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Excursion Guide A-4

Southern Continental Margin of Victoria — Basaltic Volcanism; Thermal History of Rifting

17-22 September, 1990

by

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ICOG EXCURSION A-4

EVOLUTION OF THE SOUTHERN CONTINENTAL MARGIN OF AUSTRALIA - BASALTIC VOLCANISM; THERMAL HISTORY OF RIFTING

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INTRODUCTION

THE GEOLOGICAL SETTING OF VICTORIA

There are two main episodes in the geological history of Victoria, 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. IN-1).

The Palaeozoic basement is subdivided into numerous tectonic zones of north-south strike and those of the western Victoria which are pertinent to the excursion can be taken as typical. From west to east these zones are (numbers in *italics* refer to Fig. IN-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 presumed of Cambrian in age in the west, but definitely Early to Mid-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 greenstone 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 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.

In Victoria this rift system evolved into the three major Basins now making up Bass Strait between the mainland and Tasmania. From west to east these are the Otway, Bass and Gippsland Basins. These basins, particularly Gippsland, are extremely important for their oil, gas and coal resources. The Gippsland Basin hosts some 90% of Australia's known oil reserves, supplies all the natural gas required by the city of Melbourne, and has enormous deposits of brown coal producing most of Victoria's electricity. The very similar Otway Basin, despite having many hydrocarbon shows, has so-far produced only one small commercial gas field and some small brown coal mines.

Fig. IN-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.

Basaltic volcanism in Victoria has occurred intermittently from the Jurassic to the present and is conventionally subdivided into Older and Newer phases, though this is really only a separation into well preserved, young rocks and older types. Volcanism is reviewed by Price et al. (1988). The Older Volcanics are Late Jurassic to Miocene in age and mainly found as numerous small fields in the eastern part of the state or subsurface in the rift basins. There is a complete range of compositions from basaltic icelandite to nephelinite. K-Ar geochronology (Wellman, 1974) indicates continuous pulses of activity throughout the Cainozoic with the duration of any one field approximating 5 Ma. The greatest volume of eruptives developed in the 57-42 Ma interval. Note that opening of the Tasman Sea ceased at 53 Ma and the phase of rapid sea-floor spreading forming the Southern Ocean commenced at 45 Ma. The other volumetrically major phase of basaltic volcanism, the Newer Volcanics, is 0-7 Ma in age and located in western Victoria from the Great Dividing Range to the coast (*11*); they are described extensively below.

The excursion is divided into two parts: the first traverses the Late Miocene-Holocene Newer Volcanic province, the second returns to Melbourne along the south coast through the eastern part of the Early Cretaceous-Cainozoic Otway Basin.

PART I: THE NEWER VOLCANICS BASALTIC PROVINCE

BACKGROUND

The Newer Volcanics occupy an area of 15,000 km^2 in western Victoria (Joyce, 1988; Fig. I-1). Lava flows occur as valley fills and extensive sheets and are volumetrically the most significant component. Nearly 400 eruption points have been identified as lava shields, cinder cones or maars (Fig. I-2). Two subprovinces are recognised (Joyce, 1988), which correspond in part to differences in basement geology. The highlands subprovince is located in the north-east and contains valley flows and cinder cones on Palaeozoic basement. It is distinguished by the highest density of volcanic centres, which are concentrated in an east-west band, a prolonged eruptive history (0-7 Ma), and the presence of trachytes. It will not be visited on the excursion. The plains subprovince occupies lower terrain to the south of the Great Dividing Range, where the Palaeozoic basement disappears beneath Cainozoic basaltic and sedimentary cover. The southern limit is abruptly defined by the east-west Colac Lineament (Fig. I-1) which is interpreted as a rift-defining fault and thus a major lithospheric structure. The plains subprovince (0-4.6 Ma) has numerous volcanic centres and representatives of all types will be visited. The volcanoes are usually small cinder cones and lava shields with heights of <100 m and diameters <1 km (some maars are exceptions to the latter dimension). The youngest volcanoes are surrounded by well-defined aprons of overlapping basalt lava flows which are often of the order of 10 km across. Individual valley flows may extend beyond the aprons for tens of kilometres. Flows are up to 10 m thick, and away from the volcanic centres the greater part of the plains is covered by single eruptive units. Petrographically, the rocks are undistinguished with olivine phenocrysts ubiquitous; occasionally clinopyroxene phenocrysts are distinctive. It is possible to broadly differentiate tholeiitic from hawaiitic types, the tholeiites having interstitial glass or mesostasis, the hawaiites a slightly finer grained holocrystalline texture.

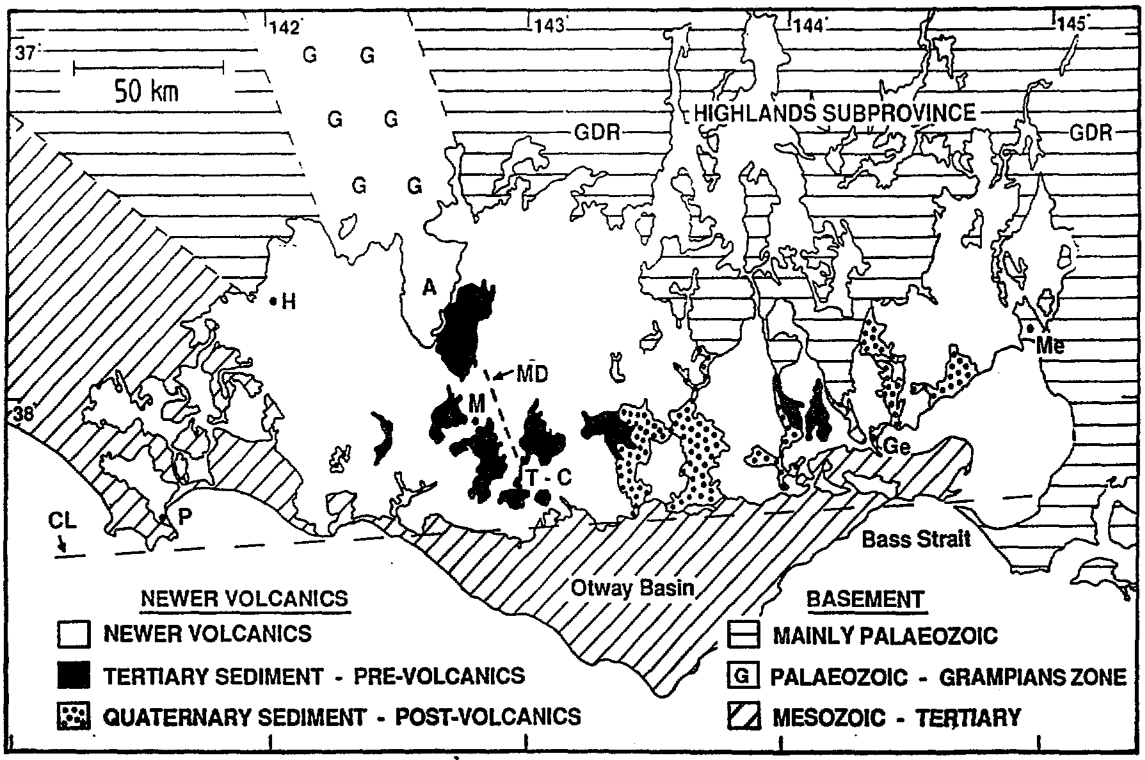

Fig. I-1: The Newer Volcanics Province of Victoria. GDR=Great Dividing Range; Ge=Geelong; H=Hamilton; M=Mortlake; Me=Melbourne; P=Portland; T-C=Terang-Camperdown area; CL=Colac Lineament; MD=Mortlake discontinuity.

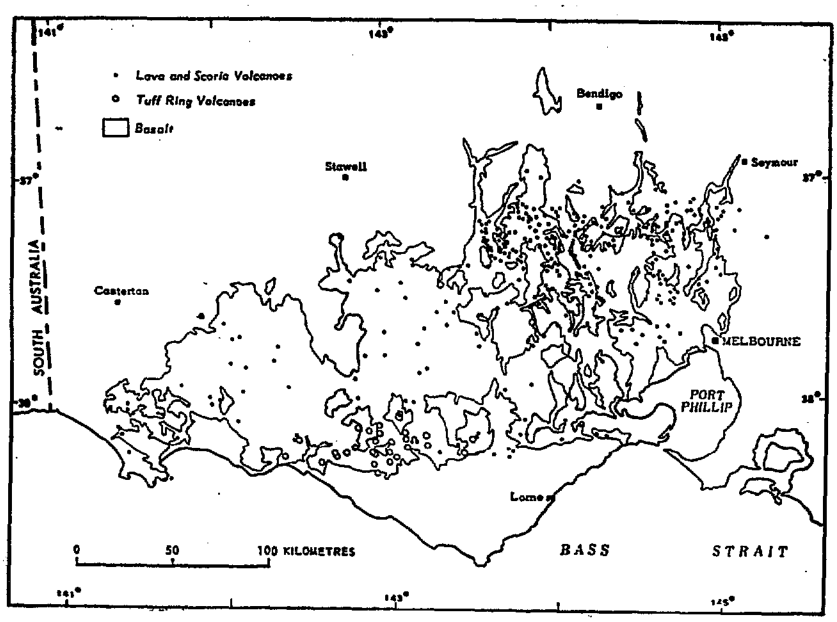

Fig. I-2: Eruption points of the Newer Volcanics Province (from Ollier and Joyce, 1976)

Modern published petrological-geochemical studies only apply to the volcanic centres (Irving and Green, 1976; Frey et al., 1978; McDonough et al., 1985), with an emphasis towards those that carry mantle-derived inclusions. The basalt types range from tholeiitic to strongly alkalic and chemical analyses may be found in the Table. Their relative proportions are indicated in Figure I-3 which shows that alkalic types dominate. 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 crystal fractionation dominated by olivine removal (Irving and Green, 1976). This view was supported by REE modelling (Frey et al., 1978), but with the additional genetic ingredient that some sources had to have an enrichment in light REE and other incompatible elements prior to melting to account for the relatively high abundances of these elements in the basalts. Basanites and nephelinites formed by approximately 5%, and tholeiites by 25% melting. Sr and Nd isotopic ratios (McDonough et al., 1985) indicate a continuum of compositions from alkalic rocks to tholeiites in the $^{87}Sr/^{86}Sr$ sequence 0.7038 to 0.7049.

