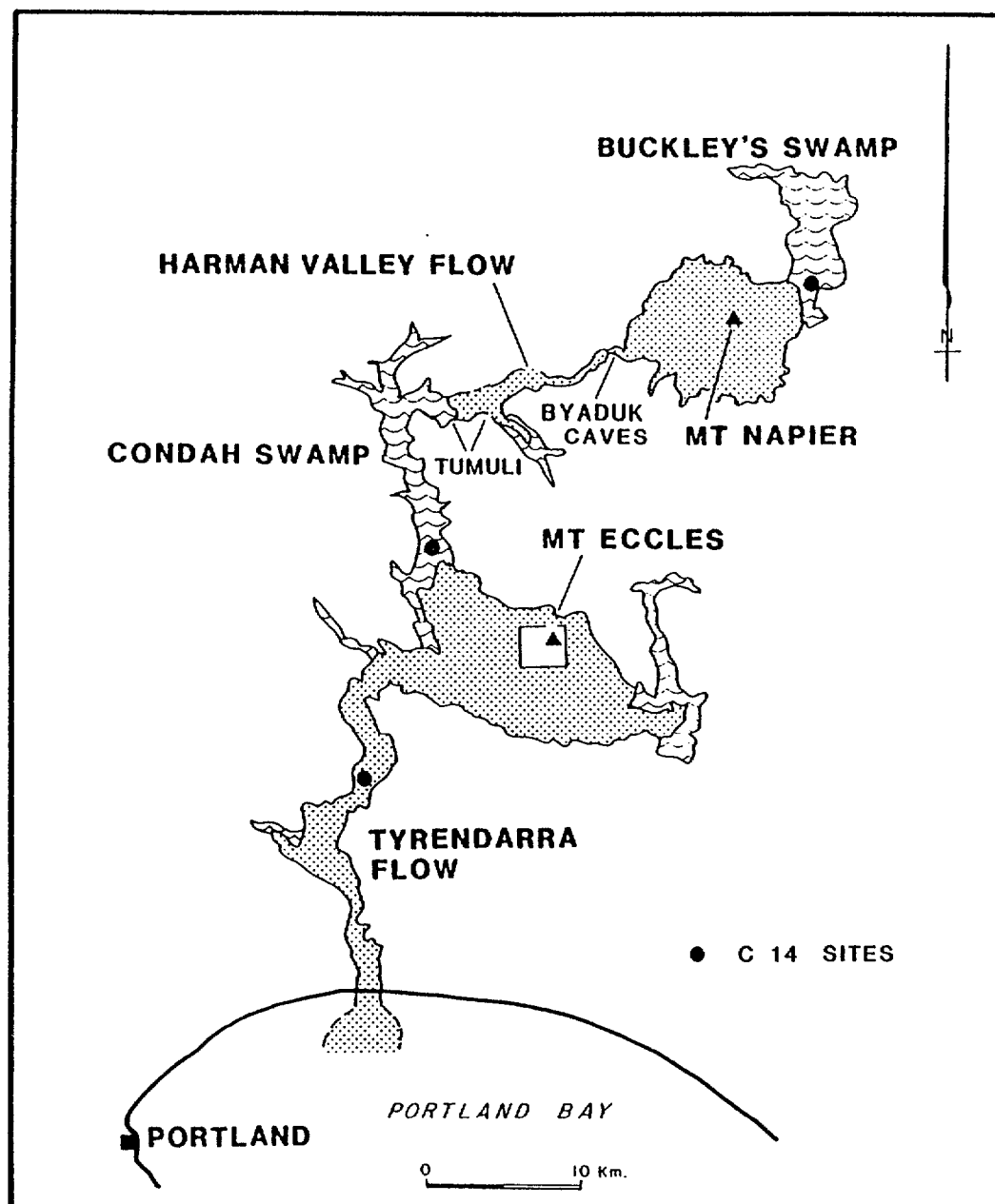
Fig. 4: Lava flows of Mts. Napier and Eccles.

The lava shield is essentially circular and ~8 km in diameter (Fig. 4). Several longer flows infill valleys within the old plains basalts surface. One of these blocked the ancestral Harman Creek northeast of the complex, leading to the formation of Buckley's Swamp. Radiocarbon dating of peat from the swamp has yielded an age of 7420±140 years BP (Gill and Elmore, 1973). A larger flow moved westward down Harman Creek, ending more than 20 km away in Condah Swamp, north-west of Mt. Eccles. This flow will be seen in the Byaduk and Wallacedale areas.

On morphological grounds, Mts. Napier and Eccles are two of the youngest volcanoes in the Newer Volcanics province. Younger dates have been obtained only for

Mts. Gambier and Schank, in south-eastern South Australia- 4000-5000 years BP, by thermoluminescence dating of sands beneath the cone deposits.

Stop 9-1: Summit of Mt. Napier (optional)

Features of the Mt. Napier summit area include the shallow crater, breached on the western side, and the excellently developed rampart of agglutinated spatter bombs ("cowpat" and "breadcrust" bombs). There is clear evidence from the lava "tide marks" on the inner slopes of the crater for varying levels of a small lava lake which fed both the spatter rampart and the small steeply-dipping hawaiite flow (with a lava tube) which issued from the breach in the crater.

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Mt. Napier to Byaduk (19 km)

The route is now westward from Mt. Napier to examine features of the major Harman Valley lava flow (Fig. 4), a young *ne*-hawaiite(Analysis 1, Table 2) with excellently preserved flow features, including lava tunnels at Byaduk and lava tumuli at Wallacedale.

Locality 10: Harman Creek valley and the Byaduk lava tunnels

Stop 10-1: Panorama of Mt. Napier
(Coleraine WD861080 - Murroa-Buckley's Swamp Road, 1.2 km east of intersection with Hamilton-Macarthur road, 8 km from Mt. Napier summit).

A brief stop gives a clear perspective of the two main components of Mt. Napier, the lower lava shield and its steeper crown of scoria cones. The Harman valley lava flow extends from the lava shield on the right of this view, although the valley itself is incised and concealed.

Stop 10-2: Byaduk lava tunnels (optional)
(Coleraine WD855038 - 8 km from Mt. Napier summit)

On the approach to the area of the Byaduk lava tunnels, the first view of the Harman Valley flow is of slopes with little outcrop grading down from the old plains basalts surface to an essentially flat valley floor 300 m wide. The infilling lava flow, at least 20 m thick at this point, is clearly visible due to its well preserved rough surface topography. At this point the flow was narrow and deep, advancing by movement of lava within tunnels beneath the semi-consolidated "skin". The tunnel system is now well exposed in 19 caves, which may be entered by circular to elliptical openings produced by collapse of sections of tunnel roofs (Ollier and Brown, 1965). The caves are essentially parts of a single tunnel system in the middle of the flow which acted as its main feeder. Typical cave dimensions are 10 m wide by 5 m high and the greatest preserved length is 400 m. In vertical section the tunnels are broadly arched with undulating floors. They were locally left empty by a final draining of lava. Preserved internal features include lava stalactites, level marks, lateral benches and ropy lava floors. Harman and Bridge Caves may be examined with relative ease.

Stop 10-3: Harman valley flow below Byaduk caves
(Coleraine WD832025 - Hamilton-Macarthur road, northern slope of Harman Creek valley between Byaduk North and Byaduk, 10.5 km from Mt. Napier summit)

The character of the Harman Valley flow is best appreciated by a view into the valley extending back towards Mt. Napier. Constriction of the flow due to the relatively steep valley walls is obvious and the irregular surface of the flow contrasts with the smooth slopes cut into the much older basalt plain and the underlying Cenozoic sedimentary succession. A further indication of youth is the absence of lateral streams at the flow margins. The most obvious features of the flow surface are the pronounced lateral ridges or barriers which stand above and parallel to the deflated bulk of the flow surface, and the transverse pressure ridges which extend across the surface of the flow and curve downstream.

Byaduk to Wallacedale (7 km)

The Harman valley flow broadens to 1 km west of the Hamilton-Macarthur road, and the road to Wallacedale follows the high country on its southern side with views down to the basalt surface. Near Wallacedale an arm of the flow extends back upstream into a closed side valley which is crossed by the road through a field of distinctive lava tumuli (Fig. 5).

Locality 11: Wallacedale area

Stop 11-1: Field of lava tumuli, Wallacedale
(Coleraine WD783007 - Old Crusher Road, 16 km from Mt. Napier summit)

The lava tumuli at Wallacedale are dome-shaped structures, almost circular in plan and up to 20 m in diameter and 10 m high. They rise abruptly from the level surface of the Harman valley lava flow, producing a unique landscape. Typical examples are more regular in form and steeper than equivalents elsewhere. As outlined by Ollier (1964), they range from simple domes through domes with breached crests from which lava has been extruded and domes with collapsed crests, to circular depressions produced by total collapse (Fig. 6). The surface layers show metre-scale polygonal jointing. Vesicles flattened parallel to the surfaces of the domes are evidence for inflation by magma pushing from below. The tumuli are randomly concentrated in the back extension of the Harman valley flow, suggesting that pressure within a stationary pool of magma due to the hydrostatic head of magma within the main flow channel is a possible explanation for the upward doming of the lava flow surface to form the tumuli.

Stop 11-2: Lateral ridges at the margins of the Harman valley lava flow, Wallacedale
(Coleraine WD766004 - Road junction at western end of Old Crusher Road, 17 km from Mt. Napier summit)

This excellent example of lateral ridges formed by rapid cooling of lava against the channel walls is located within a flow lobe on the southern margin of the Harman valley. The two parallel ridges are ~100 m long, ~15 m wide, and rise up to 4 m above the intervening depression. The more northerly of the two ridges is breached along its crest, whereas the southern is smoothly cylindrical with local breaks.

These ridges (or barriers or levees) may have several modes of origin (Hulme 1974, Sparks et al., 1976, Cas and Wright, 1987). **Initial levees** form as the margins of the lava flow cool and yield strength increases, so leading to freezing of the margins, whereas the interior continues to flow. **Accretionary levees** consist of piles of clinker accreted to smooth pahoehoe lava channels. The clinker blocks weld together to form a steep solid levee. **Rubble levees** are associated only with aa lavas and result from the avalanching of aa debris down the margins of the flow, forming piles of rubble that are approximately at angle of repose. Overflow levees form when lava repeatedly floods over existing levees. Levees can in fact be hybrids of several of these types.

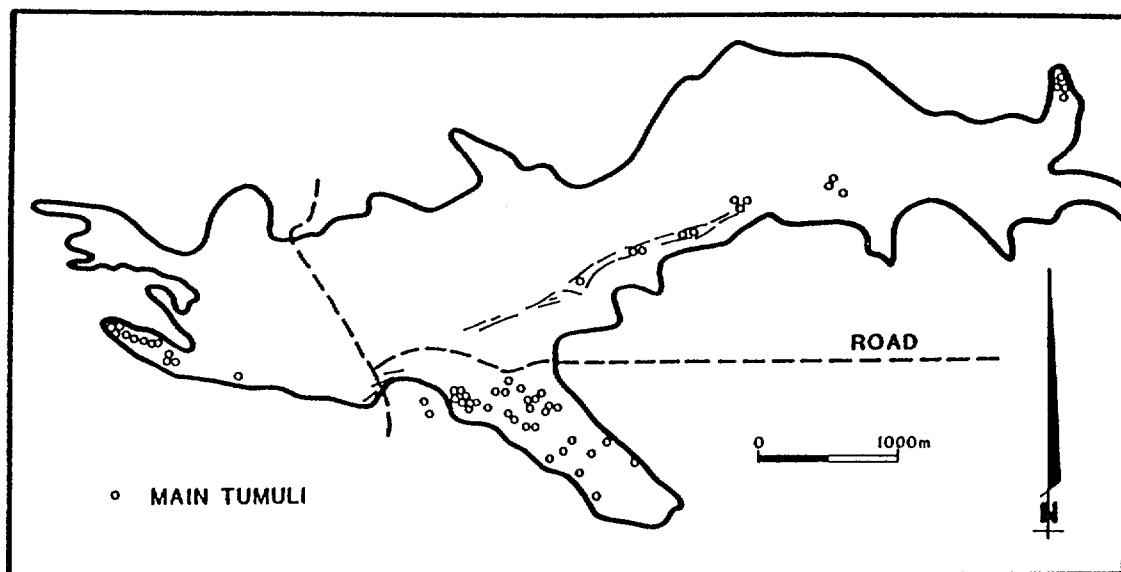Fig. 5: *Distribution of lava tumuli within the Harman valley flow in the Wallacedale area. The dashed lines represent the crests of barriers (pressure ridges) (from Ollier, 1964).*
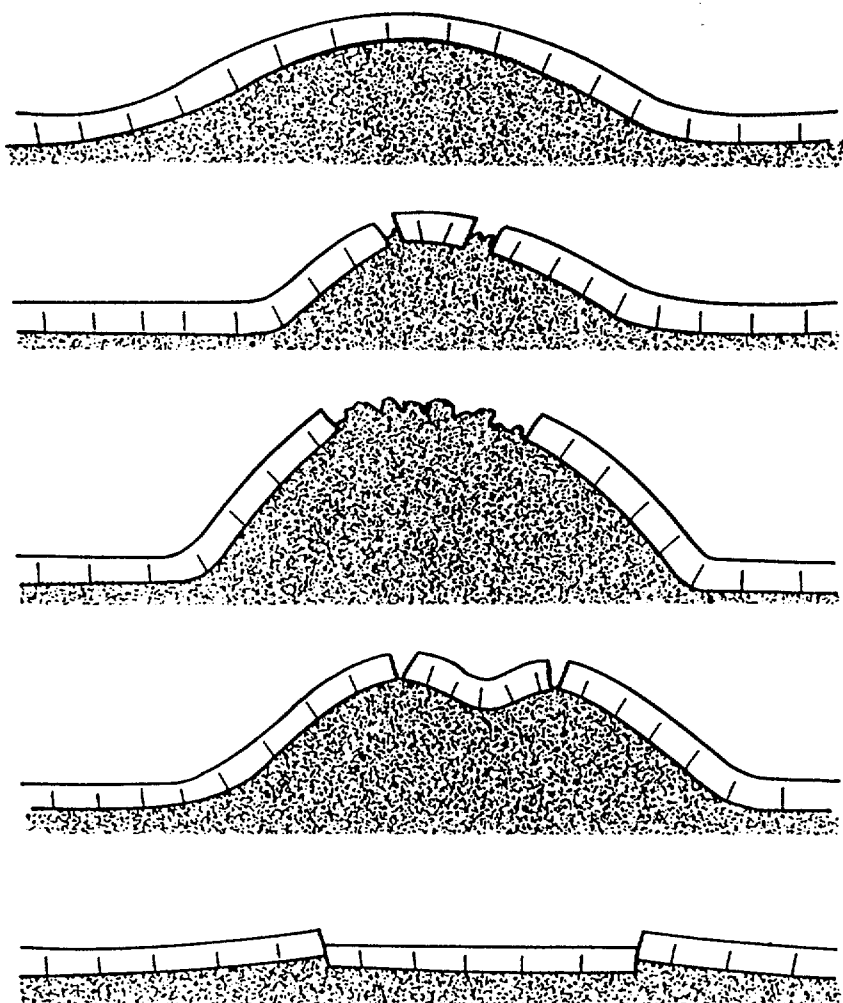
Fig. 6: *Range of variation amongst lava tumuli: simple tumulus; minor breaching of crest; breaching and inflation of crest; sagging of crest; downfaulted disc of lava crust - remains of collapsed tumulus (from Ollier, 1964).*

Wallacedale to Mt. Eccles (22 km)

The route to the Mt. Eccles complex is back to the Hamilton-Macarthur Road, then southward. About 2 km north of Macarthur township, it again turns west to approach Mt. Eccles, which may be seen on the skyline as a single low domed hill with a very obvious quarry face on its eastern side. To the north of Mt. Eccles is the broad low Bald Hill volcano, one of a group of older (~3 Ma) lava shields or composite cones (Coulson, 1941) consisting of tholeiitic to slightly alkaline basalts (ol-and qz-normative tholeiites, rare basaltic icelandites; hy- to weakly ne-normative

Swamps

Basalt (third phase) showing flow lines

Bridgewater Formation

Recent beaches and dunes

Basalt (third phase), submarine

Bridgewater Formation, submarine

Fig. 7: The lava apron of Mt. Eccles and the Tyrendarra lava flow (from Boutakoff, 1963).

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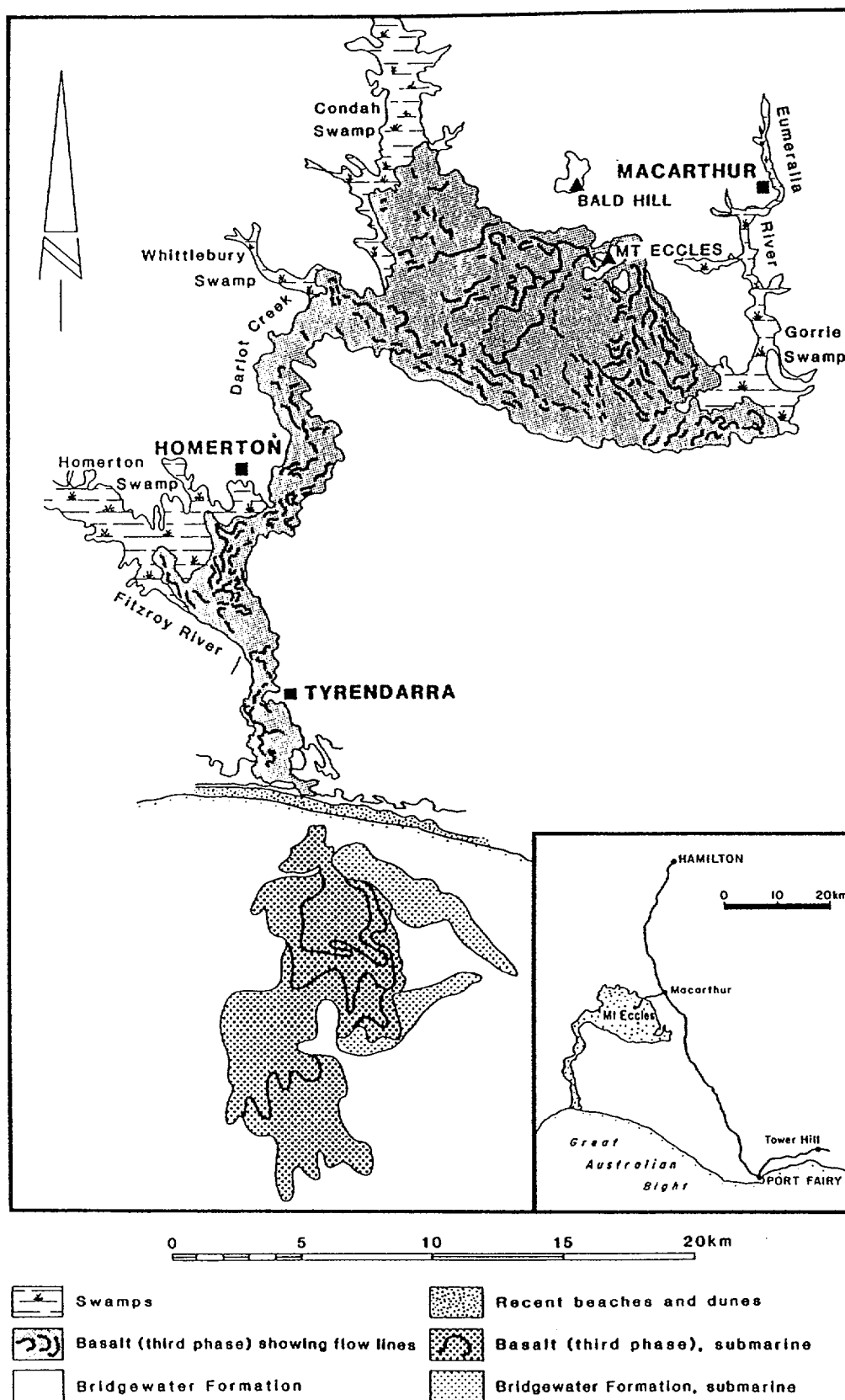hawaiites - Sukhyar, 1986; Stewart, 1987). The interiors of several of these low volcanoes are well exposed in coastal cliffs near and west of Portland (Capes Grant, Nelson and Bridgewater). Capes Grant and Nelson are dominated by thick sequences of massive lava flows. Basalts at Cape Grant have been dated at 2.9-2.7 Ma (Aziz-ur-Rahman and McDougall, 1972). The Cape Bridgewater complex includes overlapping cones consisting mainly of basaltic pyroclastic surge and air fall deposits with associated small lava flows, resting on a thick sequence of lavas.

Near the coast, these older volcanoes are partly buried by Pleistocene limestones (Bridgewater Formation) which represent dune deposits accumulated during periods of low sea level. Centres further inland, including Bald Hill, are partly covered by thin deposits of wind-blown quartz sands.

Locality 12:   The Mt. Eccles Volcanic Complex (Portland WC807870)

Mt. Eccles is the name given to the largest (180m high) scoria cone within a volcanic complex which includes a crater lake (Lake Surprise), a number of lava channels and tunnels which fed an extensive lava flow apron, various spatter cones, and a second smaller scoria cone (Little Mount - now removed by quarrying). Like Mt. Napier, the complex is one of the youngest centres within the Western Plains sub-province west of the "Mortlake line" which apparently entirely lack ultramafic xenoliths and megacrysts. Available radiocarbon dates for Mt. Eccles are within the range 29000-6000 years BP.

The magmas of the Mt. Eccles complex were of hawaiite to ne-hawaiite composition (Irving and Green, 1976) (Analysis 2, Table 2).
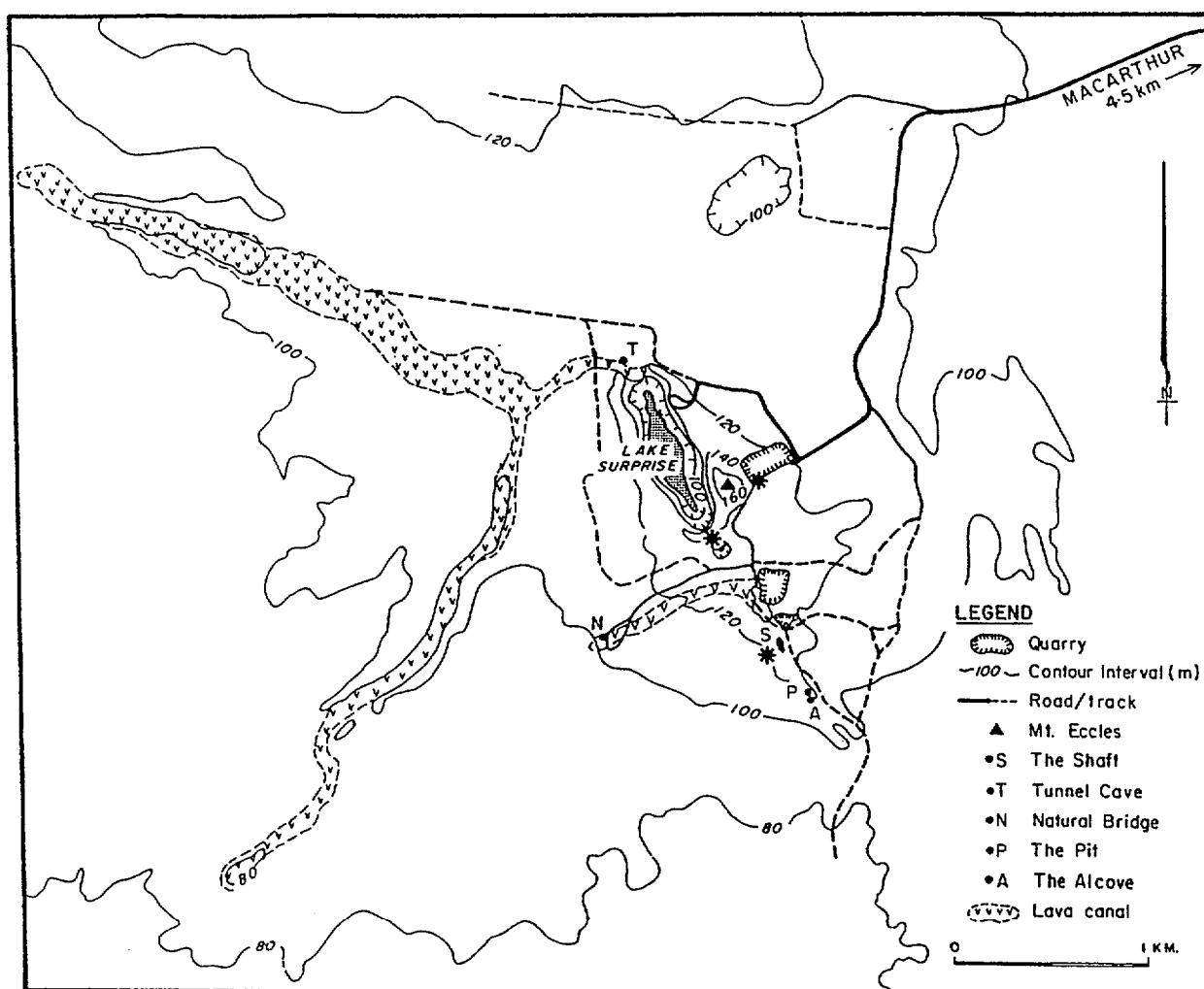
Fig. 8: Map of the Mt. Eccles volcanic complex.

As shown by spatial relationships between scoria cones and adjacent lava flows, the cones are amongst the earliest products of activity at Mt. Eccles. The minimum extent of lava flows is ~2 km toward the north, where they were diverted by Bald Hill. A lobe (the Tyrendarra Flow) moved westward into Condah Swamp, then southward down the valley of the ancestral Fitzroy River (Fig. 7). Erupted at a time of low sea level, part

of this flow now extends 15km beyond the coastline. Its total length was nearly 50km, while parts of it narrowed to 100 m where it flowed in pre-existing stream valleys. There is some evidence from boreholes for two flow units separated by a weathering surface. This may help to explain the discordance between >25000 years and <10000 years BP ages obtained for plant material or

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charcoal sampled from beneath parts of apparently the same lava flow.

The crater lake within the Mt. Eccles complex, Lake Surprise (Fig. 8), is ~700 m long and up to 150 m wide. The crater is a compound structure with cuspate sides formed from three smaller craters in the summit area of a low lava shield. It is almost enclosed by 50-70m cliffs developed in the lava flow sequence, with 7-10 flows exposed. In some places, the cliffs are draped with thin near-vertical sheets produced by flow of fountained lava back into the crater (Tunjic, 1988). The northern end of the lake is ~20m below the beginning of the largest lava channel ('canal') of the complex. The NNW-SSE trend of Lake Surprise extends into a series of small eruption points, suggesting alignment along a fissure, or a deep narrow section of a lava flow, at least 2.5 km in length (Ollier and Joyce, 1973).

The lava channels, or canals, represented lines of drainage within the extensive lava sheets centred on the Lake Surprise crater. Lava flowed mainly within the channels, occasionally overflowing the banks and raising the general level of the intervening lava sheets. When a skin was formed over parts of the channel system, and fluid lava drained out, lava tunnels resulted. The most extensive of these is Tunnel Cave, above the northern end of Lake Surprise (Fig. 8). This appears to have formed in a side flow almost perpendicular to the main lava channel. Within the smaller southern lava channel system, Gothic Cave (with its roof, the Natural Bridge), is a short section of an unusually deep and narrow lava tunnel.

A series of small spatter-related features begins at the southern end of Lake Surprise, where a deposit of agglutinated lava bombs represents part of a spatter rampart. South of the Little Mount quarry are the spatter cones named 'The Shaft', 'The Pit', and 'The Alcove' (Fig. 8). The best developed, The Shaft, is a cone formed of breadcrust bombs and lava driblets, with an open vent extending about 30m below the surrounding lava flow surface. Ollier and Joyce (1973) suggest that these features may represent adventitious cones, fed with lava from an underlying thick flow.

Stop 12-1: Southern rim of Lake Surprise

An excellent view along the length of Lake Surprise is obtained from its southern rim. Immediately to the left is a well-developed section of spatter rampart, consisting mainly of "breadcrust" bombs which have partly coalesced. To the right, high on the western flank of the Mt. Eccles cone, is a similar partial rampart, showing clearly the relative ages of the scoria cone and the lava lake within the crater complex.

Stop 12-2: Summit of Mt. Eccles scoria cone

The summit of the scoria cone gives excellent views of the region around Mt. Eccles, including Mts. Napier and Rouse and the ~3 Ma shield volcanoes (Bald Hill; Mts. Clay and Eckersley westward toward Portland). The extents of the Mt. Eccles lava apron (wooded country) and the long narrow Tyrendarra flow are also clear. Blocks of red coarse-grained basalt or dolerite, probably

derived from a thick plains basalt lava flow or sill immediately beneath the young complex, are found in the summit area.
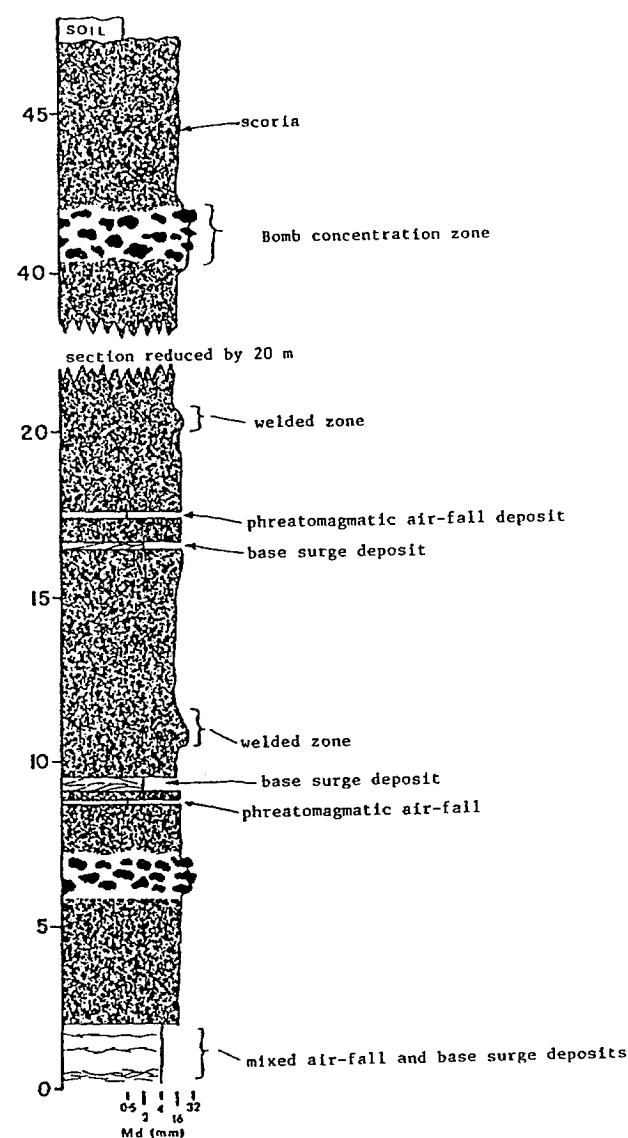
Fig. 9:   Stratigraphic section through the Mt. Eccles scoria cone (Edney, et al, 1984, ms).