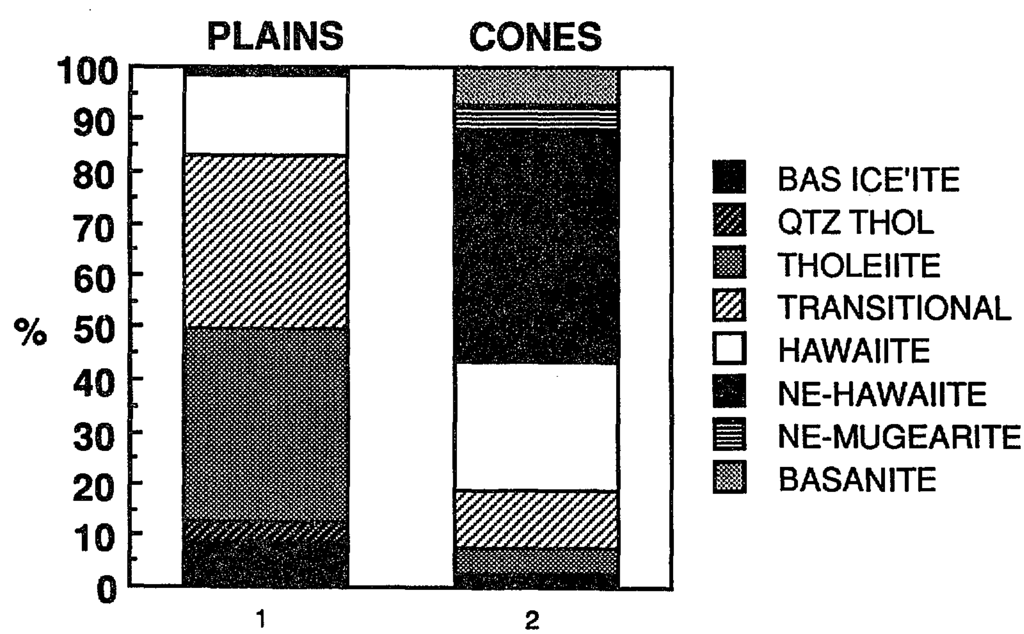

Fig. I-3 : Proportions of basalt lithologies in plains lava flows and volcanic centres in the plains subprovince. The following lithological classification is used throughout this guide. CIPW norms are calculated on an anhydrous basis assuming Fe_2O_3/FeO is 0.2. Rocks with >10% normative hypersthene 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 a recent intensive study (R.C. Price and CMG) and there are now 450 analyses comprising major and trace elements and Sr isotopic composition. An immediate point made by these data is that the proportions of basalt types differs greatly between plains and volcanic centres (Fig. I-3) and that the province is not alkalic as previously considered, but tholeiitic to transitional. (It is likely that the data set for the volcanic centres is biased toward inclusion-bearing alkalic types and that the contrast between cones and plains is not as stark as in Figure I-3; however, it is important that the overall character of the province is misrepresented in the literature). 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 often demonstrably alkaline. In many plains areas primary volcanic morphology has been destroyed by erosion and the tholeiitic basalts have very similar chemical compositions, hence geological mapping is virtually impossible. At the beginning of the plains geochemical survey the only 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 are often so variable that distinctive domains of isotopically uniform basalts can be outlined and these are taken as primary mapping units. The domains are interpreted as individual flows or groups of flows from a single volcanic centre. The Sr isotopic data also permit the subdivision of the plains sub-province into distinct eastern and western sectors. If the data are projected to an east-west section line across the subprovince a clear discontinuity is expressed near the town of Mortlake such that both maximum and minimum initial ratios differ in the eastern and western sectors (eastern sector - maximum 0.7058, minimum 0.7040; western sector: maximum 0.7049, minimum 0.7037). While this difference exists, the overall geochemistry and eruptive histories of the eastern and western sectors are very similar and the subprovince is still considered a geological entity. The Mortlake discontinuity coincides with the projection across the subprovince of the Grampians tectonic subzone (see Introduction), which is a major basement structure interpreted herein as a Palaeozoic convergent plate boundary. Thus a significant lithospheric structure is imprinted in a fundamental aspect of the basalt geochemistry; the geochemistry is therefore interpreted to have a strong lithospheric influence.

The chronology of the Newer Volcanics is based upon conventional total rock K-Ar ages mainly on plains lava flows and predominantly determined at the 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 had 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 are part of a regional study of the plains basalts (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 subprovince. Volcanism commenced at 4.6 Ma, and until 3.0 Ma involved the eruption of compositions in the tholeiite to transitional hawaiite range. The volumetric peak of activity occurred from

3-2 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). Subsequent to 2 Ma, basalt compositions have become more hawaiitic with the alkalic influence stronger in the western sector. There are insufficient data to permit a chronology of volcanic centres. 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 BP is recorded in Victoria and the last few thousand years in south-eastern South Australia.

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, Ludwig 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-4). 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 hawaiite trend extends from low to high Sr and Rb concentrations within a narrow band of $^{87}Sr/^{86}Sr$ from 0.7040 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 subprovince 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 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 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 continental 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.

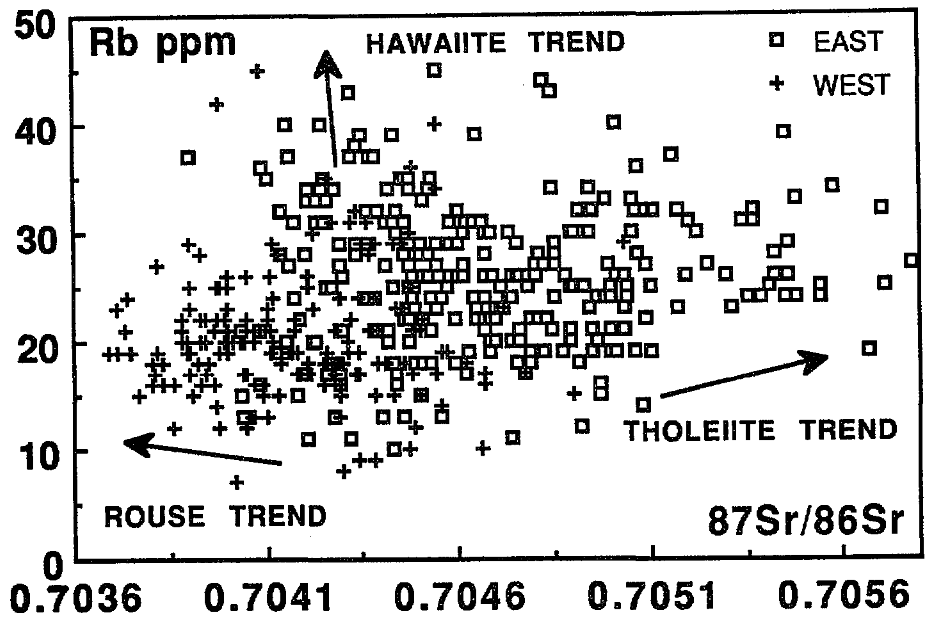

Fig. I-4: Rb concentration (ppm) versus $^{87}Sr/^{86}Sr$ ratio for basalts from the eastern and western sectors of the plains subprovince outlining the tholeiite, hawaiite and Rouse compositional trends.

The Newer Volcanics are widely known for an abundance of high pressure inclusions and megacrysts in some alkalic volcanic centres; four of the intensively studied localities are visited on the excursion - The Anakies and Mounts Shadwell, Noorat and Leura The literature is sufficiently extensive to be beyond simple summary here and only a general review is attempted. Lherzolite inclusions reveal a complex petrological, geochemical and isotopic history. The petrology and geochemistry of spinel lherzolites are considered by Frey and Green (1974) who conclude that (a) the lherzolites are accidental inclusions in the host magma (b) major element compositions and mineralogy are derived from a refractory residue formed by the extraction of a basaltic melt from a peridotitic parent (c) minor and trace incompatible trace elements are an independent geochemical component derived from a highly fractionated undersaturated melt composition. Burwell (1975) analysed the total rock and mineral separates of seven spinel lherzolites collected at Mt Leura, showing both a wide range of bulk $^{87}Sr/^{86}Sr$ ratios (0.7035-0.7076) compared to the host basalt (0.7041), and also internal mineral isotopic disequilibrium. The regional Sr and Nd isotopic survey of spinel lherzolites and harzburgites by McDonough and McCulloch (1987) shows that comparable isotopic heterogeneity between total rock samples is widespread in the central parts of the subprovince and also occurs at Mt Gambier, S.A. Other high pressure inclusions, mainly pyroxenitic rocks, are less abundant than the lherzolites, but are also widespread. They are described petrologically by Irving (1974a) and Ellis (1976), who attribute them to crystallisation from basaltic magmas. One area, the Lakes Bullenmerri and Gnotuk maars, contains an abundance of

Table 1: Representative Analyses of Basalts from the Plains Subprivince, Newer Volcanics