Stop 12-3: Quarry in Mt. Eccles scoria cone

The complex incorporates no constructional features recognisably of phreatomagmatic origin, but minor pyroclastic surge deposits are exposed within the quarry section through the main Mt. Eccles scoria cone (Figs. 8, 9). The history of this cone appears to have commenced with phreatomagmatic explosions, with a further two short bursts of phreatomagmatic activity of variable efficiency and intensity occurring later in the cone-building period (Fig. 9). The initial phreatomagmatic activity produced diffusely-bedded deposits of weakly vesicular basaltic lapilli, accompanied by small blocks of a variety of country rock types (both sedimentary and volcanic). The phreatomagmatic layers higher in the sequence are much finer and more uniform in grainsize, indicating the influence of higher water/ magma ratios and more efficient magma fragmentation.

The water source for phreatomagmatic activity was probably one of the many aquifers in the area.

The eruption style subsequently reverted to Strombolian magmatic activity, producing the scoria, bombs and spatter deposits which form the bulk of the scoria cone (Fig. 9). These deposits are massively bedded and show variable grainsize, density and vesicularity. Some intervals are partly welded, reflecting periods of rapid accumulation. The ejecta display little gravity sorting and begin to show graded bedding only at greater distances from the vent.

Stop 12-4 : Gothic Cave and the Natural Bridge

Gothic Cave lies beneath a short section of preserved roof (the Natural Bridge) of a deep narrow lava tunnel within the southern "canal" system. The tunnel walls appear to have been bulged inward due to pressure from surrounding plastic lava. Successive levels of draining lava are recorded by 'tide marks' and benches.

Stop 12-5: Spatter cones on the southern line of eruption points; The Shaft

Several small spatter cones, 10-30 m high and 50-100 m in diameter, are developed on the surface of the southern lava canal west of the remains of Little Mount. Features produced by eruption of highly fluid lava (breadcrust bombs, lava driblets, etc.) are very well

preserved, especially at the Shaft, with its ~30 deep opening into the lava tunnel system. The spatter cones are composed of ne-hawaiites distinctly more alkaline than the major hawaiite lava flows of the complex.

Stop 12-6: The northern lava canal and Tunnel Cave (Optional)

The north-western end of Lake Surprise is the low point on the crater rim and the site at which lava escaped from a lava lake within the crater complex. The main northern lava canal system originates here and the walking track follows its floor. The canal is ~40 m wide and ~6 m deep and locally thin-layered basalt makes up the levee banks. Numerous lava canals radiate from this point across the lava apron and attain lengths of 3 km and a maximum width of 300 m. Returning to the crater wall, a small exposure contains several pahoehoe toes and the entrance to a lava tunnel. Tunnel Cave is excellently preserved and has a triangular cross-section with lava levels and drain-back dribbles on its walls.

Mt. Eccles to Port Fairy (57 km)

After leaving Mt. Eccles, the route is to Macarthur, then southward toward Port Fairy. Over the last 10 km into Port Fairy, the road passes through an extensive belt of degraded stony rises, developed on the lava flows from Mt. Rouse, about 65km to the north. (Fig. 3).

DAY 4: PORT FAIRY TO CAMPERDOWN AND NOORAT

Composite maar/tuff ring-scoria cone complexes of the southern Western Plains sub-province; xenoliths of the Bullenmerri-Gnotuk complex

Day 4 of the field trip will be spent in the southern part of the Western Plains sub-province, which rests mainly upon Cenozoic sedimentary successions. Aquifers within these successions, particularly within limestones, have supplied water to drive phreatomagmatic activity, resulting in the widespread occurrence of tuff deposits of pyroclastic surge origin. These make up the bulk of the characteristic maars and tuff rings of the region. In a number of cases, the transition from phreatomagmatic to magmatic activity, reflecting the declining influence of water, may be seen at volcanic centres which include both maar/tuff ring structures and scoria cones. Many of the volcanic centres in this part of the sub-province, just to the east of the "Mortlake line" are rich xenolith and megacryst localities.

Port Fairy to Tower Hill (15 km)

The initial route is eastward via the Princes Highway, which in this area runs close to a low coastline backed by Pleistocene aeolian dune deposits of the Bridgewater Formation (Fig. 10). The gentle outer slopes of Tower Hill, with its prominent microwave tower, may be seen ahead.

Locality 13: The Tower Hill complex

The Tower Hill complex lies beside the Princes Highway 12km west of Warrnambool (Fig. 10). It is

composed of an unusually large (~3 km maximum diameter) roughly elliptical maar, with multiple nested scoria cones within its crater lake (Fig. 11). Several cones have been removed by quarrying. Tower Hill is a Wildlife Reserve, and in recent years reafforestation has been undertaken to return it to its natural state prior to European settlement. The centre has been described by Gill (1967) and Edney (1984). Radiocarbon dating of plant debris from the maar lake and peat from craters within the scoria cone complex has indicated that its most recent activity was at ~10,000 years B.P.

Tower Hill is dominated by basanite (Analysis 3, Table 2) to strongly ne-normative hawaiite compositions (Irving and Green, 1976). The geochemistry of its products has not been studied in detail. Ultramafic xenoliths are very rare or absent.

The maar was formed by dominantly phreatomagmatic activity, a result of interaction between rising magmas and groundwater from a high flow rate aquifer within Cenozoic limestones some 600m below present lake level (Edney, 1984). The area of tuff deposits surrounding Tower Hill is ~150km^2, representing a volume of volcanic debris of the order of 10 km^3 (Fig. 10). The maar rim deposits in general dip gently (5-10°) away from the crater, and more steeply inward dipping beds (~40°) are rare. The water/magma mass

ratio fluctuated considerably during the period of maar-forming activity, producing ejecta with a wide range of characteristics indicative of eruptive processes ranging from purely phreatomagmatic to purely magmatic. Phreatomagmatic eruptions gave rise to pyroclastic surge and minor air-fall deposits of microvesicular lapilli and ash, with a variable but significant country rock component, dominantly limestone fragments. Magmatic eruptions gave rise to intervals of strongly vesiculated dark scoria.
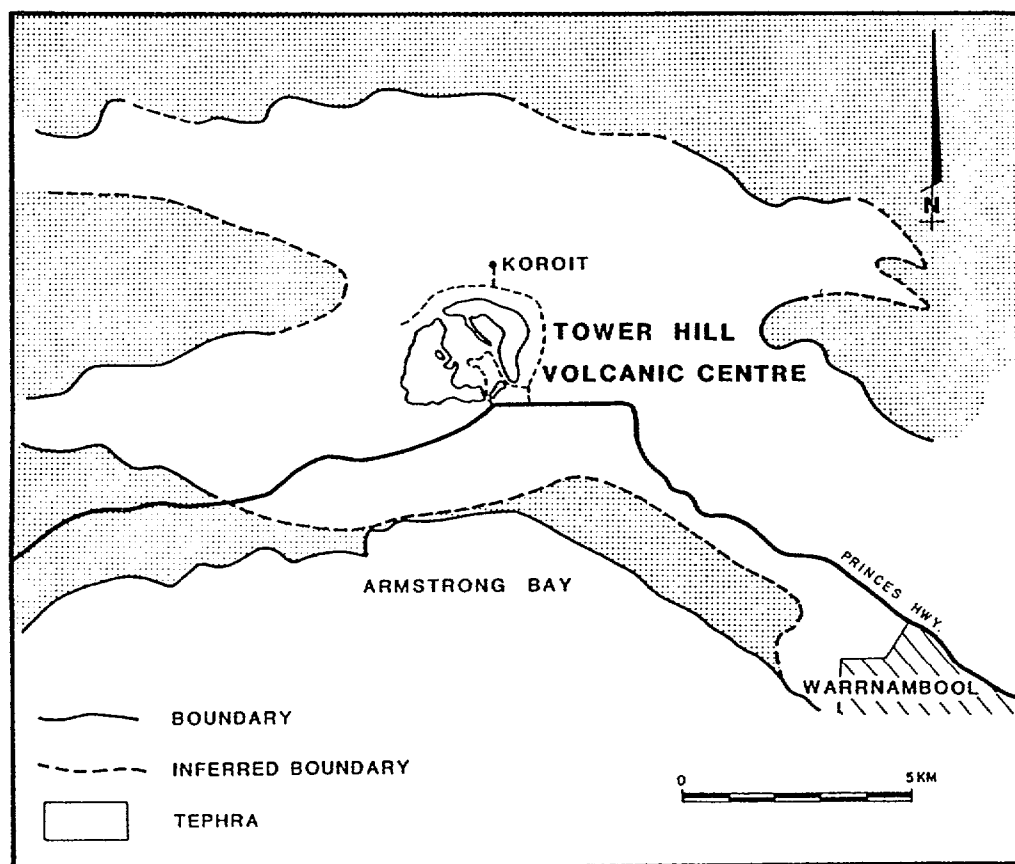

Fig. 10: Distribution of surge and air-fall tephra from the Tower Hill volcanic centre (Edney, 1984).

The scoria cones within the maar lake were produced almost entirely in the last stages of eruptive activity, along two NNW-SSE aligned fissures (Fig. 11). The longest and probably most recent period of activity occurred along the western fissure, which had nine scoria cones sited on it, only two of which are now well preserved. The deposits of the scoria cones are the result of dominantly magmatic eruptions, ranging from strombolian and hawaiian activity producing scoria, vesicular bombs, dense blocks, spatter and agglutinate to effusive activity producing four lava flows of limited areal extent. Interbedded with the strombolian and hawaiian deposits are phreatomagmatically derived explosion breccias and proximal base surge deposits.

The Tower Hill volcanic centre emphasises the complexity of controls on explosive basaltic volcanism. The interplay of factors such as rate of ascent of magma, depth of formation and rate of ascent of gas bubbles within the magma, depth of interaction between magma and water, water/magma mass ratio and rate of accumulation of ejecta, determines the ultimate nature of the deposits (Edney, 1984).

Stop 13-1: The C.R.B. quarry within the southern maar rim (Warrnambool 195568)

Excellent exposures of the pyroclastic succession of the maar rampart occur in quarries in the steep crater walls, which rise from 20 m on the southwest (where a "pinnacle" of the old limestone surface may be seen) to 90m on the eastern side of the compex (Fig. 11). The C.R.B. Quarry is one of many and is located on the entrance road to the Wildlife Reserve and Visitors' Centre.

The eruption sequence exposed in the C.R.B. Quarry is complex. Products of phreatomagmatic activity are interbedded with magmatically-derived ejecta, and at least thirteen reversions to solely magmatic activity have taken place in producing the observed stratigraphy (Fig. 12). The magmatic deposits are characteristically strombolian in nature and consist of scoria fall deposits (up to 3m thick) and thinner units of blocks and bombs (Fig. 12). The phreatomagmatic deposits display a variety of bedforms and grainsizes. The major bedform types are massive to diffusely bedded, planar-bedded or -laminated and cross-bedded or -laminated. The depositional mechanism for the massive to diffusely bedded units is variable. Some units are internally more massive and mantle-bedded and are probably of air-fall origin; others display erosive basal contacts and are of surge origin, displaying a variety of unidirectional

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traction structures (especially low-angle cross bedding) which indicate palaeoflow directions radially away from the crater (Fig. 11). Disruption of bedding due to impact of large ballistic blocks is a prominent feature. At least one interval of accretionary lapilli occurs high in the C.R.B. quarry sequence. A large block of glassy basanite is found right on the quarry rim. This appears to be part of a very coarse explosion breccia deposit.
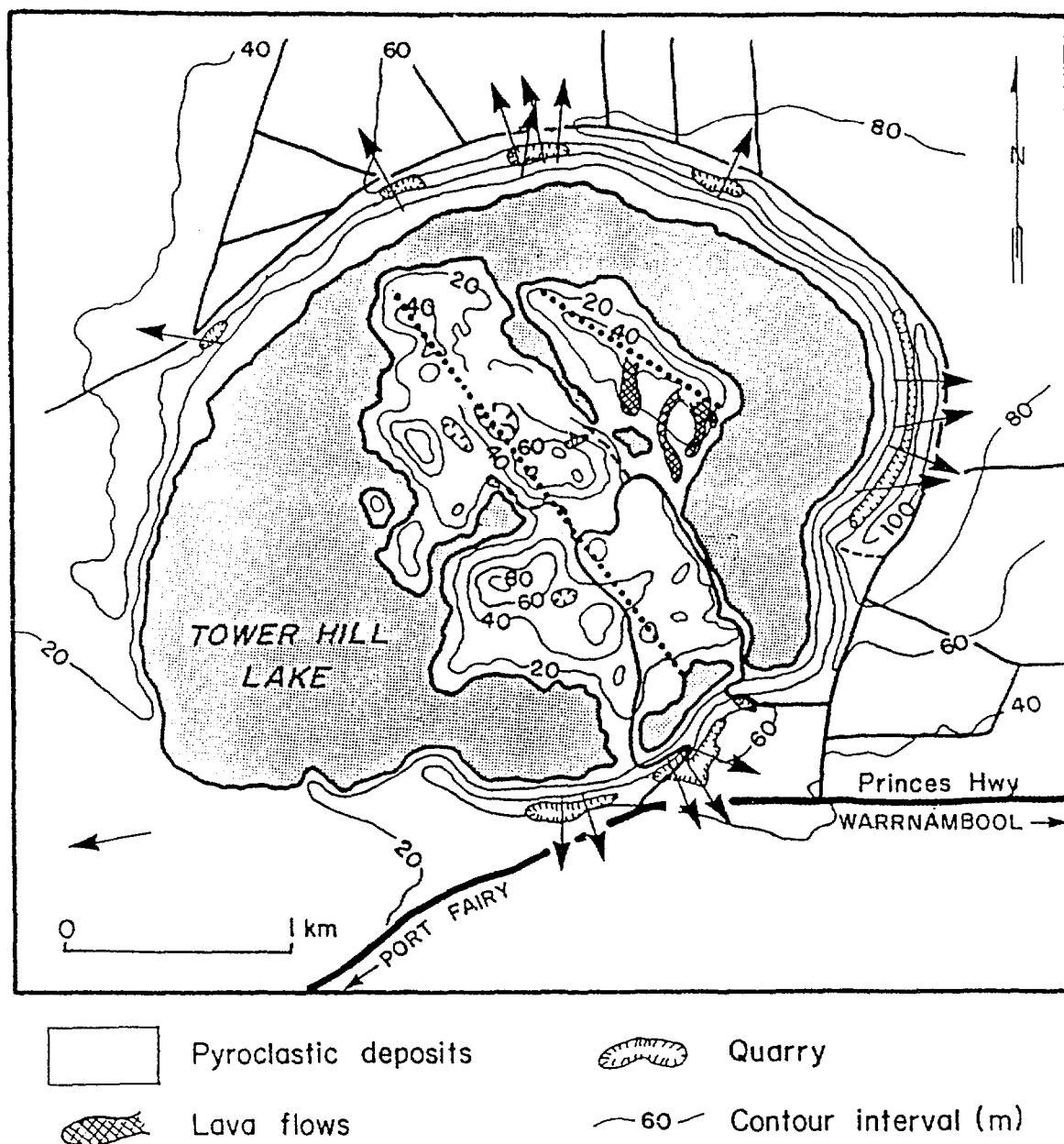

Fig. 11: Map of the Tower Hill complex (Edney, 1984).

If time permits, we will visit the lookout within the scoria cone complex, and also the Tower Hill history display in the Visitors' Centre. Be careful of the emus (large flightless birds), which while not dangerous are highly inquisitive, especially when they see humans with food. Kangaroos and koalas are also found within the Reserve, but they are more retiring than the emus.

Tower Hill to Camperdown (80 km)

The route beyond Tower Hill is along the Princes Highway via Warrnambool and Terang to Camperdown. Between Tower Hill and Warrnambool, almost flat-lying thin-bedded tuffs of the Tower Hill maar apron are exposed in low road cuttings. These deposits contrast with the steeply cross-bedded aeolian dune limestones which crop out between the Highway and the coast.

East of Warrnambool is some of the richest pastoral country in Victoria, with the advantages of basaltic soils and substantial rainfall. If time permits, we will make a short detour to Hopkins Falls, on the river of the same name. These are typical of waterfalls on the basalt plains, cascading over a face defined by columnar jointing within a lava flow. Two adjoining maars lie to the east of the Falls on the route back to the highway.
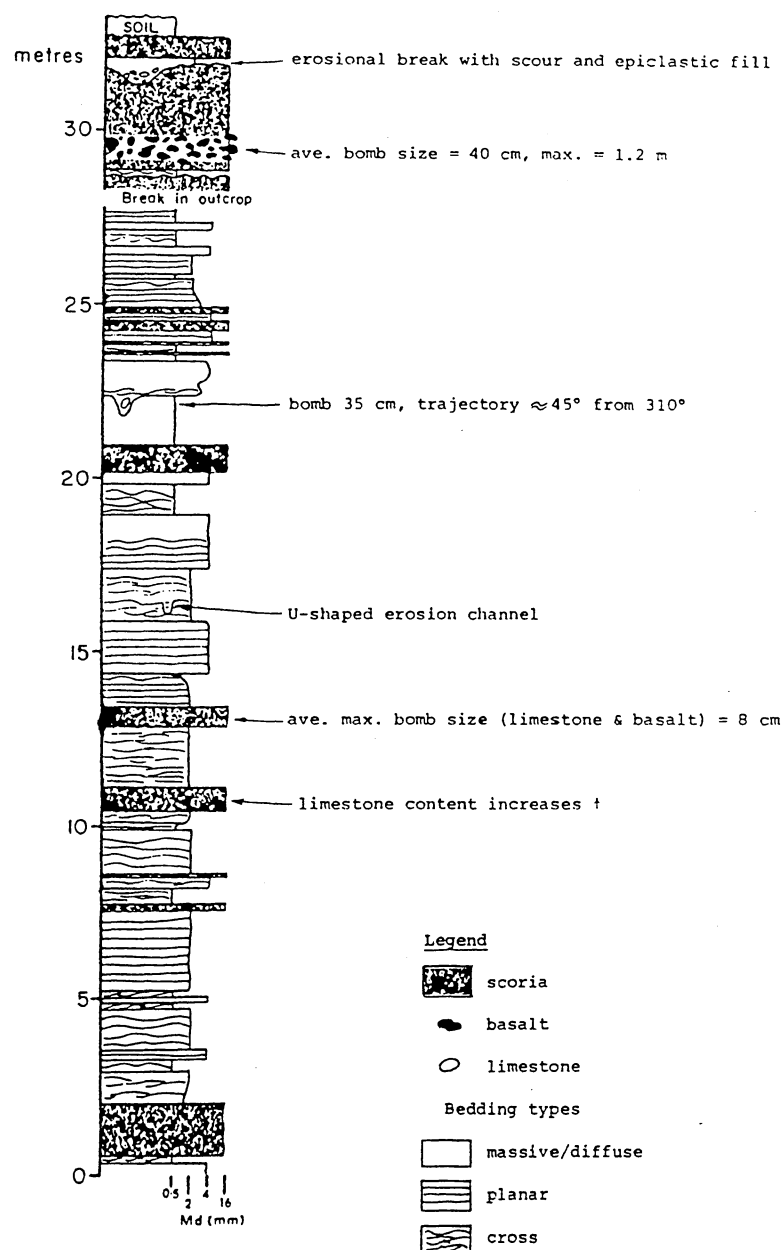
Fig. 12: Stratigraphic section through Tower Hill maar rim deposits, CRB quarry (Edney, 1984).

The prominent cone north of the highway near Panmure is Mt. Warrnambool, a large *ne*-hawaiite scoria cone within a low tuff ring. Thick basalt flows in this area are extensively quarried. At the town of Terang, the golf course is within an obvious dry maar depression. Beyond Terang, the cone of Mt. Noorat may be seen to the north. We will visit the Noorat complex in late afternoon, spending the night at Glenormiston Agricultural College, 2 km from the foot of Mt. Noorat.

Between Terang and Camperdown (~20 km) the highway traverses basalt plains studded by volcanic cones, with several large shallow lakes formed by lava flow damming. The plains basalts in this area are hawaiites or *ne*- hawaiites, forming the most extensive area of mildly alkaline basalts within the Western Plains. Although many of the volcanic centres are as young as 20,000 years BP, outcrop within their lava aprons is limited, largely due to burial by extensive

pyroclastic deposits from the many maars and tuff rings in the area. This area is distinctive in a number of ways: it has the highest density of volcanic centres within the sub-province, with almost all the major maars and tuff rings (~40); basalts of the volcanic centres are significantly more alkaline than those of the underlying plains sequences; it includes most of the best xenolith and megacryst localities of the sub-province, including the only locality with common garnet-bearing xenoliths - the Bullenmerri/Gnotuk maar complex (Fig. 13).

The Warrnambool-Camperdown region lies close to the Colac Lineament, a major boundary fault, and Camperdown lies at the intersection between this lineament and the "Mortlake line". The unique features of volcanic activity in this area may be related to this tectonic setting, with strongly alkaline magmatism being favoured by major faults penetrating deep into the lithosphere.
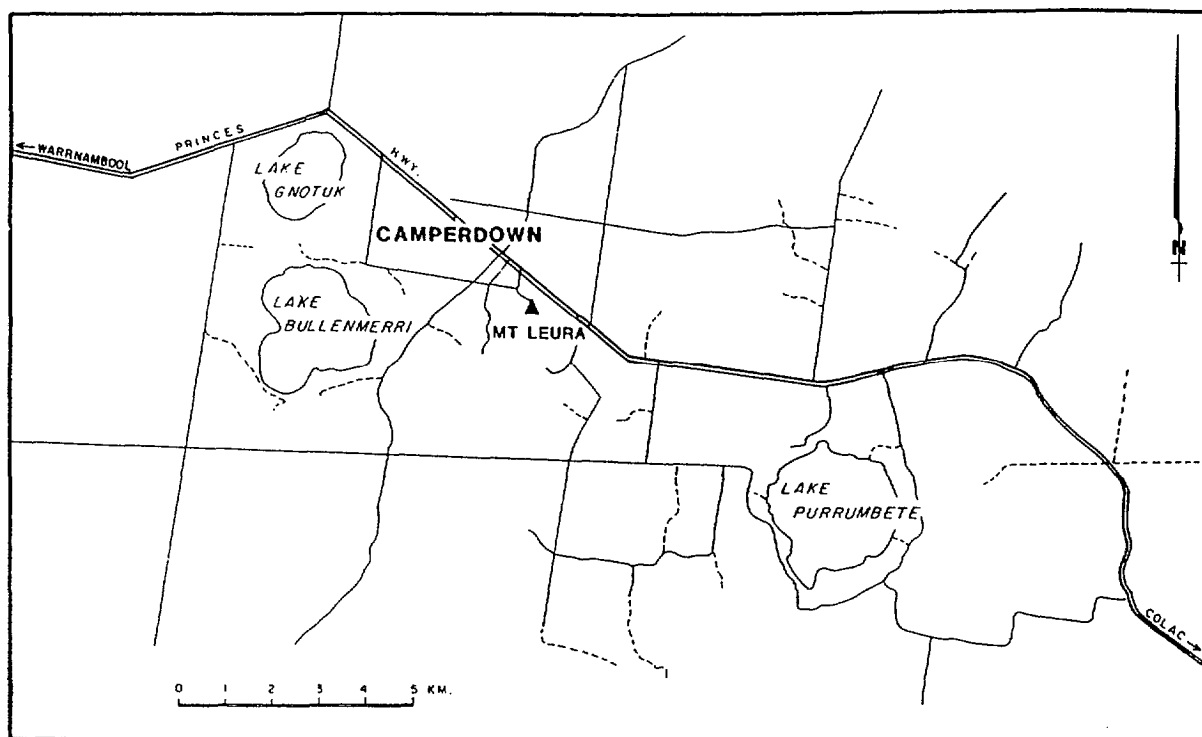
Fig. 13: Locality map of the Camperdown area - Lake Bullenmerri/Lake Gnotuk, Mt. Leura and Lake Purrumbete.

Locality 14: Lake Bullenmerri/Lake Gnotuk maar complex

About 2 km west of Camperdown, the route leaves the Princes Highway to climb southward onto the outer slopes of the Lake Bullenmerri/Lake Gnotuk complex. From the summit, it descends along the divide between the two lakes. Bedded basanitic pyroclastic surge deposits of the Bullenmerri structure, dipping lakeward at 30-50°, are poorly exposed in weathered outcrops along the road. Lake Bullenmerri, the higher lake by about 20m, is slightly saline; that of Lake Gnotuk is strongly saline, showing that the lakes are related to independent groundwater systems.

In overview, the Lake Bullenmerri shoreline shows embayments suggesting an origin from at least two overlapping craters. Exposures on the western shore contain thin-bedded basanitic tuffs of pyroclastic surge origin, rich in small pyroxenitic and peridotitic fragments. Part of a tuff ring is exposed in quarries on the western side of the near-circular Lake Gnotuk. Only lava flows are seen elsewhere on its margins, indicating that it is largely a collapse structure.

The Bullenmerri/Gnotuk complex is well known for a very wide range of ultramafic xenoliths, up to 30 cm in diameter, of shallow mantle/deep crustal origin and also mafic types of shallower origin. The ultramafic suite includes garnet-bearing pyroxenites in abundance unique within the Newer Volcanics province. The mafic suite includes gabbros, some of them pegmatitic. The peridotitic, pyroxenitic and gabbroic xenolith suites have been studied in considerable detail (see Introduction) and this work has recently been summarised by O'Reilly, et al (1989). Peridotitic xenoliths at this locality are notable for strong evidence

of fluid metasomatism, in the form of veins and dispersed patches of hydrous mineral assemblages (amphibole±apatite±phlogopite) and abundant CO_2-rich fluid inclusions. Pyroxene-rich xenoliths show evidence for progressive recrystallization and adjustment to lower temperatures and/or pressures. This evidence includes initial exsolution of garnet or Al-spinel from sometimes >5 cm crystals of low-Ca, high-Al clinopyroxenes of wehrlites, followed by recrystallization and grainsize reduction to produce the two-pyroxene assemblages of garnet websterites. Geothermometry-geobarometry suggests that these processes took place within a complex transition zone between the lithospheric mantle and crust at 40-50 km.

Stop 14-1: Northern shoreline of Lake Bullenmerri (Corangamite XC850650)

The Lake Bullenmerri xenolith localities are depleted, especially those on the northern shore which were richest in garnet pyroxenites. However, a walk along the shoreline may allow examples to be found.

The next locality, the Mt. Leura complex, lies at the eastern end of Camperdown, about 3 km from Lake Bullenmerri (Fig. 13).

Locality 15: Mt. Leura tuff ring/scoria cone complex

At the eastern end of Camperdown, the Princes Highway rises over a gentle ridge which curves southward. This is the rim of a 2.5 km diameter tuff ring, the interior of which is now occupied by the Mt. Leura scoria cone complex. Parts of the thin-bedded sequence of pyroclastic surge deposits of the tuff ring are exposed in a low cutting on the highway, and in quarries beside it.

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The Mt. Leura complex has previously been described by Evans (1980) and Edney, et al (1984, ms). Eruptive activity of the centre essentially comprised two stages. The first commenced with phreatomagmatic activity, producing the thin bedded and internally stratified and cross-stratified deposits of the tuff ring. Later activity mantled the tuff ring with proximal pyroclastic fall deposits within the lapilli to block and bomb range, spatter and minor lava flows, some of them clastogenic. These magmatic deposits were produced by Strombolian to Hawaiian activity along a fissure beneath the interior of the tuff ring. This activity eventually also produced a single large scoria cone with a deep crater.