Analysis Number	1-1	1-2	1-3	1-4	1-5*	1-6	1-7	1-8*	2-1	2-2*	2-3	2-4	2-5	3-1	4-1*
SiO_2	51.80	43.48	50.96	42.73	47.81	51.77	48.60	48.69	46.53	44.74	50.34	49.41	49.36	48.99	45.03
TiO_2	1.63	3.56	1.84	3.19	2.13	1.69	2.10	2.14	2.14	2.75	1.65	1.84	2.11	2.03	3.24
Al_2O_3	14.17	10.45	14.46	10.91	13.85	13.78	13.82	15.16	11.32	12.61	14.42	13.37	13.74	13.73	12.97
Fe_2O_3	2.52	7.69	3.98	6.64	4.55	3.14	2.82	4.24	4.44	2.95	5.23	3.04	4.72	2.87	3.28
FeO	7.74	4.92	6.48	5.67	6.80	7.24	7.98	6.05	6.81	8.95	5.99	7.58	6.45	8.30	9.32
MnO	0.16	0.18	0.16	0.20	0.16	0.16	0.17	0.16	0.18	0.16	0.18	0.17	0.16	0.16	0.17
MgO	7.74	10.08	6.61	10.52	11.34	8.30	8.79	6.29	12.44	12.47	8.13	9.60	8.62	9.44	9.88
CaO	8.43	10.52	8.68	12.19	8.32	8.25	8.49	6.65	8.17	8.70	8.33	8.94	8.77	8.65	8.51
Na_2O	3.25	4.44	3.57	4.59	3.22	3.10	3.62	5.33	2.89	3.46	3.61	3.63	3.41	3.58	4.06
K_2O	0.81	0.68	1.02	0.78	1.18	0.79	1.53	2.85	1.65	1.78	0.91	1.10	1.12	1.12	2.22
P_2O_5	0.28	1.32	0.34	1.40	0.51	0.29	0.46	0.63	0.73	0.88	0.33	0.42	0.43	0.45	1.14
H_2O^+	0.81	1.56	0.94	1.06	0.46	0.64	0.65	0.39	1.58	0.58	0.60	0.44	0.65	0.36	0.10
H_2O^-	0.15	0.95	0.43	0.41	n.a.	0.38	0.37	0.28	0.86	0.16	0.41	0.22	0.27	0.07	0.06
CO_2	0.28	0.07	0.48	0.06	0.03	0.06	0.55	0.54	0.03	0.13	0.04	0.15	0.02	0.06	0.07
S	0.00	0.04	0.00	0.02	n.a.	0.01	0.00	n.a.	0.01	n.a.	0.00	0.01	0.00	0.00	n.a.
Total	99.77	99.94	99.95	100.36	100.36	99.60	99.95	99.40	99.78	100.42	100.17	99.92	99.83	99.81	100.15
Rb	23	54	32	38	24	26	32	67	34	36	16	21	19	21	45
Sr	353	1198	450	1231	543	377	598	995	718	830	453	504	527	498	950
Zr	148	372	173	370	152	148	199	480	297	281	99	159	142	144	327
Ni	141	333	85	210	364	154	162	131	370	342	170	174	179	180	263
Mg No	61.9	64.2	58	65.5	68.6	63.4	63.7	57.3	70.8	69.3	61.5	66.0	62.9	64.6	62.9
Location	P	C	P	C	C	P	P	C	C	C	P	P	P	P	C
Lithology	T	NM	T	B	H	T	H	NM	H	B	TR	H	TR	H	NH

Location code - P = plains, C = cones

Lithology code - T = tholeiite, TR = transitional hawaiite, H = hawaiite, NH = nepheline hawaiite, NM = nepheline mugearite, B = basanite.

Samples analysed by R.C. price excepting those marked * which are from Irving (1971), Frey et al.(1978) and McDonough et al. (1985).

the above types of inclusions, but is unique in having garnet metapyroxenites (Griffin et al., 1984). It has been described in considerable detail and Sr and Nd isotopic data may be found in Griffin et al. (1988). Megacrysts found in some alkalic volcanoes include anorthoclase, clinopyroxene, orthopyroxene and kaersutite (Irving, 1974b; Ellis, 1976). Stuckless and Irving (1976) used Sr isotopes to show that while clinopyroxene is in isotopic equilibrium with the enclosing magma, slight disequilibrium is exhibited by anorthoclase, kaersutite and orthopyroxene.

The ICOG excursion guide follows. A 1984 excursion guide on Continental Basaltic Volcanism Western Victoria by numerous authors describes several of the localities visited and is a very useful source, referred to below as CBVWV.

EXCURSION ITINERARY
DAYS 1-4, SEPTEMBER 17-20, 1990

DAY 1:
MELBOURNE TO GEELONG -
A TRAVERSE OF THE MELBOURNE-WERRIBEE-GEELONG SECTION OF THE PLAINS SUBPROVINCE AND THE VOLCANIC CENTRES OF MOUNTS FRASER AND KOROROIT, AND THE ANAKIES.

Topics: sampling of type basalts; isotopic domain mapping; land surfaces of varying age; composition of plains versus cones basalts. The region to be traversed has been systematically sampled on a 5 km grid and is of particular interest because it displays the greatest compositional variation and most complete history in the subprovince.

LA TROBE UNIVERSITY TO WOODSTOCK 27 km
The university is situated on the easternmost limit of the Newer Volcanic province and the surrounding low hills consist of Silurian turbiditic basement. The low valley immediately to the east of the campus (Darebin Creek) contains narrow flows of tholeiite and transitional hawaiite which are 0.95 Ma old (K-Ar - total rock). The Alphington quarry site 6 km down drainage was dated at 0.83 Ma by McDougall et al. (1966) in their original work on the magnetic reversal time scale. Adjacent to the township of South Morang abrupt elevation changes of several metres mark the flow front of a local basalt sheet erupted on the 0.95 Ma surface. The degree of erosional degradation of the flow front gives an immediate impression of weathering rates in the province. Between Epping and Woodstock the landscape is typical of the 0.95 Ma basalt surface and many of the minor topographic irregularities are eroded primary volcanic surface features, either flow fronts or depressions associated with collapsed lava tubes. The amount of exposed basalt and the degree of irregularity of the surface is a broad function of age as demonstrated by K-Ar dating, and the 'eyeball' method of basalt dating will be a theme for several days.

STOP 1: ROADSIDE CUTTING IN THOLEIITE LAVA FLOW, WOODSTOCK

(Ringwood CU245424 Road cutting 1.4 km west of Woodstock)

The cutting exposes the upper levels of a tholeiitic lava flow in a domical outcrop which is a residual from the original hummocky flow surface. The low hills to the east are composed of Devonian turbidites and define the eastern boundary of the province. The plain is made of basalt which drowned a Tertiary land surface which had considerable relief. The surface in sight has an age of 0.95 Ma and this degree of outcrop, with moderate amounts of exposed rock at changes of elevation, is characteristic. The basalt at this site serves as our typical tholeiite for the province (Analysis 1-1) and is chemically very similar to those observed along the way from the university. To that extent the region examined can be considered homogeneous and cannot be subdivided from a first examination of geochemical data. However, Sr isotopic compositions are quite varied, with $^{87}Sr/^{86}Sr$ from 0.7041 to 0.7047, and the measurements are geographically clustered so as to indicate several distinct domains of otherwise indistinguishable basalts (Fig. 1-1; the following domain numbers refer to the figure). For example, in the vicinity of Stop 1 basalts to the north are less radiogenic than those to the south, with $^{87}Sr/^{86}Sr$ ratios 0.7044-5 (Domain 6) and 0.7046-7 (Domain 4) respectively; more significantly, those basalts on the far eastern margin of the basalt field near the university are distinctly less radiogenic at 0.7041-2 (Domain 5). The shapes of the isotopic domains are elongate down drainage, and locally the domains are bordered by topographic features of the pre-basalt basement (Fig. 1-1). Isotopic gridding of this region (5 km sample spacing) has proved to be a first order mapping technique, locally supported by petrography or gross changes in chemical composition.

Hayes Hill, the knoll to the north-west of Stop 1, is a small composite volcano with basal pyroclastics and a capping basaltic lava flow which can be seen extending southward as a ramp along the skyline. It was thought to be the eruption point of the adjacent plains tholeiitic lavas which extend southward through the Melbourne metropolitan area (Hills, 1975), and the form of the basaltic ramp is very suggestive of this proposition. However, the lava flow is a nepheline mugearite (Analysis 1-2) and the cone rocks are alkalic in composition and chemically and isotopically distinct from the nearby plains basalts. This contrast is a common problem in the district for the obvious volcanoes are often alkalic, and the voluminous plains basalts are generally tholeiitic. The search for the less than obvious tholeiitic eruptive sites is thus an important issue.

WOODSTOCK TO MOUNT FRASER 16 km

The excursion proceeds westward across the basalt plain, initially on the same surface as at Stop 1. The pale coloured hill to the south is an island of Silurian basement protruding through the basalt and marks a ridge line of the pre-volcanic topography. Immediately before the railway crossing at Donnybrook the land surface to the north is slightly more irregular than before, and reveals the trace of a narrow tholeiite flow; the topographic recognition of this flow is confirmed by its distinctively low $^{87}Sr/^{86}Sr$ ratio of 0.7041. This basalt is reputed to have been erupted at our destination, Mt Fraser 9 km to the north (Hanks, 1955), but that volcano is hawaiitic; the flow is more plausibly from Spring Hill, an elevated area of irregular terrain immediately north of Mt Fraser with an identical tholeiitic composition. The Merri Creek is reached beyond the railway crossing, just before the hamlet of Donnybrook. Basalt exposure in the banks of the creek is considerable, but the plain further to the west has much less outcrop. The creek marks a major basalt domain boundary (Fig. 1-1), for to the west the age of the flows has increased to 2.3 Ma and $^{87}Sr/^{86}Sr$ ratios have jumped to 0.7050 (Domain 3), even though the rocks (Analysis 1-3) are compositionally very similar to those discussed previously. The domain boundary also corresponds in part to the basement ridge mentioned above, with the older and younger basalts flowing down different valleys. The 0.95 Ma domains are particularly interesting in that quartz tholeiite, tholeiite and transitional hawaiite with an $^{87}Sr/^{86}Sr$ range from 0.7041 to 0.7047 were being erupted simultaneously within a restricted area; the eruption points have not been identified. The association of tholeiitic and mildly alkalic rocks is typical of the subprovince post-2 Ma. At Donnybrook the Hume Highway is taken to the north, to cross the western flank of the nepheline hawaiite-basanite volcano of Bald Hill (Analysis 1-4, basanite). The next peak to the north has unmistakeable volcanic form and the highway is left at Beveridge to gain access to the quarry on its southern face.