This now has two peaks - Mt. Leura and Mt. Sugarloaf - which represent less degraded crater rim sectors. The remaining landforms within the tuff ring include a number of small scoria and spatter cones. The flanks of the scoria cone slope at 35-40°, while the gentler spatter cone slopes slope at 25-30°, depending upon the degree of degradation. The single known lava flow associated with the cone complex is approximately 65m wide, 5-6m thick and travelled less than 1 km northward. This is a ne-hawaiite (Analysis 4, Table 2) rich in peridotitic xenoliths. Parts of it show distinctive grey mottling, apparently due to spherulitic devitrification of glassy groundmass.
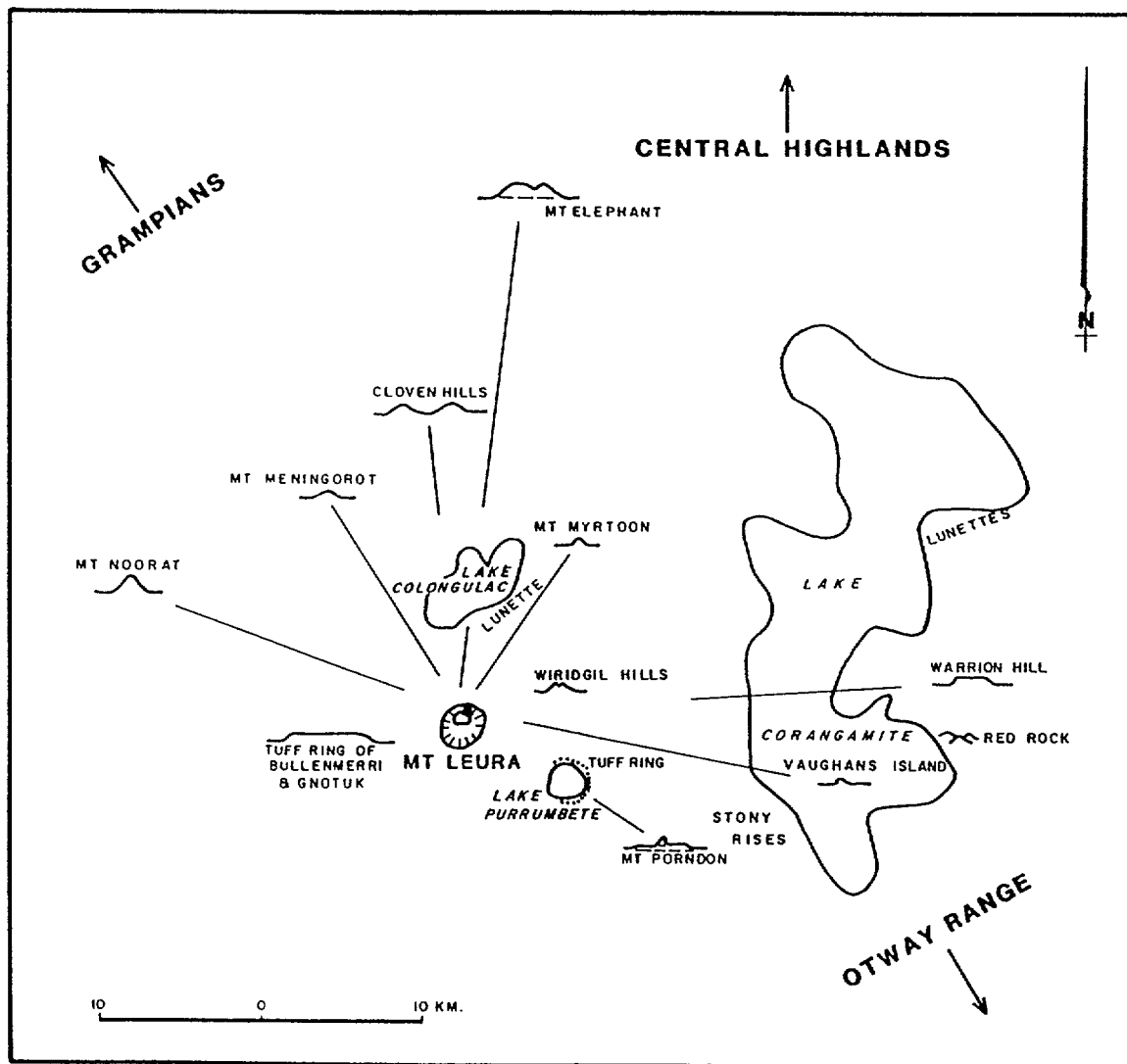
Fig. 14: Volcanic and other topographic features visible from Mt. Leura lookout.

Ultramafic xenoliths are also abundant within the scoria cone complex of Mt. Leura, and fragmented xenolith material, with olivine dominant, is an important constituent of pyroclastic surge and air-fall deposits within the tuff ring. Megacrysts are common, but not abundant. Xenoliths are readily found in two quarries in the northeastern foot of the main scoria cone. Cr-diopside spinel lherzolite is the dominant type, occurring mainly as sub-spherical blocks 5-15 cm in diameter with or without a basalt rind. Spinel wehrlites

are fairly common; dunites, spinel websterites, spinel clinopyroxenites and hornblendites are rare, and plagioclase or garnet-bearing websterites are very rare. As in most Newer Volcanics centres, black glassy Al-Ti-augite is the most abundant megacryst mineral. Ti-pargasite and anorthoclase are common and ilmenite very rare (Wass and Irving, 1976; Ellis, 1976).

Most lherzolite xenoliths show the coarse equant textures typical of almost undeformed material. Olivine

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crystals are often unusually coarse (10-20mm). Both pale and dark green lherzolites are present, the latter taking their colour partly from their pyroxenes, which have often undergone melting and are charged with tiny glass inclusions. Some have rare phlogopite crystals, visible in hand specimen. Occasionally, strongly deformed lherzolites (mylonites) with <1 mm grainsizes and weak planar fabrics are found (Nicholls and Greig, 1989). Examples from Mt. Leura have been included in a number of geochemical studies of Newer Volcanics xenoliths. Abundances of Th, U and K have been studied by Green, et al. (1968), Pb- and Sr- isotopic ratios by Cooper and Green (1969), Dasch and Green (1975), Stuckless and Irving (1976) and McDonough, et al (1985), and rare earth and incompatible element abundances by Frey and Green (1974). The latter authors first noted the common depletion in major and some trace elements associated with basaltic melt extraction, overprinted by enrichment in highly incompatible trace elements associated with melt or fluid metasomatism.
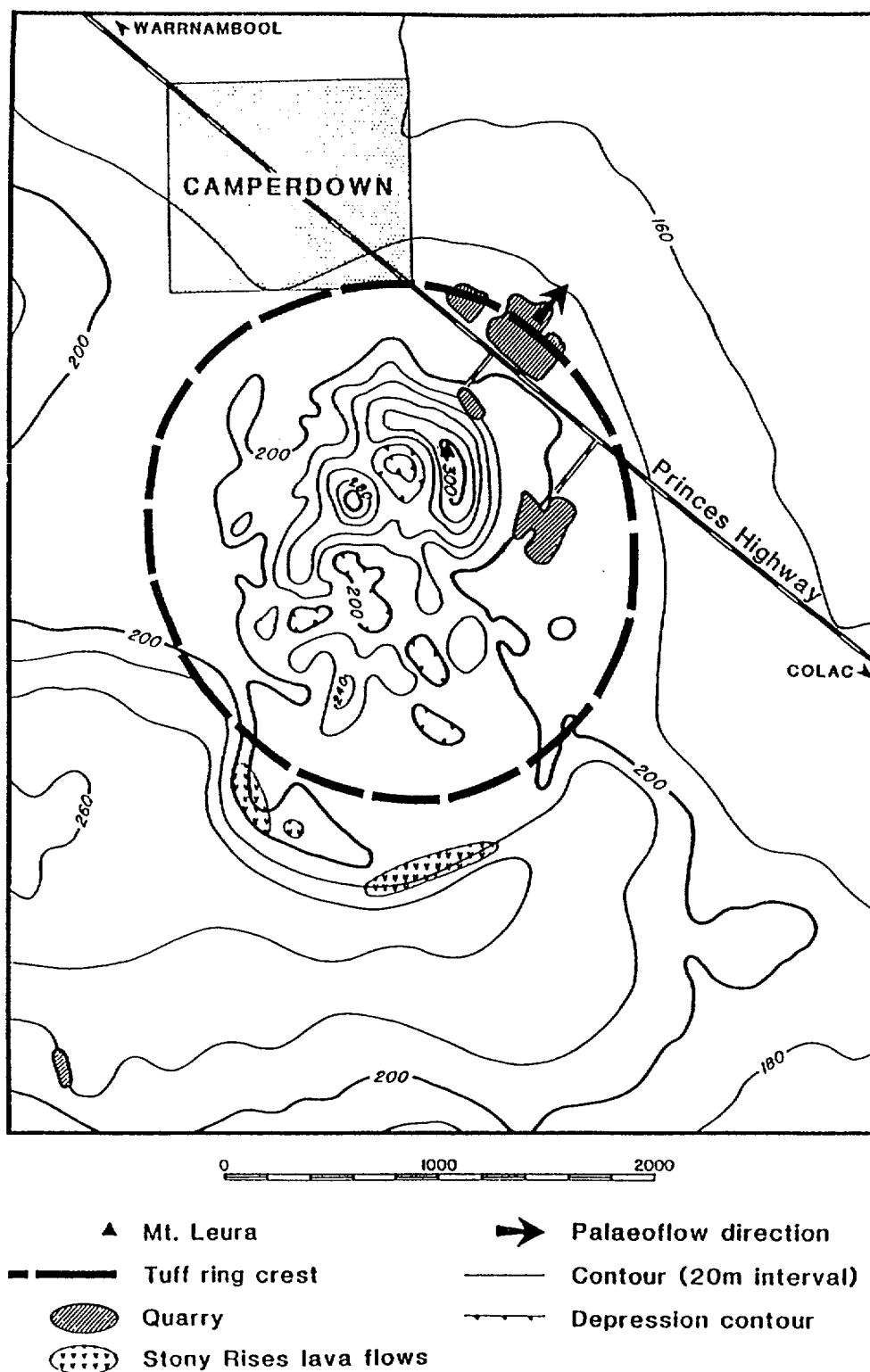

Fig. 15: Map of the Mt. Leura complex (Edney, et al, 1984, ms).

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Pyroxene-rich xenoliths from Mt. Leura have been included in Newer Volcanics suites described by Irving (1974a, 1980) and Ellis (1976). As noted by Ellis, the occurrence of amphibole megacrysts at a given volcanic centre usually indicates that coexisting pyroxenite xenoliths will carry minor amphibole. This is the case for Mt. Leura. Coarse-grained hornblendite xenoliths consisting mainly of Ti-pargasite are also present.

Stop 15-1: Mt. Leura lookout
(Corangamite XC887647)

From the summit of Mt. Leura, more than 20 volcanoes may be seen, including several of those visited earlier in the field trip to the west, northwest and north. To the northeast and east may be seen others which will be visited briefly on Day 5, including the nearby Lake Purrumbete maar, Mt. Porndon and its Stony Rises and beyond the large lava flow dammed Lake Corangamite, the Red Rock complex (Fig. 14). The basalt plains stretch north for more than 50km where they begin to rise along broad lava-filled valley systems into the Central Highlands. Striking features of this region of internal drainage are the numerous lakes, both large ones such as Colongulac (just north of Camperdown) and Corangamite, which have lunettes of windblown material on their eastern shores, and numerous smaller lakes and depressions.

The direction marker on the summit indicates distant points such as the Otway Ranges, the Grampians, and the Central Highlands in addition to the nearer volcanoes (Fig. 14).

The region was first mapped by Grayson and Mahony (1910) and later by Gill (1965). The Hampden Tuff is the largest area of volcanic ash in the Western Plains sub-province, and may represent material from Mt. Leura as well as from maars such as Lakes Bullenmerri and Gnotuk. Gill (1978) has suggested an age of some 22,000 years for this tuff, from its occurrence between dated non-volcanic sediments at Lake Colongulac.

The Mt. Leura tuff ring can be traced toward the south, where landsliding has occurred on the rim. Mt. Sugarloaf, the conical peak opposite the lookout across the unusually deep crater, has been described as one of only three perfect volcanic cones of its type in the world, and on this basis was purchased by the Victorian government and the National Trust to prevent further quarrying (Joyce and King, 1980). Aerial photographs suggest that it is actually a prominent portion of the crater rim, perhaps built up by directed fire-fountaining of lava fragments.

The quarries immediately north of the Princes Highway lie within the tuff ring. They expose excellent cross-sections with inward and outward dipping beds preserved as continuous units. An upward change from pale coloured pyroclastic surge deposits to black strombolian scoria is clearly evident. The quarries at the northern and eastern foot of Mt. Leura are within scoria deposits (Fig. 15).

Stop 15-2: Quarry within tuff ring

(Corangamite XC892651 - permission required for entry)

The nearer of the two northern quarries to the Princes Highway exposes the phreatomagmatic deposits of the tuff ring and mantling scoria deposits, as well as the single known significant lava flow (Fig. 15). The rim beds have near-symmetrical inward and outward dips, generally less than 15°. The deposits are dominated by cross-bedded lapilli units which pinch and swell markedly and are dominantly of surge origin (Fig. 16).

The degree of cross stratification varies greatly from unit to unit, ranging from climbing-dune bedforms to highly truncated planar trough cross-sets. This variation is believed to reflect mainly the velocities of surges at the time of deposition, the proportion of finer material and the water content. Highly truncated bedforms developed during periods when surges were produced in rapid pulses of variable intensity, with some being highly erosive. The thicker climbing-dune units were produced during longer periods of steadier eruption and deposited by surges which were slowing and deflating. Condensation of trapped steam would also aid this process by increasing cohesion of surge material.

Undoubted deposits of air-fall origin make up only a minor part of the tuff ring stratigraphy, in the form of relatively thin deposits of massive ash or diffusely bedded lapilli (Fig. 16). Massive ash units often mantle dune bedforms and may reflect elutriation of fines from moving surge clouds ('co-surge ash'). Accretionary lapilli are mainly restricted to finer grained air-fall units. Diffusely bedded lapilli deposits, on the other hand, show no mantling relationship with cross-bedded units and seem to have been deposited as discrete units during surtseyan-type eruptions.

Later explosive activity seems to have been almost solely magmatic, with only three minor reversions to phreatomagmatic activity. The dominant mode was strombolian activity which produced scoria fall deposits. Minor intervening stages of hawaiian lava fountaining forming laterally restricted thin lava flows and spatter deposits. Within the strombolian deposits an erosional surface separates two scoria fall deposits. In epiclastic deposits above this surface, probably produced by fluviatile processes, the occurrence of rounded basaltic lava pebbles suggests a significant time break (months-years?), but no soil has been identified. Reddened, altered and oxidised horizons developed at the top of several scoria fall units suggest smaller time breaks (days-weeks?).

The lava flow is exposed in the wall of the quarry nearer Mt. Leura. Part of it moved along a narrow gully within the underlying scoria deposits, perhaps between neighbouring cones. The base of the flow is distinctly platy, and the scoria beneath is strongly oxidized and red. The lava contains abundant small lherzolite xenoliths and fragments derived from them.

Stop 15-3: Quarry in scoria cone apron
(Corangamite XC892644 - permission required for entry)

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An operating quarry at the north-eastern foot of the Mt. Leura cone (Fig. 15) exposes a variety of coarse-grained products of magmatic eruption, including crudely bedded scoria layers, block and bomb beds and rare spatter agglutinate and associated clastogenic lava flows. Within these deposits, the abundance of rounded ultramafic xenoliths, typically 5-10 cm in diameter, is unusually high. Coarse-grained Cr-diopside spinel lherzolites are overwhelmingly dominant. Careful search reveals a range of recrystallized fine-grained lherzolites, rare harzburgites, dunites and wehrlites, and pyroxene and anorthoclase megacrysts.

At the end of the visit to Mt. Leura, the field trip will return 16 km westward along the Princes Highway, then turn 4 km north to the Mt. Noorat complex.
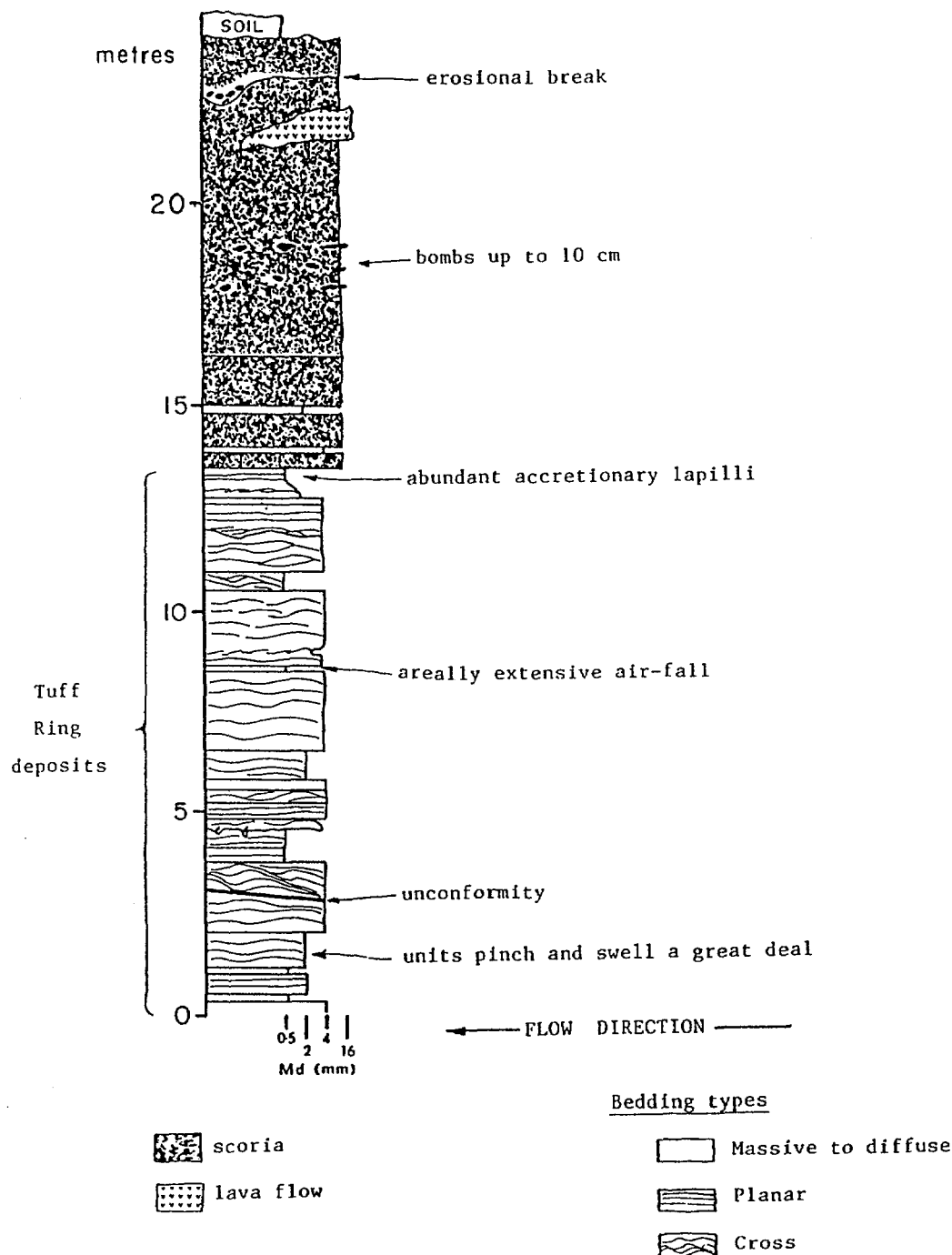
Fig. 16: Stratigraphic section through the tuff ring and mantling scoria deposits, Mt. Leura (Edney, et al, 1984, ms).

Locality 16: Mt. Noorat tuff ring/scoria cone complex (Mortlake XC685724)

The Mt. Noorat complex, like that of Mt. Leura, consists of a tuff ring overlain by scoria cone deposits. The magma type involved is *ne*-hawaiite to basanite (Analysis 5, Table 2) (Irving and Green, 1976; McDonough et al, 1985). As at Mt. Leura, lava blocks have distinctive grey mottling due to incipient devitrification. Scoria deposits contain abundant

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ultramafic xenoliths and megacrysts, which have been extensively studied as part of broader investigations of Newer Volcanics material.

Stop 16-1: Quarry in tuff ring
(permission required for entry)

A quarry near the Noorat-Mortlake road, on the western side of the complex, exposes phreatomagmatic surge deposits overlain by black magmatic scoria.

Stop 16-2: Quarries in scoria cone complex
(permission required for entry)

Quarries within the scoria cones are accessible from a road which runs from the village of Noorat on the south side to the beginning of an official Mt. Noorat walking track on the eastern side. Within these quarries may be found both xenoliths (dominantly spinel lherzolite, but also phlogopite-bearing lherzolite, wehrlite - including rare garnet-bearing types - and websterite) and megacrysts (abundant Al-Ti augite and anorthoclase and rarer bronzite and ferrokaersutite - Irving, 1974b).

After this stop, we will drive ~3 km to Glenormiston Agricultural College for the final overnight stay .

DAY 5: NOORAT TO MELBOURNE

Volcanic complexes between Camperdown and Colac; The Anakies scoria cones

The final day of the field trip will start with a return through Camperdown to visit probably the best example of a simple maar within the Newer Volcanics province - Lake Purrumbete, 10 km southeast of the town (Fig. 13). Just beyond is the large "stony rises" field of lava flows of the Mt. Porndon hawaiite complex, capped by a group of scoria cones which are a further well known locality for ultramafic xenoliths and megacrysts. This will not be visited. After a stop within the lava field, the route is eastward along the Princes Highway, then north to the summit lookout of the Warrion Hill-Red Rock lava dome/maar/ scoria cone complex, which may include up to 40 eruption points. If time is available, other localities within the complex will be visited. After returning to the Princes Highway, the route is *via* the port of Geelong to the final locality - the Anakies group of scoria cones, north of Geelong. Further volcanic cones may be seen on the basalt plains to the west of Melbourne during the final 80 km into the city

Locality 17: Lake Purrumbete maar

Lake Purrumbete is a simple near-circular maar, with the crater now occupied by a 45m deep lake (Fig. 17). The most recent description is that of Edney, et al (1984, ms). The crater rim is constructed entirely of well-bedded, generally fine grained phreatomagmatic surge deposits which in the southeastern part of the structure overlie the lava apron of the Porndon complex. Maar rim heights range from 5 m in the west to 40m in the north-east. This asymmetry is similar to that at Tower Hill, and may be related to the prevailing wind direction during pyroclastic eruption, although no conclusive evidence of aeolian transport affecting the maar rampart deposits has been found. A pronounced angular unconformity due to faulting and slumping of inward-dipping deposits during volcanic activity is exposed in the eastern rim. No soil layer, and evidence for only minor erosion, is found on the unconformity, which apparently represents a very short time break. Surge deposits overlying the unconformity are plastered against the well-exposed fault plane, and ramp over it.

The rim deposits show only minor variation in size and degree of vesiculation of juvenile basaltic clasts, and in the proportion of country rock (mainly limestone)

fragments. By contrast with similar sequences at Tower Hill and Mt. Leura, there are no scoria interbands indicative of dominantly magmatic eruption intervals. Hence the overall characteristics of the rim sequences suggest only minor variation in water/magma ratio through the period of eruption.

The maar rim deposits of Lake Purrumbete display the widest range of well developed sedimentary structures in the Western Plains. Bedforms range from planar laminations and low angle truncations to climbing dunes with regular metre-scale wavelengths and rare poorly developed anti-dunes. All are apparently of base surge origin (Fig. 18). Massive to diffusely bedded deposits are rare and they often show transitional contacts with cross-bedded units. As at Mt. Leura, some of the massive fine-grained units which mantle dune forms have been interpreted as co-surge ashes resulting from the elutriation of fines from a moving surge and subsequent fallout (Walker, 1983). Again as at Mt. Leura, diffusely-bedded lapilli units may represent phreatomagmatic (surtseyan type?) air-falls (Fig. 18).

Stop 17-1: Quarry in maar rim
(Corangamite XC963598)

A quarry on the eastern rim of Lake Purrumbete exposes ~26 m of the lower part of the maar rim stratigraphy (Fig. 18), including a sequence of bedded surge deposits with spectacular climbing dune structures which dips away from the crater at ~3-4°.

At the southwestern corner of the quarry, slumped deposits of a second surge sequence rest against a high-angle fault scarp. A much better exposure may be seen in a low bluff above the lake shore 50m south of the quarry. Here the fault dips gently toward the crater and is buried beneath deposits of a younger surge sequence which dip lakeward at ~10-30°. Further from the crater, these deposits lie disconformably on the older sequence.

At the foot of the buried fault scarp, the beds of the younger surge sequence have developed small scale reverse faults, probably reflecting compaction or slumping of the semi-consolidated deposits soon after emplacement.
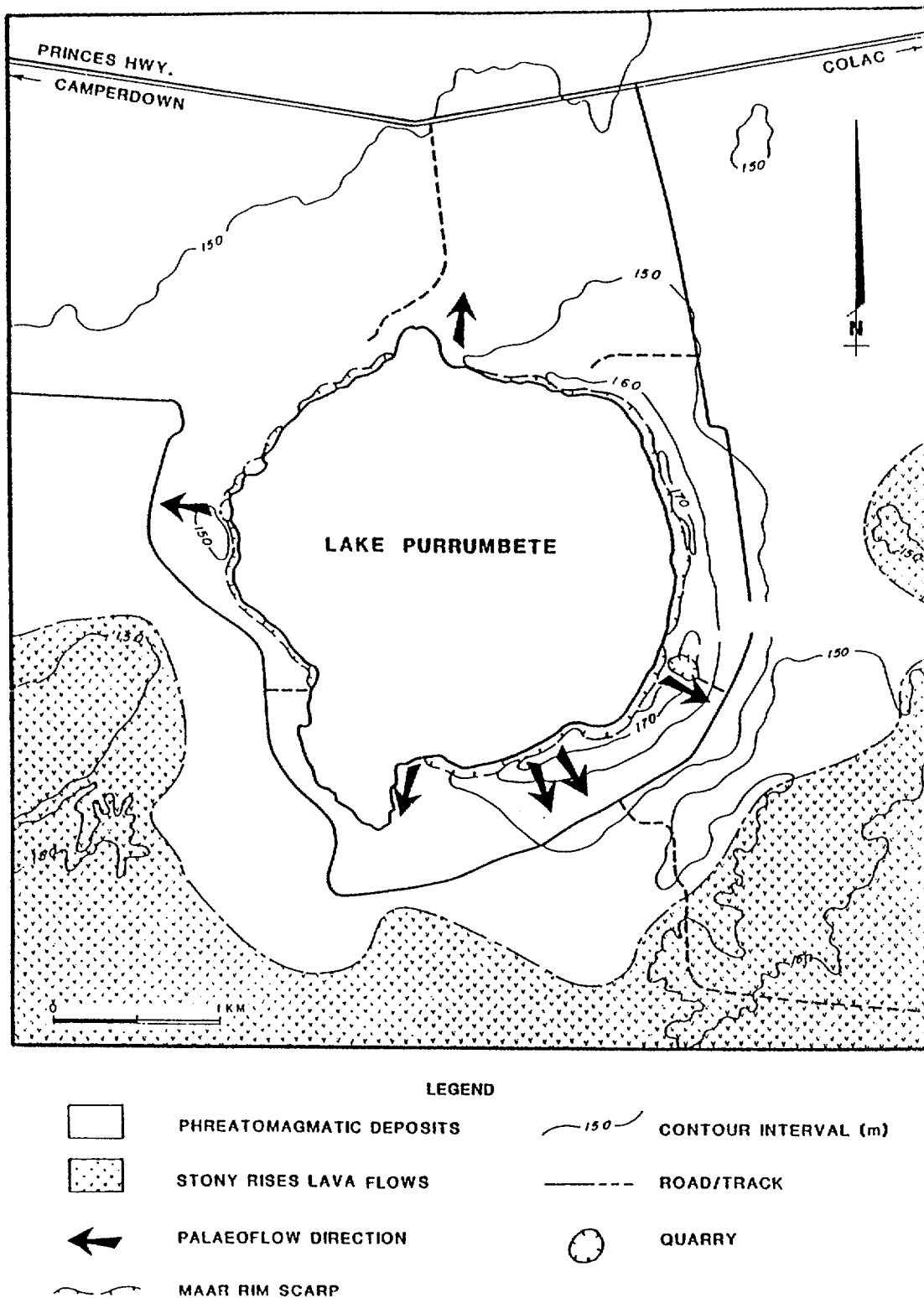
PRINCES HWY.
CAMPERDOWN
COLAC

150

150

150

160

170

150

LAKE PURRUMBETE

150

170

150

150

180

0   1 KM

LEGEND

☐ PHREATOMAGMATIC DEPOSITS   ⌒*150*⌒ CONTOUR INTERVAL (m)

▧ STONY RISES LAVA FLOWS   — — — ROAD/TRACK

⬅ PALAEOFLOW DIRECTION   ◯ QUARRY

⌒⌒ MAAR RIM SCARP

Fig. 17: Map of the Lake Purrumbete maar (from S. Bull, project report, Monash University, Department of Earth Sciences, 1982).