STOP 2: MOUNT FRASER QUARRY
(Woodend CU211514 Adjacent to Beveridge - permission required for entry)
Mt Fraser is a compound of a dominant cinder cone making up the main peak, with lesser satellites on its southern flank. It is significant, firstly as a relatively young cinder cone in an area where most volcanoes are distinctly older, and secondly as the easternmost lherzolite inclusion locality in the province. The quarry is in the dipping flank sequence of a cinder cone which contains bedded cinders with blocks of hawaiite (Analysis 1-5) up to a metre in size, pronounced zones of alteration, and the solid mass of a basalt feeder pipe. Small lherzolite inclusions are moderately abundant.

MOUNT FRASER TO TULLOCH HILL 19 km
The highway is retraced past the Bald Hill volcano and the next domical hill, to the south is climbed via a westward side road. Outcrop on Mt Ridley is poor and conceals an apparently interesting history as there are two peaks and both tholeiite and nepheline mugearite compositions are reported; the surrounding plains are tholeiitic. On descending Mt Ridley our objective at Tulloch Hill is visible as a low rise 5 km directly ahead.

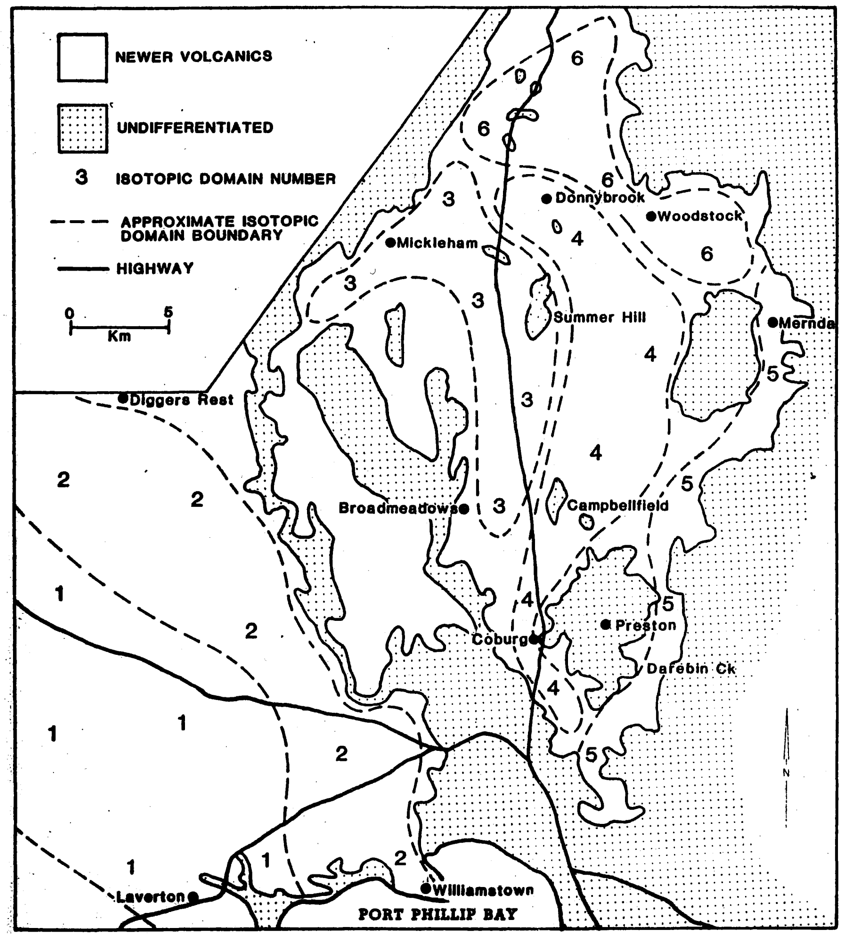

Fig. 1-1: Major Sr isotope basalt domains of the Melbourne area (from Price et al., 1988). Details of the domains are given in the text.

STOP 3: TULLOCH HILL
(Melbourne CU117406)

Tulloch Hill is hardly distinguishable as an elevated point from some angles, yet is slightly, but distinctly higher than the plains surface. The hill is composed of basalt though there is nothing distinctive about the outcrop, and for that reason the bus will briefly turn on the summit before departing. Elevation alone suggests that this must be a small volcano, presumably of lava shield type given the gentle domical profile. Significantly, Tulloch Hill is composed of tholeiite which is identical to that exposed on the adjacent plains (Domain 3) and therefore probably has an age of 2.3 Ma. The dilemma of the missing volcanic sources for the extensive plains tholeiitic basalt domains is resolved by the proposition that they are very subdued lava shields like Tulloch Hill, the majority of which have yet to be recognised; they may be such insignificant topographic features as to be virtually unrecognisеable, or may have been drowned by younger flows. The other volcanic peaks visible in this area have alkalic affinities, whereas all the plains basalts are strongly tholeiitic.

TULLOCH HILL TO MOUNT KOROROIT 39 km

This leg of the journey is unexceptionable apart from the descent into two steep-sided valleys which cut through the basalt plain and expose Palaeozoic basement on their floors. In the township of Bulla the valley cuts through a Cainozoic deep weathering profile developed on the ancient, pre-basaltic Australian land surface. The profile is developed on Devonian granite, which was severely kaolinised, as can be seen from the white scars on the hillside. Throughout this region isolated hills on the plains are usually extinct volcanoes.

STOP 4: MOUNT KOROROIT

(Melbourne BU936298 - permission required for entry)

Mt Kororoit is an eroded composite volcano which is unusual in the Victorian context in showing fragments of its internal petrological history. The geological components are: (a) a broad lava apron several kilometres in diameter which merges with the regional plain; (b) a sequence of lava flows and pyroclastics; the uppermost flows on the summit dip inward to a presumed central crater; and (c) a feeder dyke extending down and bifurcating on the north-eastern slope. The summit lava flows and the dyke are distinguished by abundant phenocrysts of plagioclase and clinopyroxene. A climb to the summit presents a view of the volcanic plain which will be crossed for the remainder of the day and indicates the density of volcanic centres in this part of the province. The topographic expression of three additional volcanoes is of note. Sheoak Hill to the north is a composite alkalic volcano dominated by pyroclastics, with thin intercalated lava flows, and the remnants of a crater. The elongate, low ridge to the east is a basaltic icelandite lava shield with eruptive centres on its two highest points. Due south, Mt Cottrill has the characteristic profile of an hawaiite lava shield, which rises to the steeper crest of its final flows. Other volcanoes to be encountered later in the day are Mt Atkinson, Spring Hill and The Anakies. The plains are a patchwork of basalt domains derived from these centres.

MOUNT KOROROIT TO SUNSHINE QUARRY 33 km

The next stage of the journey introduces basaltic icelandite as a significant tholeiitic variant in the province. The basaltic icelandite lava shield crossed to the east of Mt Kororoit is topographically quite undistinguished and is only clearly apparent as a positive feature on its eastern side; its dimensions are 4 x 0.7 km. However, this is the eruption point for at least two major lava flows which extend up to 27 km to the south-east (Fig. 1-1; Domain 2), an eloquent demonstration of the subdued form of volcanoes that are the significant contributors to the lava plain. The basaltic icelandite domain of this area was recognised by its relatively radiogenic Sr ($^{87}Sr/^{86}Sr$ ~0.7052) and subsequently confirmed geochemically and by K-Ar dating (2.6-2.8 Ma); the domain is 27 x 6 km and extends down the regional gradient to the head of Port Phillip Bay. Having seen the source for this domain the next step is to view a distal part of a component flow. Alas this takes us into some less than glamorous suburbs and comments on the route are suspended!

STOP 5: BASALTIC ICELANDITE DOMAIN, DUKE STREET QUARRY, SUNSHINE
(Melbourne CU104177 - permission required for entry)
The stop in the quarry will be brief, to indicate the scale of the flow (Domain 2) and to permit sampling of a typical strongly tholeiitic rock if desired. Lithologies in the domain vary from basaltic icelandite to quartz tholeiite to tholeiite. Analysis 1-6 classifies as a tholeiite, but is very close to the basaltic icelandite boundary and is typical of the domain. The sample comes from the abandoned quarry immediately adjacent to this working quarry in Duke Street. Unusually, this flow has a distinctive texture, with in addition to the ubiquitous olivine, small clinopyroxene phenocrysts ophitically enclosing plagioclase laths. The K-Ar total rock age is 2.70 Ma with normal magnetic polarity (McDougall et al., 1966). This domain exemplifies the strongly tholeiitic component erupted during the peak of activity between 3 and 2 Ma.

SUNSHINE QUARRY TO DEER PARK QUARRY
A major domain boundary is located between Stops 5 and 6 (Fig. 1-1) with a change from basaltic icelandite (Domain 2) to hawaiite (Domain 1). The domain boundary is broadly located by regional sampling and corresponds to the trace of Kororoit Creek which is considered to be a lateral stream constrained by the margin of the younger hawaiite flow. The eruption point of the hawaiite is under investigation, but is suspected to be Mt Atkinson.

STOP 6: HAWAIITE FLOW IN DEER PARK QUARRY
(Melbourne BU997160 - permission required for entry)
The hawaiite (Domain 1) of Stop 6 introduces the third main basaltic variant of the lava plains and a short stop will enable sample collection; Analysis 1-7 is of a sample taken 8 km south-east from the quarry. The K-Ar age of the domain is 1.43 Ma and the rock is typical of the most alkalic plains basalts of the 2-0 Ma interval. The land surface is virtually level compared with the younger 0.95 Ma domains north of Melbourne; however, outcrop in paddocks is still locally much more abundant than in older domains to be viewed on Day 2. Comparison of hand specimens of the three type basalts examined today is unilluminating as they are very similar; all have comparable olivine phenocrysts and the only distinguishing feature is slightly smaller grainsize in the hawaiite. In thin section, the rocks are texturally distinct: the tholeiites have abundant interstitial glass in varying stages of devitrification and most basaltic icelandites are similar; hawaiites are usually finer grained and holocrystalline.