Lake Purrumbete to Pirron Yallock (22 km)

Lake Purrumbete maar lies on the margin of the major northwestern flow lobe of the Mt. Porndon hawaiite lava apron, with its very well preserved "stony rises" features (Fig. 19). The road past the quarry runs northward along the margin of part of this lobe and joins the Princes Highway. The route is then southeast along the

highway through further flow lobes, passing about 3 km north of the Mt. Porndon scoria cones. Between Stoneyford and Pirron Yallock, the highway passes the southern margin of Lake Corangamite, formed partly due to damming by the Mt. Porndon lava apron. A stop at the eastern margin of the apron, near the settlement of Pirron Yallock, will allow features of flow surfaces and the characteristics of the lavas themselves to be seen.
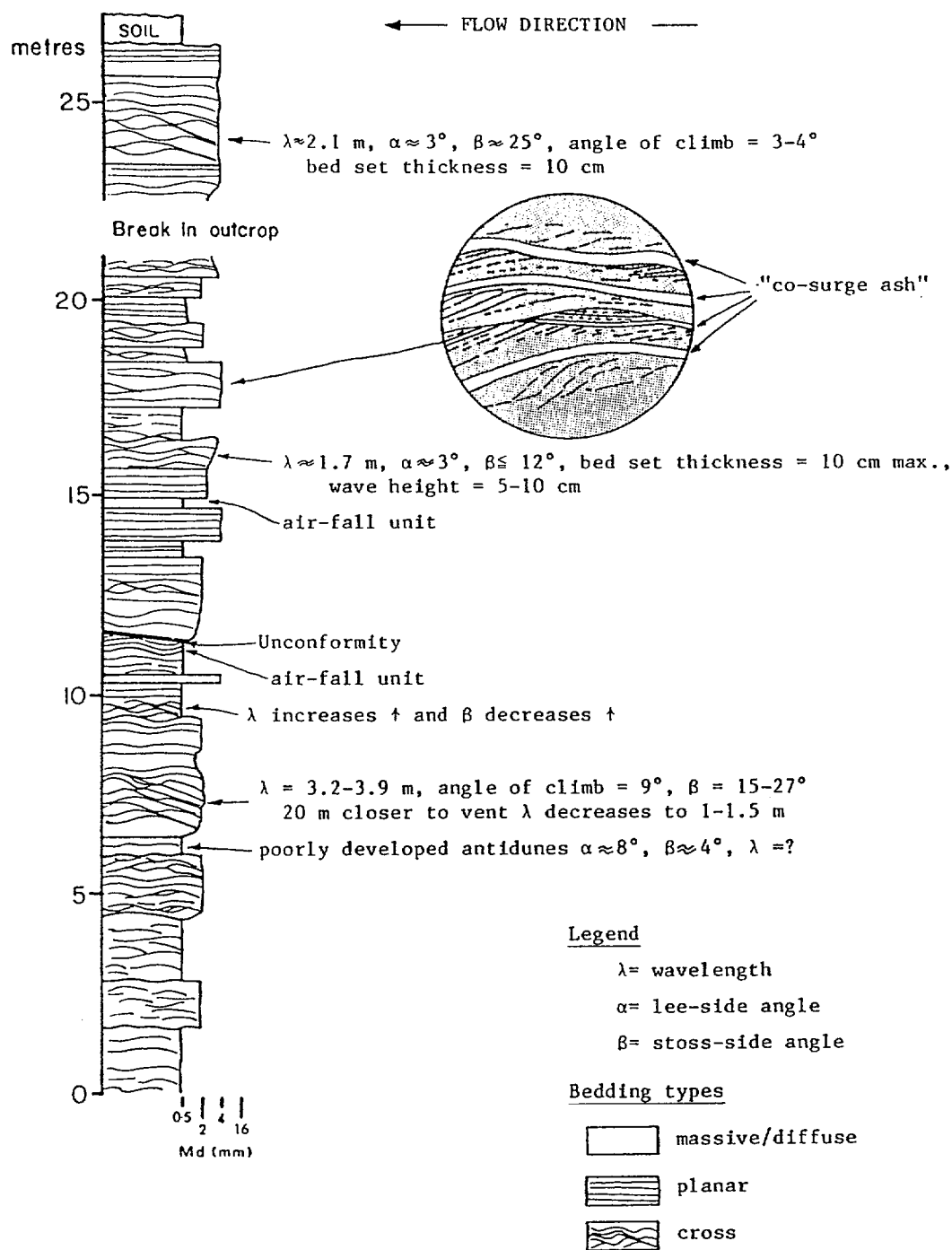
39

metres

SOIL

25

⟵— FLOW DIRECTION ——

⟵— λ≈2.1 m, α≈3°, β≈25°, angle of climb = 3-4°
bed set thickness = 10 cm

Break In outcrop

20

."co-surge ash"

⟵— λ≈1.7 m, α≈3°, β≤ 12°, bed set thickness = 10 cm max.,
wave height = 5-10 cm

15

air-fall unit

Unconformity

air-fall unit

10

⟵— λ increases ↑ and β decreases ↑

λ = 3.2-3.9 m, angle of climb = 9°, β = 15-27°
20 m closer to vent λ decreases to 1-1.5 m

⟵— poorly developed antidunes α≈8°, β≈4°, λ =?

5

Legend

λ= wavelength

α= lee-side angle

β= stoss-side angle

Bedding types

	massive/diffuse
	planar
	cross

0

0·5 2 4 16
Md (mm)

Fig. 18: Stratigraphic section through the phreatomagmatic deposits of the Lake Purrumbete maar rim (from S.
Bull, project report, Monash University, Department of Earth Sciences, 1982).

Locality 18: Lava apron of the Mt. Porndon lava disc/scoria cone complex

Mt. Porndon lies 3 km south of the Princes Highway over rough topography of the earliest very extensive lava flow from the complex ('Hawaiite I' - Ellis, 1971). The dominant magma type involved is ne-hawaiite (Analysis 6, Table 2). The complex consists of a group of six scoria cones resting on the surface of a 'lava disc' 2-3 km in diameter (Fig. 19), formed by the youngest hawaiite flow ('Hawaiite IV'). The edge of the lava disc stands up to 25m above the surrounding lava apron and up to 10m above its own interior surface (McKee and

Thomas, 1976). It may be seen from the highway as a pronounced "step" in the lava field. According to Ollier (1969), the disc formed from a single lava flow which developed a 'skin', inflated in the manner of a water-filled balloon, then sagged as fluid lava drained away. However, a gravity study by McKee and Thomas (1976) suggested a maximum thickness of >300m for the disc, which if correct is most compatible with the infilling of a caldera or maar crater by lava. There is little direct evidence for the existence of such a crater, although bedded tuffs occur east and north of Mt. Porndon (McKee and Thomas, 1976).

LAVA FLOW DIRECTIONS IN THE STONY RISES

PRINCES HWY

Lake Corangamite

Lake Purrumbete

Mt.Porndon

←— PROBABLE LAVA FLOW DIRECTION

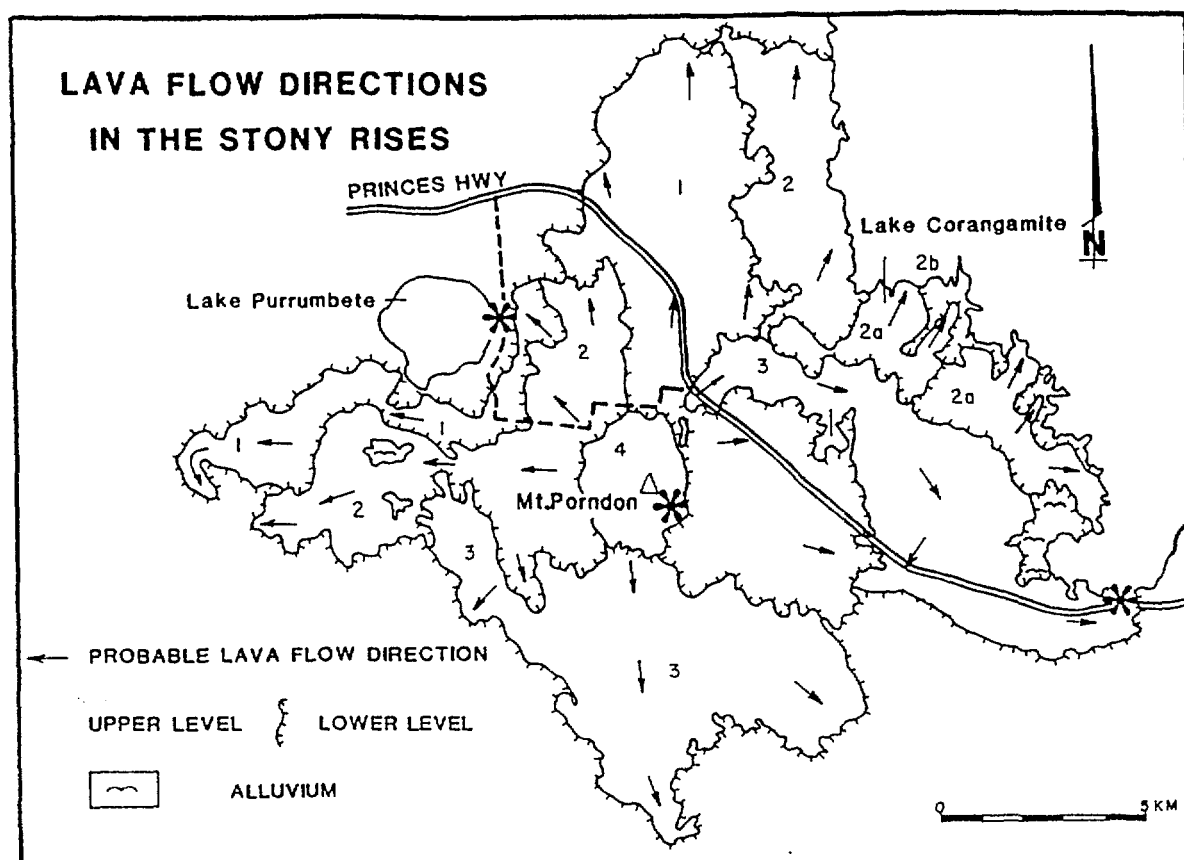UPPER LEVEL ⌇ LOWER LEVEL

⌐~⌐ ALLUVIUM

0 _____ 5 KM

Fig. 19: Flow units and flow directions within the lava apron (the "Stony Rises") of the Mt. Porndon complex, based upon interpretation of aerial photographs and surface mapping. Numbers on flow units refers to sequence of emplacement, from the earliest large lava flow ("Hawaiite I" - 1) to the "lava disc" or "ring barrier" (4) (from Ellis, 1971).

The largest of the scoria cones (110m above its base) gives the complex its name. Its internal structure is exposed in quarries at the foot of the northern and eastern slopes. At the base of the cone is a thin succession of bedded tuffs, probably of phreato-magmatic origin. This is overlain by a 1m thick zone of interbedded tuff and scoria, then the main sequence of black and red scoria and lava blocks and bombs. The best exposures of the scoria deposits are in Harrison's Pit, on the eastern apron of the cone. This is well-known xenolith and megacryst locality, but it has been declared "off limits" to large groups of geologists in recent years. Large xenoliths (>10cm diameter) are rare, and most xenolith material forms small partly disaggregated fragments a few centimetres in diameter. Olivine-rich lherzolites of the Cr-diopside series are overwhelmingly dominant, with rare cumulate wehrlites of the Al-Ti augite series. Megacryst species include abundant black glassy Al-Ti augite and common dark brown bronzite and anorthoclase.

The hawaiite lava apron of Mt. Porndon is up to 12 km in diameter and more than 200 km^2 in area. Ellis (1971) has studied the extent and flow directions of the various lava sheets (Fig. 19) and the distribution of aa and pahoe lava types. The various flows of the apron are isopically similar ($^{87}Sr/^{86}Sr = 0.7044$-0.7046) and distinct from both the underlying plains basalt sequence

(0.7041 -0.7043) and the overlying scoria cone deposits (0.7039 - McDonough, et al, 1985). Flows of the apron have not been explicitly dated, but by comparison with the state of preservation of dated examples, they are probably younger than 20,000 years BP. Little surface weathering or soil development is seen, and flow surface features are well preserved. The "stony rises" topography has a typical relief of up to 10m, and it can be subdivided into areas separated by flow fronts 6-12 m high. Near the edge of the stony rises fronting Lake Corangamite, narrow lava flows may be seen issuing from the base of breached flow fronts. Ponds occur in some of the larger depressions and freshwater springs run into Lake Corangamite. Plateau-like areas remain undisturbed further west along the Princes Highway.

Stop 18-1: Cuttings on Princes Highway near Pirron Yallock

A cutting on the former route of the Princes Highway shows a section through a lobe of the third major group of lava flows from Mt. Porndon (Fig. 19). The flow consists of highly vesicular dark grey hawaiite with readily visible olivine phenocrysts and labradorite-andesine laths. Vesicles, ranging from spherical to flattened parallel to the flow surface, occur in sub-horizontal trains. Joints are approximately vertical and horizontal.

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Pirron Yallock to Red Rock summit (21 km)

Beyond Pirron Yallock a road which leaves the Princes Highway toward the north leads to the easternmost part of the shore of Lake Corangamite, formed by lava flows from the Red Rock complex. About 2 km along this road are two small but deep maar craters - "The Basins" (Fig. 20) - which will be visited briefly if time permits.

These are the sites of detailed studies of rates of accumulation of sediments and plant material in Western District lakes by Monash University Geography staff members. From the edge of Lake Corangamite, the route runs east and north through the settlements of Coragulac and Alvie to the summit lookout of Red Rock.
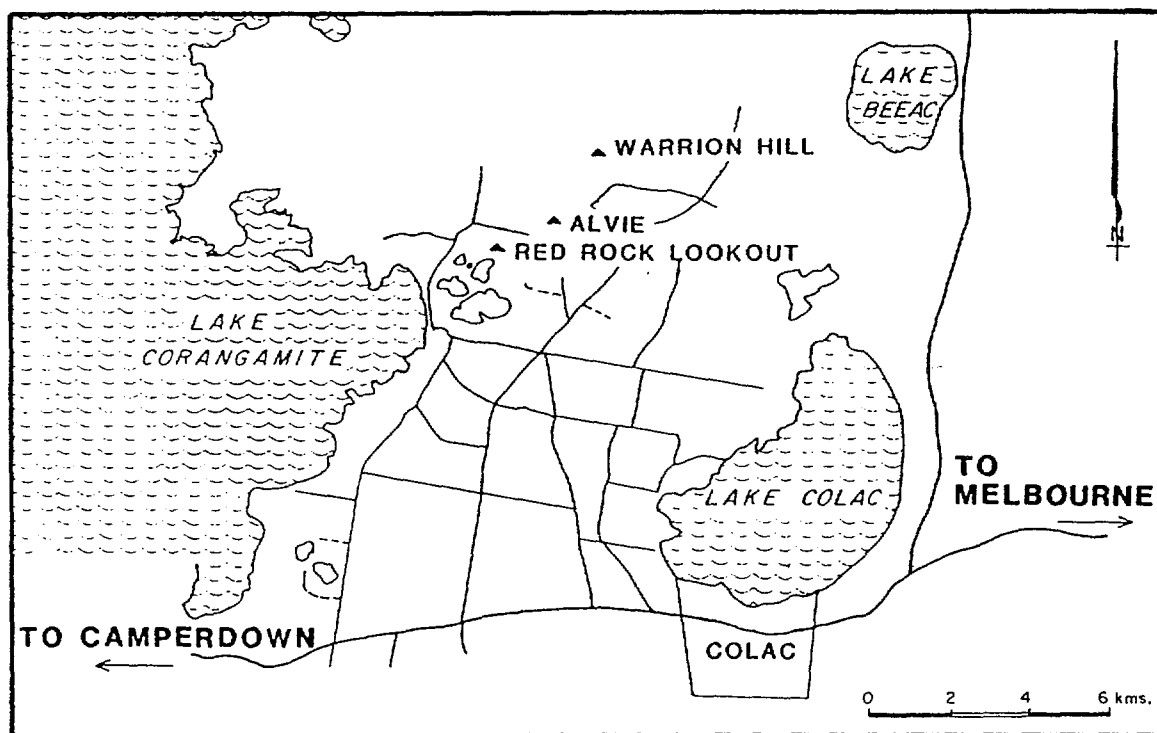

Fig. 20: Location map of the Red Rock volcanic complex, Mt. Alvie and Warrion Hill.

Locality 19: The Red Rock complex

The Red Rock complex lies northwest of Colac in an area that illustrates well the geomorphic character of the Western Plains (Fig. 20). The slightly undulating surface of the lava plains is marked by two types of lakes: those ponded on the landscape by the damming effects of lava flows blocking pre-existing drainage systems (e.g. Lakes Colac and Corangamite) and the crater lakes of maars or tuff rings Rising above the plains and lakes are the maars, tuff rings and scoria cones of three closely spaced volcanic complexes: Red Rock (south), Mt. Alvie and Warrion Hill (north). The basement of this area consists of the Miocene Port Campbell Limestone and Gellibrand Marl Formations, locally overlain unconformably by quartz sands of the Pliocene Moorabool Viaduct Formation. These are overlain by the plains lavas and by deposits of the three volcanic centres. A radiocarbon date of 7810 ± 115 years was obtained by Gill (1978) for a fossil soil within the volcanic succession .

The Warrion Hill lavas are mainly *ol*-tholeiites to hawaiites (Analysis 7, Table 2) similar to plains basalts compositions; the pyroclastic deposits of Mt. Alvie and Red Rock are dominantly *ne*-hawaiite (Analysis 8,

Table 2). Small peridotitic xenoliths occur in glassy lava blocks within explosion breccias of the Lake Purdigulac maar rim deposits.

Leach (1977) has proposed a composite stratigraphy for the Corangamite region, including not only the various volcanic phases, but also phases of lake and aeolian lunette sedimentation associated with the development of Lake Corangamite (Fig. 21). The principal elements of this stratigraphy in terms of the volcanic history are, in chronological order:

1. The earliest phase of plains lava flow activity, which dammed the landscape to produce the ancestral lake deposits of the Corangamite system
2. Eruption of Red Rock stony rises lavas
3. Eruption of Warrion Hill stony rises lavas
4. Warrion Hill scoria eruptions
5. Final Warrion Hill. lava dome extrusions
6. Mt. Alvie tuff ring/maar formation
7. Mt. Alvie scoria cone formation
8. Eruptions producing Red Rock maars
9. Eruptions producing Red Rock scoria cone complex

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                          Modern sediments
                          Period 3 lunette

Beach
                          Period 3 lake sediments
Rock
                          Red Rock scoria

                          Tuff rings of the
                          Red Rock volcanic complex

                          Mt. Alvie scoria

                          Mt. Alvie tuff ring

                          Period 2 lunette (secondary)
Red-brown                 Period 2 lunette (primary)
soil
                          Period 2 lake sediments

                          Final phase Mt. Warrion lava

                          Mt. Warrion scoria

                          Mt. Warrion stony rises

                          Period 1 lunette

                          Period 1 lunette lake sediments

                      ₦ = Vertebrate fossil locality

                          Red Rock stony rises

Alluvium

                          Possible early lake sediments

                          Earlier Phase Newer Volcanics

                          Laterite

                          Tertiary marine marl
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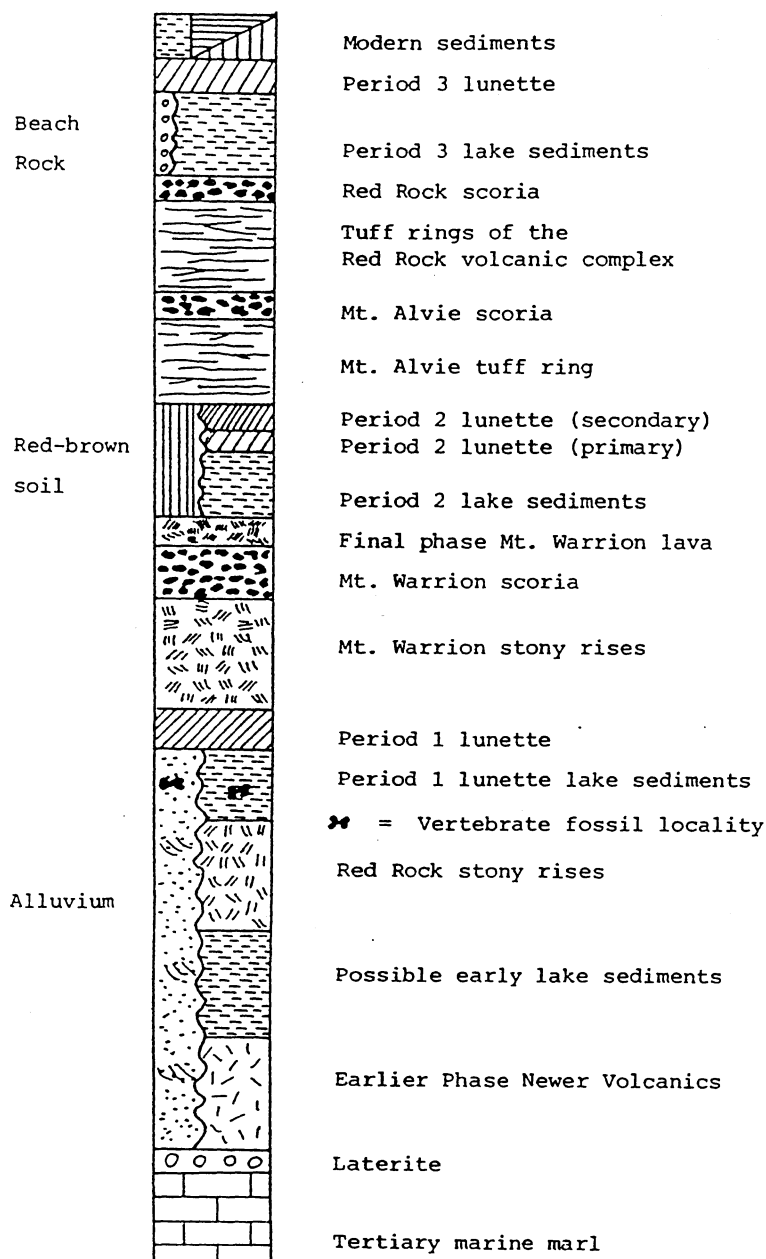
Fig. 21:   Composite stratigraphic section for the Corangamite area, including volcanic activity and sedimentation
events (from Leach, 1977).

Stop 19-1: Red Rock summit

The summit of the largest scoria cone of the Red Rock
complex stands 100m above the plains (Fig. 22).
According to Leach the complex was initiated with the
outpouring of stony rises lavas between Lake
Corangamite (west) and Lake Colac (southeast). These
are partly preserved southwest of Red Rock. The second
phase was that of maar formation, producing the Lake
Coragulac (east), Lake Purdigulac (south), and Lake
Gnalinegurk (southeast) structures The final phase was
that of scoria cone formation, producing the hills and

several small craters and crater lakes surrounding the
Red Rock lookout (Fig. 22). Leach has suggested that
there are some 14 eruption points contained within the
scalloped margins of the maars, and some 28 eruption
points within the scoria cone complex.

If time permits, we will make a brief stop on the eastern
shore of Lake Coragulac, where the products of both
phreatomagmatic activity and near-vent magmatic
activity, including very abundant large ballistic blocks
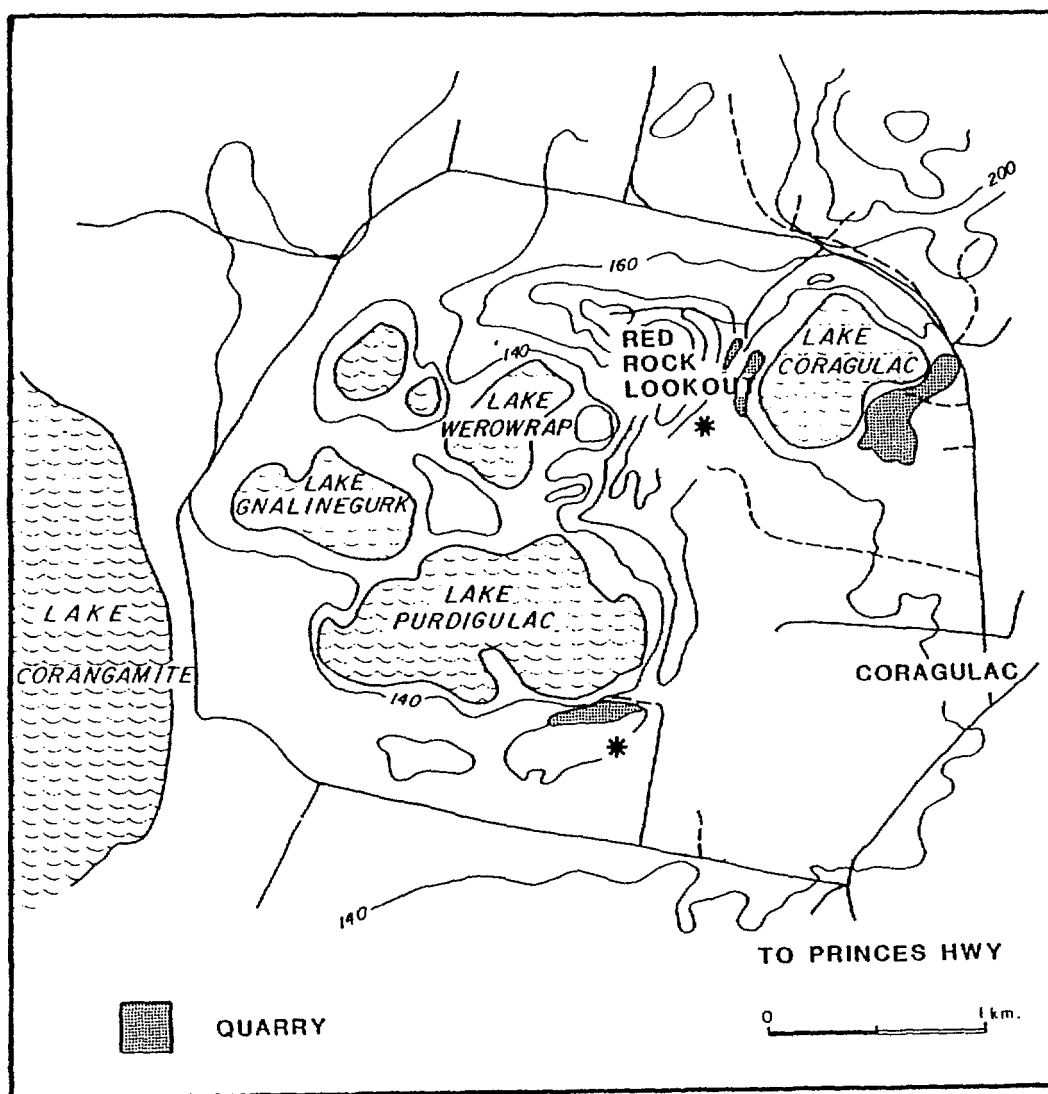of both plains basalt and juvenile basalt, are well
exposed.

Fig. 22: Map of the Red Rock complex.

Red Rock to the Anakies (115 km)

The route taken from the Red Rock complex leads back to the Princes Highway west of Colac, then east to Geelong, on the western shore of Port Phillip Bay. The only large volcanic cone seen east of Colac is Mt. Gellibrand, although the highway also passes the older low Mt. Moriac cone near Geelong. From Geelong, the route runs northward toward Bacchus Marsh along the Lovely Banks Monocline-Rowsley Fault system, which forms the western margin of the Port Phillip Bay depression (Fig. 23). Near the village of Anakie, the Rowsley Fault forms a prominent scarp, with the Ordovician marine sandstones of the Brisbane Ranges on the upthrown western side. At the foot of the scarp are the three Anakies scoria cones, resting on a surface developed on Late Devonian granite. The same pluton also forms the prominent peaks to the east, named the You Yangs, with the highest peak being Flinders Peak.

Locality 20: The Anakies scoria cones

The three Anakies scoria cones rest on a poorly preserved apron of ~1.5 Ma *ne*-hawaiite to *ne*-mugearite lava flows, partly deformed by movements on the Lovely Banks Monocline system. The largest (western) cone, Mt. Anakie (395 m ASL), has no major quarries. Ultramafic xenoliths are found on its slopes. The eastern cone contains a large operating quarry, exposing a range of oxidised pyroclastic products of dominantly magmatic origin, with very abundant large but not very fresh ultramafic xenoliths and small crustal granulite xenoliths (Wass and Hollis, 1983). Analysed basalts from this quarry have yielded a range of compositions, including weakly *ne*-normative hawaiites (Price and Gray, unpublished data) and mugearites (Irving and Green, 1976) (Analysis 10, Table 2). The middle and western cones consist mainly of *ne*-hawaiite pyroclastics (Analysis 9, Table 2). We will visit the quarry in the central cone, the basalts of which are black and fresh, with abundant but small ultramafic xenoliths.

The rich xenolith suite of the eastern cone is reported to include abundant spinel lherzolites (often unusually rich in Cr-diopside) with rarer wehrlite, harzburgite, orthopyroxenite, garnet websterite, hornblendite and plagioclase-bearing pyroxenite. The reported megacryst population includes abundant ferrokaersutite and anorthoclase, common apatite and rare bronzite, kaersutite, phlogopite and ilmenite.

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Fig. 23: Map of the Anakie area, showing the Anakies scoria cones at the foot of the Rowsley Fault scarp.

Stop 20-1: Quarry in middle Anakie cone

The entrance road to the quarry in the middle Anakie scoria cone passes a small circular depression which is probably a small tuff ring crater. This structure may be the source of some of the phreatomagmatic layers exposed in the quarry, which also contains a varied sequence of fresh dark pyroclastic deposits of magmatic origin. The sequence in the deeper part of the quarry consists of:

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1) Lower proximal magmatic breccias, containing angular basalt blocks up to 15 cm in diameter in a matrix of finer fragments.
2) A thin (5-10 cm) layer of phreatomag-matic material wthin the ash to lapilli size range, including both poorly vesiculated basalt fragments and country rock fragments, mainly granitic. This layer marks a first short period of access of water to the magmatic system.
3) A 5-10 m crudely bedded layer of medium-coarse strongly vesiculated magmatic scoria, with significant variations in clast size (5-50 mm) and some large blocks and bombs.
4) An upper bedded phreatomagmatic interval consisting of poorly vesiculated juvenile basalt fragments and country rock fragments up to a few centimetres in diameter.

In the higher parts of the quarry, the exposed deposits are dominantly coarse and of magmatic origin, including large vesicular lava blocks and bombs. These deposits are often oxidized and red-brown in colour.

Small peridotitic xenoliths and granite fragments are common thoughout the sequence. The dominant peridotitic type is again Cr-diopside spinel lherzolite. A very wide range of textural types may be observed in xenoliths at this quarry, including strongly deformed and recrystallized mosaic porphyroclastic to granuloblastic types ("mylonites").

Anakie to Melbourne (~90 km)

This is the final stop of the field trip. The return to Melbourne will be either *via* the Princes Highway (Geelong Road) or northward toward Bacchus Marsh to join the Western Highway before heading for Melbourne Airport. Both routes traverse the lava plains to the west of Melbourne, passing a number of small volcanic cones.

ACKNOWLEDGEMENTS

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