DEER PARK QUARRY TO THE ANAKIES
A roundabout drive across the Werribee plain completes the inspection of the most varied sector of the plains subprovince. The apron of the hawaiite lava shield at Mt Cottrill is crossed first, and with an age of 2.25 Ma has lost most surface detail. The valley of the Werribee River at Exford provides another section into the lava plain, here excavated subsequent to the formation of Mt Cottrill. Further west a low ridge marks the Spring Hill complex, a substantially degraded collection of hawaiitic eruption points

aligned north-south. The road crosses the northern end of Spring Hill between two of three main craters constructed from pyroclastics and minor lava flows which can be seen poorly outcropping in the crater walls. The adjacent Bald Hill is typical of the form of many degraded single volcanic peaks in the province.
The route is then southward and the skyline is cut by the profiles of the three cinder cones of The Anakies, which have a clear north-west to south-east alignment and presumably developed on a basement fault.

STOP 7: SOUTH-EASTERN CINDER CONE AT THE ANAKIES
(Bacchus Marsh BU625008 - permission required for entry)
This quarry cuts deep into the heart of a cinder cone and exposes an homogeneous, loosely consolidated pyroclastic deposit with three size components - approximately 5 cm-sized angular scoria fragments, much finer interstitial cinders, and occasional metre-sized bombs flattened in the layering. The scoriaceous basalt evidently varies in composition, as our sample is a transitional hawaiite, whereas those of Irving and Green (1976) are nepheline mugearites (Analysis 1-8). The other two cones are hawaiites (Irving and Green, 1976). The Anakies are particularly noted for xenoliths and megacrysts. The ultramafic xenoliths in the eastern cone are predominantly lherzolites (abundant) with minor wehrlite, harzburgite, orthopyroxenite, garnet websterite, hornblendite, and plagioclase pyroxenite; pyroxene granulites (pyroxene-plagioclase rocks) are common; granite from an exposed wallrock pluton is also abundant and may show partial melting textures and inversion of feldspars to high temperature structural state. As the quarry has expanded there have been considerable changes in the nature of the inclusions, with a decline in abundance and quality of preservation, such that most lherzolites found today are hydrothermally altered. The reported megacryst population is ferrokaersutite and anorthoclase (abundant), apatite (common), and orthopyroxene, kaersutite, biotite, phlogopite and ilmenite (rare). However, only anorthoclase is readily found in the quarry and much of the more elaborate mineral assemblage is limited to a thin flow on the crest of the hill.

THE ANAKIES TO GEELONG
The Anakies are surrounded by an apron of hawaiite and nepheline mugearite 1.5 Ma old. The relatively alkalic composition is prone to accelerated weathering and outcrop is poor. The apron has been deformed by the Lovelybanks monocline forming a pronounced escarpment which is followed to Geelong.

DAY 2:
GEELONG TO HAMILTON - AN EAST-WEST TRAVERSE OF THE PLAINS SUBPROVINCE AND THE VOLCANIC CENTRES OF MOUNTS ELEPHANT, SHADWELL AND ROUSE.

Topics: further basalt domains as a function of age; construction of the lava plain (contrasting aprons of Mounts Elephant and Rouse); tectonic controls on volcanism - the Mortlake discontinuity; youthful hawaiitic volcanism.

GEELONG TO DERRINALLUM 110 km

The Hamilton Highway extends due west from Geelong across a multitude of basaltic lava flow units. At Fyansford, 4 km from Geelong, thick columnar jointed tholeiite flows exposed in a road cutting and adjacent quarries are dated at 2.1 Ma (reversed polarity; Aziz-ur-Rahman and McDougall, 1972). At various points along the route distant volcanic peaks cut the skyline: the three cinder cones of the Anakies visited yesterday (north), Mt Buninyong south of Ballarat (north), Mt Gellibrand (south), Warrion Hill a locality on Day 4 (south), and finally many cones to the south of the road at Lismore. The continuous hills to the south are the east-west trending front of the Otway Range, with outcrop of the Cretaceous and Tertiary sedimentary rocks deposited in the rift valley associated with the separation of Australia and Antarctica. This northern boundary of the range is the trace of major rift-bounding faults which abruptly define the southern margin of the Newer Volcanic Province (Colac Lineament). One of the oldest surfaces of the plains subprovince is passed 25 km west of Cressy, a featureless plain with a deep weathering profile and very little exposure of its 3.6 Ma tholeiites. The total destruction of surface volcanic features in this relatively short time is all too apparent, as is the difficulty of studying these basalts, samples of which are hard to locate and usually weathered. The distinctive landmark of the district is now visible in the west as the bluff steep-sided cinder cone of Mount Elephant.

STOP 1: PANORAMA OF MT ELEPHANT

(Skipton XC977975 Hamilton Highway roadside, 8 km west of Lismore, 3 km east of Derrinallum)

Mt Elephant is an almost symmetrical cinder cone rising 190 m above the plain, and is physically the most striking and largest of the cinder cones in the province. It has a pronounced crater which is breached at a high level on the northern side. The cone caps a broad apron of lava flows, which is seen in profile as the surface of low gradient extending away from the break in slope at the base of the cone.

STOP 2: MT ELEPHANT QUARRY, DERRINALLUM

(Skipton XC923960 Quarry on the western flank of Mt Elephant; turnoff from Hamilton Highway along Mt Elephant road, 2.9 km west of Derrinallum - permission required for entry)

The western flank of Mt Elephant is extensively quarried exposing vertical sections in cinders of scoriaceous basalt ranging in size up to small (15 cm) bombs and containing dispersed basaltic blocks. The materials on the floor of the quarry are extensively disturbed, but the excavated basalt blocks warrant a brief inspection. The blocks range up to several metres in size and are a very fine grained hawaiite (Analysis 2-1), which often contains abundant small cm-sized inclusions of spinel lherzolite and rare wehrlites and megacrysts of augite (abundant) and anorthoclase (sparse) (Irving, 1974b).

STOP 3: MT ELEPHANT BASALTIC APRON
(Skipton XC890954 Hamilton Highway roadside, 7 km west of Derrinallum)
On leaving the quarry and travelling westward along the highway the land surface is relatively irregular with abundant outcropping basalt, a subdued and eroded form of an upper lava flow surface known locally as 'stony rises'. Accumulated lava flows of nepheline hawaiite cover a crudely circular area 8 km in diameter with Mt Elephant located 2 km inside its northern margin; relative to the volcanic vent the basaltic apron is asymmetric down drainage. The abrupt edge of the apron is visible as a ~5m-high flow front superimposed on the older surface of the plains lavas. The apron serves as a model for the simplest geometry of older plains basalt domains in which surface features have been destroyed by erosion or concealed by younger deposits. Other patterns of aprons will be seen at Mounts Rouse (Day 2) and Eccles (Day 3). It is envisaged that much of the plains is underlain by overlapping basalt units in the shape of these aprons.

DERRINALLUM TO MORTLAKE 43 km
Immediately to the south-west of Mt Elephant the two volcanic peaks are Mts Kurtweeton (hawaiite) and Koang. Half way to Mortlake the skyline to the south-west presents the extensive, irregular peaks of Mt Noorat, a maar and nested cinder cones (Day 4, Stop 1). A similarly-shaped collection of intermingled cinder cones then becomes apparent on the western horizon as Mt Shadwell, the next locality. Adjacent to Darlington the plains are capped by 2 Ma tholeiites, and volcanism of this age dominates the plains for many kilometres around Mt Shadwell. These basalt domains formed during the peak of volcanism in the subprovince, range in composition from tholeiite to hawaiite, and in this area have shapes elongate on a slightly west of south trend down the regional gradient. The hawaiites were the first voluminous manifestation of more alkalic volcanism which commenced during the peak of activity and became more pronounced towards the present day. The field geology is undistinguished and the only distinctive aspect is the very extensive tract of 2 Ma surface with its limited outcrop; hence the excursion rapidly passes through the area. However, it is necessary to enlarge upon regional tectonics for this is the site of the Mortlake discontinuity, which strikes approximately north-west to south-east and is defined by an hiatus in the isotopic composition of the basalts (see Background above). The majority of comparable basalts have similar chemical compositions on either side of the discontinuity apart from slight variation in mean Rb/Sr ratios. However, there are basalt types that are restricted to one sector, the most radiogenic basaltic icelandites found only in the east, and a young hawaiitic type restricted to the west (Rouse component - Day 2, Stop 9). The eruptive histories of the eastern and

western sectors are chronologically identical. Nonetheless, within 15 km there is a significant change in Sr, Nd and Pb isotopic compositions; both maximum and minimum $^{87}Sr/^{86}Sr$ ratios are more radiogenic in the east though there is considerable overlap. The discontinuity corresponds to the projection across the basalt field of a Palaeozoic basement structure, the Grampians subzone, which contains structurally dismembered basalt-andesite-dacite volcanics of probable Cambrian age. The volcanics probably formed at a convergent plate boundary with the subzone marking a major lithospheric boundary. These rocks are unconformably overlain by Late Silurian - Early Devonian fluviatile sandstones now seen as the Grampians Range, one of the most scenic parts of Victoria; if time permits in the afternoon, we will make a scenic-cum-geological diversion to the southern end of the range. In the vicinity of Mortlake the basement structure is only manifested by a low tableland of Tertiary rock uncapped by basalt visible as an escarpment to the north-west of Mt Shadwell. On the basalt plain the only apparently related geological feature is unusually extensive pre-basalt Tertiary sediment which implies a low intensity of volcanism; there is no geomorphological representation of the discontinuity in the basalts themselves.

STOP 4: MT SHADWELL SHIRE QUARRY, MORTLAKE
(Mortlake XC593867 Quarry on the eastern flank of Mt Shadwell; access from Ararat road - permission required for entry)
Mt Shadwell is a composite of numerous cinder cones of basanite (Analysis 2-2) with a limited apron on the southern side (Stop 5); it has not been geologically studied and the eruptive history is unknown. The quarry is located in the flank of a cinder cone. Small, fresh spinel lherzolite inclusions are moderately abundant and other minor types are dunite, wehrlite, websterite, clinopyroxenite, and garnet-bearing lherzolite. According to Irving (1974b) megacrysts are clinopyroxene (common) and anorthoclase (abundant); rare orthopyroxene is reported by Ellis (1976).

STOP 5: MT SHADWELL APRON
(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 5 is highly unusual, with a jumble of massive vesicular basalt and fragmental material. The massive basalt is a nepheline hawaiite, which contains abundant lherzolite inclusions reaching 10 cm in size, and anorthoclase megacrysts; it varies from apparently *in situ* flow bodies up to 10 m long and 3 m thick with vertical columnar joints, to dyke-like masses up to 50 cm across and exposed vertical extents of 2 m. The fragmentals have angular basalt clasts (2 - 40 cm) in a fine, orange-coloured weathered matrix.

MORTLAKE TO PENSHURST 59 km
On leaving Mortlake the highway continues to traverse a 2 Ma land surface composed of numerous basalt domains. The tholeiitic domain immediately

to the southwest of the town (Analysis 2-3), is one of the largest in the province and may be a single flow 43 x 12 km which extends almost to the sea; it is identifiable by a distinctive plagioclase texture and $^{87}Sr/^{86}Sr$ ratio of 0.7041. Thereafter, the plains are unexceptional until the peak of Mt Rouse is visible on the western horizon. Again, the background terrain was created by extensive lava flows extruded at the peak of activity around 2 Ma. Some 300,000 years ago the new volcano of Mt Rouse was superimposed on the older plain.

STOP 6: PANORAMA OF MT ROUSE
(Hamilton XD159082 Hamilton Highway roadside, 6 km east of Penshurst)
The plains basalt that occupies the low country at this site is a 1.95 Ma hawaiite (Analysis 2-4); domains in this area are elongate in a south-west direction away from the basement upland south of Glenthompson. There is a dramatic contrast between this virtually featureless eroded upper surface of a lava flow and the hummocky basalt apron erupted from Mt Rouse where the younger flows abruptly end in fronts up to 7 m high. Mt Rouse comprises two hawaiite cinder cones reaching an altitude of 370 m ASL, with the crest 100 m above plain level and the steep sides having gradients up to 20^{o}; only the higher cone is visible in this perspective.

STOP 7: MT ROUSE SUMMIT
(Hamilton XD143063)
The road ascends from the lava apron in a sinuous route from the southern to the northern cinder 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 environs. Mt Rouse has been intensively studied by Whitehead (1986) and the description is derived from that source. The summit is located on the northern flank of the higher cinder cone. The northern crater is elongate east-west and formed 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 cinder cones are composed of hawaiites (Analysis 2-5)

The small ridge adjacent to 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 (1986) has 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 proximal unit of stony rises (4 x 8 km) are clearly seen from the extent of irregular topography around the peak; the stony rises are examined in detail at Stop 9.

> 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 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. Whitehead (1986)

Individual valley flows emerge from the apron and extend up to 60 km to the south (Figs 2-1, 3-1), in places channelled down to widths of 200 m, and in sum covering areas up to 10 km across (Day 3, Mount Eccles to Tower Hill); they reach the sea at Port Fairy. The flows have been K-Ar dated at 0.3-0.4 Ma near Port Fairy (McDougall and Gill, 1975) and 15 km south of Mt Rouse (unpublished results). Because of their youth these flows are readily mapped and are used as a further model for the likely geometry of the older plains basalt domains, namely a circular to elliptical apron and protruding, relatively narrow distal valley flows infilling pre-existing drainage.

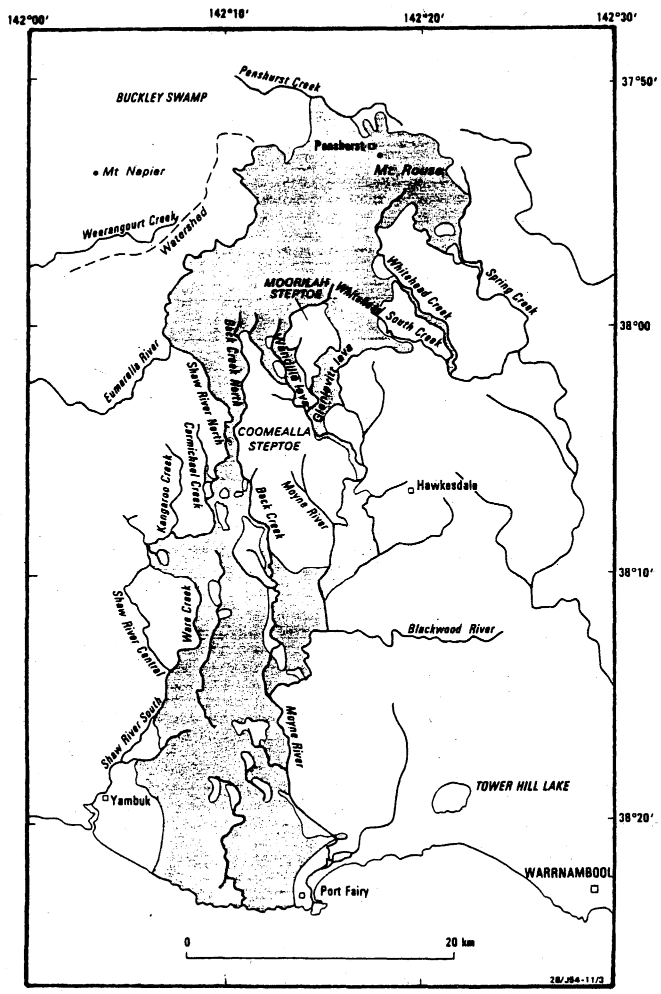

Fig. 2-1: Geographic sketch of basalt lava flows from Mt Rouse (from Ollier, 1985)

<u>STOP 8</u>: QUARRY ON THE EASTERN FLANK OF MT ROUSE
(Hamilton XD147055 Access adjacent to reserve entrance)

The quarry contains an excellent section through the flank of the southern cinder cone at Mt Rouse. At the northern end of the quarry pyroclastics are perfectly planar bedded on a centimetre to metre scale. The bulk of the material comprises cinders in the 5 mm-2 cm range with occasional bombs and blocks up to 10 cm in size. The cinders are often exceedingly well-preserved showing the sheen of original glassy surfaces even though 300,000 a old. Some coarser horizons have bombs with dimensions up to 1 m. Near the southern end of the quarry adjacent to the entrance, a columnar-jointed hawaiite flow 2 m-thick overlies the pyroclastics and dips off the flank of the cinder cone. The flow preserves a ropy lava surface on its underside and rapidly lenses out to the north over a distance of 200 m.

STOP 9: HAWAIITE LAVA FLOWS FROM MT ROUSE
(Hamilton XD132037 Intersection of Penshurst-Hawkesdale road and Stonefield Lane, 4 km south of Penshurst)
This site is on typical stony rise terrain of the apron around Mt Rouse.

> 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. Whitehead (1986)

The jumbled flow surface is very apparent although signs of erosional modification in the last 300,000 a are also clear. Retain an image of this surface for comparison with much younger examples to be viewed tomorrow (Day 3, Stop 3) to further calibrate your 'eyeball' method of determining basalt age and rates of erosion. The rock is a transitional hawaiite with an unexceptionable major element composition (Analysis 2-5). However, hawaiitic rocks such as this from the young volcanoes of the western sector are distinguishable by low Rb/Sr ratios, and in conjunction with their relatively unradiogenic Sr isotopic compositions (0.7037-0.7041) form a distinct geochemical component in the basalt system (see Background).

PENSHURST TO HAMILTON
The direct journey to Hamilton crosses progressively older land surfaces (0.3 Ma hawaiite, 1.8 Ma transitional hawaiite, 4.5 Ma tholeiite) with corresponding loss of volcanic surface morphology and increasing depth of the weathering profile. However, 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 WARRNAMBOOL - BASALTIC VOLCANISM AT MOUNTS NAPIER AND ECCLES, AND TOWER HILL

Topics: Mt Napier lava shield; Harman Valley hawaiite flow; Byaduk lava caves; Wallacedale tumuli; Mt Eccles crater, lava channels, and spatter cones; distal flows of Mt Rouse; and Tower Hill maar and cinder cones.

HAMILTON TO MT NAPIER (15 km)

The journey south from Hamilton crosses one of the oldest segments of the regional basalt plain, a 4 Ma surface having no basalt outcrop and a weathering profile up to 10 m thick. The surface is more irregular than those with younger basalt cover, and locally there are broad and relatively deep valleys cut into it, a further indication of antiquity in this area. Throughout the subprovince basalts older than 1 Ma may exhibit distinctive geochemical effects of weathering of a type particularly pronounced in this relatively old area. Anomalously high Ba and/or rare earth element concentrations up to 4 times expected values are erratically developed, though the shape of rare earth patterns is unaffected (Price et al., in prep.). The exaggerated concentrations are due to the release of these elements from weathered material and incorporation in secondary phases developed in residual rock. The landscape ahead is dominated by Mt Napier (pronounced 'Napeer'), the highest volcano (400 m ASL) superimposed on the western plains (base level at the foot of the mount 200 m). The broad base of Mt Napier is a lava shield composed of numerous hawaiite flows, frequently concealed beneath cinders and locally punctuated by small cinder cones (Whitehead, 1986). Our approach to the mount terminates at the margin of the forest, which is preserved on the irregular terrain of the lava shield; low flow fronts are visible protruding into the cleared area. The distinctive steeper cap to the shield is constructed from several overlapping larger cinder cones. The geological features of the summit include an excellent spatter rampart, a crater breached on the west side, and an issuing steeply-dipping hawaiite flow and lava tube. The summit was originally forested, but is now bare due to the lethal effects of bushfires, during which intense heat has been concentrated on the steeper slopes as a result of combustion of the forest below. The lava shield is essentially circular in plan with a diameter of 8 km (Fig. 3-1). However, several elongate flows radiate beyond this apron, infilling valleys of the old basalt plain surface. One of these blocked the ancestral Harman River to the north-east of the mount, leading to the formation of Buckley Swamp. Radiocarbon dating of peat from the swamp gives an age of 7420±140 BP, a younger limit to, but probably approximating the time of eruption (Gill and Elmore, 1973). On morphological grounds, Mt Napier is one of the youngest volcanoes in Victoria. Chemically, all rocks from the area are hawaiites.

MT NAPIER TO HARMAN VALLEY, BYADUK 19 km

The greater part of the morning is devoted to examining features of the major Harman Valley lava flow that extends for at least 15 km from Mt Napier in a south-westward direction (Fig. 3-1). The Harman Valley flow is a young hawaiite (Anal 3-1) with numerous well-preserved flow features. The next stages of the excursion move steadily westward to intersect this flow at several points.

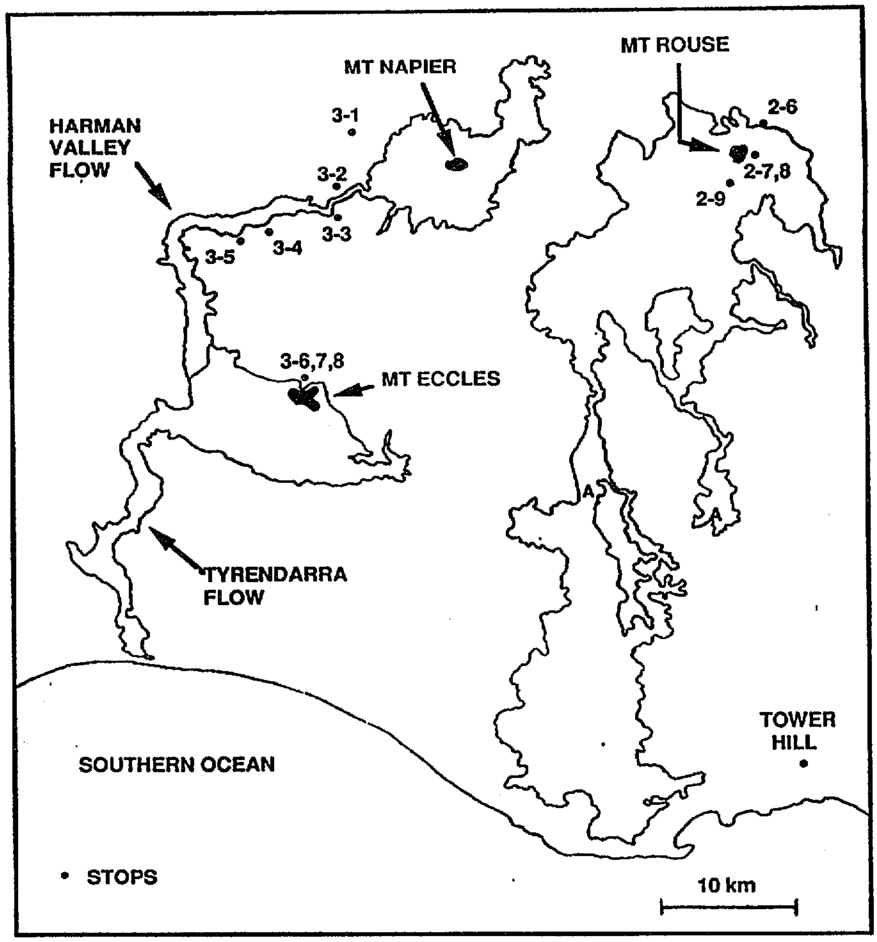

Fig. 3-1: Outline map of the basaltic aprons and major lava flows associated with Mounts Rouse, Napier and Eccles. The route from Mt Eccles to Tower Hill crosses the flows from Mt. Rouse at the points marked A.

<u>STOP 1</u>: MT NAPIER PANORAMA (8 km from the summit)
(Coleraine WD861080 Murroa-Buckley Swamp Road, 1.2 km east of intersection with Hamilton-Byaduk road)
A brief stop gives the best perspective of the two main components of Mt Napier, the lower lava shield and its steeper crown of cinder cones. The Harman Valley flow extends from the lava shield on the right of this view, though the valley itself is incised and concealed.

<u>STOP 2</u>: BYADUK LAVA CAVES (8 km from the summit)
(Coleraine WD855038)
On approach to the caves, the first view of the Harman Valley flow entails bland slopes grading down from the old basalt surface to an essentially flat valley floor 300 m wide. The infilling lava flow is clearly visible with an irregular hackly surface in detail, and is at least 20 m thick at this point. The site provides an excellent demonstration that the long valley flows were fed by lava tubes. The lava tube is excellently exposed as a series of 19 caves entered via circular to elliptical openings where the roof of the tube has collapsed (Ollier and Brown, 1964; Fig. 3-2). The caves are essentially one

system located in the middle of the flow and acting as its main feeder. Typical cave dimensions are 10 m wide by 5 m high and the greatest length is 400 m; a vertical section has a broadly arched shape and floors undulate along their lengths. The lava tube was locally left empty by a final draining of the lava. Preserved internal features include basalt stalactites, level marks, benches, and ropy lava floors. We will examine Harman and Bridge Caves.

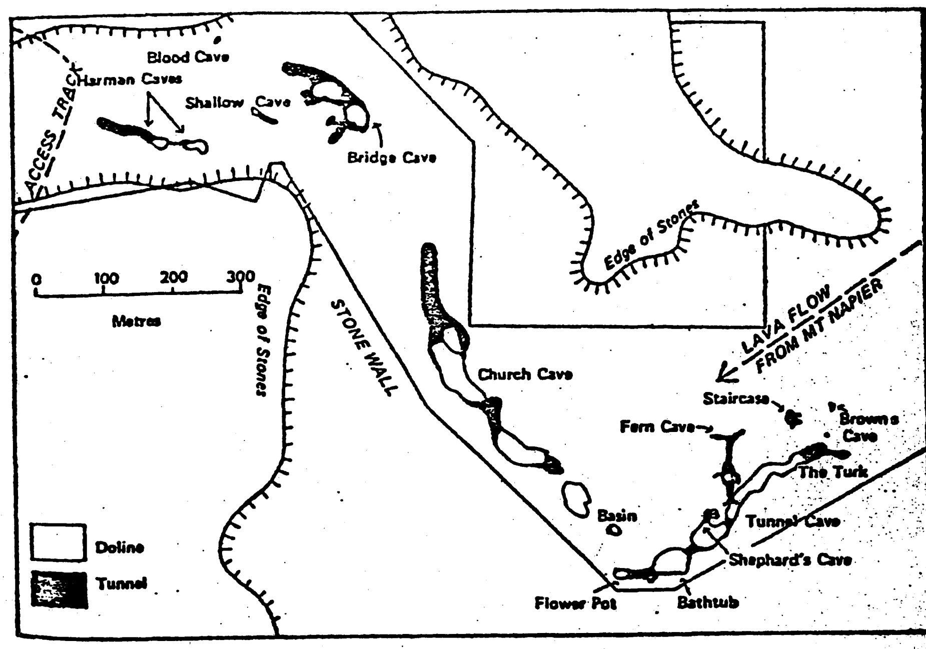

Fig. 3-2: Map of the Byaduk caves area (from Joyce, CBVWV)

<u>STOP 3</u>: HARMAN VALLEY FLOW, BYADUK (10.5 km from the summit)
(Coleraine WD832025 Roadside on northern slope of Harman Valley between Byaduk North and Byaduk)

The character of the Harman Valley flow is better expressed at Byaduk by a view into the valley extending back towards Mt Napier. The constraint of the valley is obvious and the irregular surface of the flow contrasts with the smooth slopes cut into the much older basalt plain. A further indication of youth is the absence of a new lateral drainage. The features of the flow surface in this region are described by Ollier (1967) and are summarised in Figure 3-3. The obvious structures here are the pronounced lateral barriers and depressed interior.

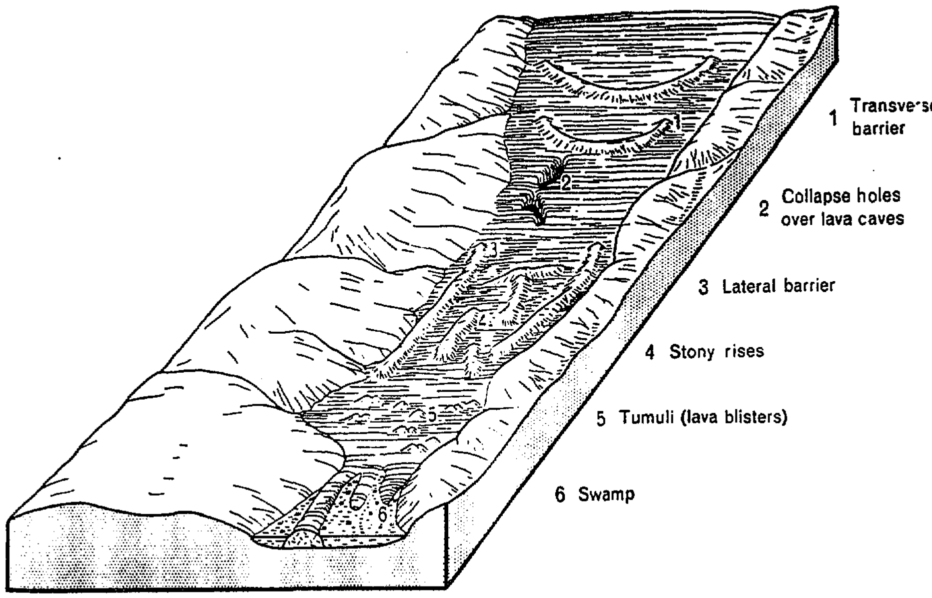

Fig 3-3: Surface features of the Harman Valley lava flow at Byaduk (Ollier, 1967)

HARMAN VALLEY, BYADUK TO WALLACEDALE 7km
The Harman Valley flow broadens to 1 km wide west of Byaduk, and the road follows the high country on its southern side with occasional views down to the basalt surface. Near Wallacedale a short arm of the flow extended into a closed side valley which the road crosses through a field of distinctive tumuli.

STOP 4: TUMULI, WALLACEDALE (16 km from the summit)
(Coleraine WD783007 Old Crusher Road)
The tumuli are often remarkably symmetrical domes, up to 10 m high and 20 m in diameter, that rise abruptly from the level surface of the flow, producing a unique landscape. The typical domical examples are more regular in form and steep-sided than in many other provinces. The complete variation in form is (Ollier, 1964): simple domical; domical with a cracked crest from which lava has been extruded; domical with a collapsed crest; circular depressions produced by total collapse. Joints at the crests have opened to define individual blocks of basalt, thereby conveying an igloo-like appearance. Vesicles flattened parallel to the surfaces of the domes are evidence for inflation by magma pushing from below. The tumuli are concentrated in, and randomly distributed across, the extension of the Harman Valley flow into a closed side valley to the main drainage. Over-pressuring of a pool of magma in the closed valley by a hydrostatic head of magma upflow in the Harman Valley is a possible explanation for the formation of the field of tumuli.

STOP 5: LATERAL BARRIERS, WALLACEDALE (17 km from the summit)
(Coleraine WD766004 Road junction at western end of Old Crusher Road)
The lateral barriers are located on the southern margin of the Harman Valley flow immediately south-east of the junction. The two parallel ridges are ~100 m long, ~15 m wide, and rise up to 4 m above the intervening

depression, which is ~15 m wide. The northern of the two ridges is broken along its crest whereas the southern is smoothly cylindrical with local breaks.

WALLACEDALE TO MOUNT ECCLES

The region traversed today contains the best preserved young volcanoes and associated basalt aprons and valley flows. Having seen Mt Napier and its Harman Valley flow, the following series of stops at Mt Eccles examines the source of a similar impressive array of flows (Fig. 3-1). Mt Eccles is located on the northern margin of an elliptically shaped apron (7 x 17 km) which has an east-west elongation. The apron is densely forested with very irregular terrain across which radiate numerous large lava canals. The Tyrendarra valley flow (which will not be visited) is the longest and extends from the apron at its south-western extremity due southward 20 km to the sea. It was erupted at a time of low sea level and has a submarine extension 15 km off the present coast, giving a total length of 35 km. The Mt Eccles volcano has a subdued topographic expression and the 'mountain' itself is a relatively minor cinder cone within a much larger structure (a stratigraphic section from the cinder cone can be found in Figure 4-1). Nonetheless, the Mt Eccles complex is the most interesting of the Victorian volcanoes, with a unique combination of features that complements the other centres. The following description is primarily derived from Tunjic (1988). The elongate main crater and a series of spatter cones define a lineament 2.25 km long (Fig. 3-4) which is considered to be controlled by an underlying fissure. Eruptions are estimated to have occurred in the 25,000-6,000 BP interval from ^{14}C dating. For the purposes of our visit, there are three main aspects to the complex and these give rise to the following three stops.

<u>STOP 6</u>: MT ECCLES CRATER

(Portland WC807870)

Mt Eccles crater is infilled by the appropriately named Lake Surprise, and is 700 m long, with a maximum width of 150 m, and a maximum depth from rim to lake level of 70 m. Overall, the crater is a compound structure elongate north-west to south-east and formed by the overlap of three individual smaller craters causing the long sides to have cusped shapes (Fig. 3-4). The vertical walls and elongation along a fissure indicate that the feature is a pit crater with a collapse rather than explosive origin (Tunjic, 1988). The area around the crater is envisaged as initially forming a gently-sloping, elongate lava shield as a result of fissure eruption along a basement fault. Withdrawal of magma from the subterranean conduit then led to the formation of three coalescing collapse craters along the line of the fissure. As exposed, the greater part of the walls of the crater are composed of 7-9 horizontal basalt flows, one of which near the top of the sequence can be traced around much of the crater. Locally, however, the walls are unlayered, massive, little vesiculated vertical sheets about 35 cm thick and of the order of 35 m high; vesicle elongations in this material are vertical. These massive walls are perpendicular to the layered flows and are interpreted as marginal crystallisation or spatter from a lava lake that filled the pit crater (Tunjic, 1988). The walls of the south-eastern end of the crater are composed of spatter from a cone with layering dipping into the crater. Mt Eccles proper is marginal to the Lake Surprise crater and is the oldest feature of the complex, a cinder cone of interbedded lapilli tuff, some of which is welded, and layers of basaltic bombs and spatter. The features of Lake Surprise are best examined from the walk around the lake edge.

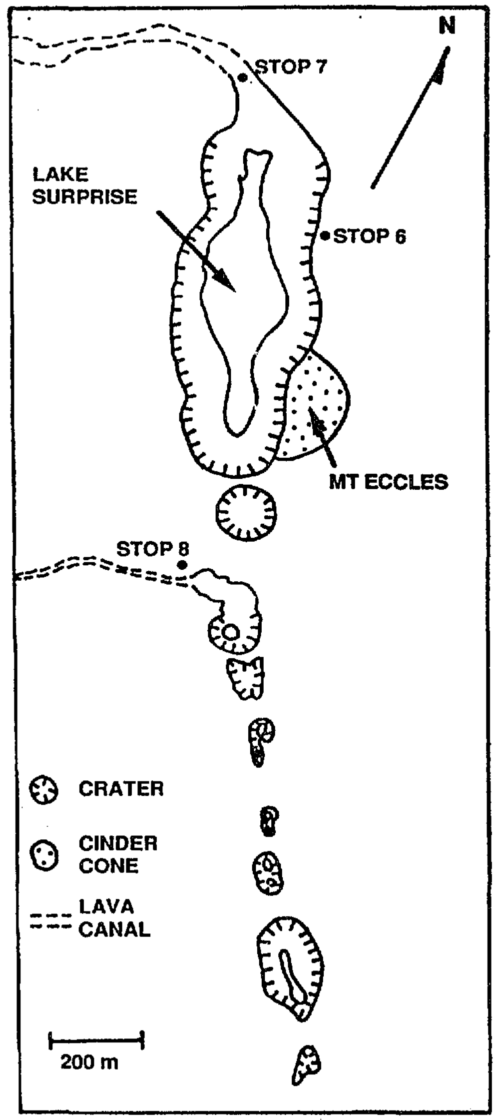

Fig. 3-4: Sketch map of the Mt Eccles volcanic complex (after Tunjic, 1988).

STOP 7: LAVA CANAL AND TUBE

The north-western end of Lake Surprise is the low point on the crater rim and the site at which lava escaped from the lava lake. The main lava canal has its origin 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 basalt apron around Mt Eccles 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 tube. Tunnel Cave is excellently preserved and has a triangular cross-section with lava levels and drain-back dribbles on its walls.

STOP 8: SPATTER CONE AND LAVA CANAL
(Portland WC811861)
The Mt Eccles fissure extends from the Lake Surprise crater in an alignment of spatter and cinder cones. The cones have heights of 10-30 m, diameters of 10-50 m, and are constructed from welded spatter (Tunjic, 1988). The first cone has a complex breached crater from which extends a leveed lava canal 800 m long, part of which is roofed as a 30 m-long lava tube (Natural Bridge). The spatter cones are composed of nepheline hawaiite (Tunjic, 1988) and are distinctly more alkalic than the major lava flows of the complex.

MOUNT ECCLES TO TOWER HILL 79 km
On leaving Mt Eccles, the margin of the basalt apron is visible to the west along the edge of the forest and is briefly crossed at the eastermost point of the apron. The route from Mt Eccles to Tower Hill is indirect and has been chosen to cross major lava flows from Mt Rouse at a point 30 km from the source (Figs 2-1, 3-1). The proximal equivalent of the flows was visited on the apron around Mt Rouse (Day 2, Stop 9), and the lavas extend a further 30 km to the coast at Port Fairy. The flows filled the ancient valleys of the Shaw and Moyne Rivers and vary in width from 200 m to 14 km (Ollier, 1985). The 'Shaw River flow' is crossed first where three branches pass around low basement positives which are isolated as 'islands' (geomorphologically referred to as steptoes). The lava flows are readily identified by their hummocky surfaces (stony rises) and abundance of outcrop. Following the burial of the ancient drainage new river channels were established as lateral streams on the margins of the flows, in this instance Carmichael Creek (west) and Back Creek (east). A further 5 km along the road the 'Moyne River flow' is crossed where it is 3 km wide and bounded on the western side by the modern Moyne River. This set of lava flows is a dramatic demonstration of how relatively minor volcanic sources may produce very extensive products. The great distance travelled by the flows was achieved on a surface with the very low gradient of 1 in 200 or 300 m in 60 km (Ollier, 1985). To extend over this great distance the lava must have travelled in lava tubes as suggested by the collapse features of the stony rises.

> If this is so, it was probably emplaced in a relatively short time, perhaps only days or weeks. The fluidity of the lava flows is further indicated by the apparent ease with which the lava divided into several different flows which re-united further downstream after they had flowed around obstacles. (Ollier, 1985)

We have now completed the examination of the three youngest volcanic centres of the Newer Volcanics which have associated major lava flows - Mts Rouse, Napier and Eccles. The next stage of the journey is routine travelling until, in the vicinity of the township of Kirkstall, the domical shape of Tower Hill is apparent to the south-east; the ridge is an unusually prominent rim to a maar.

STOP 9: VIEW OF TOWER HILL MAAR AND CINDER CONES
(Warrnambool XC203578 Road on maar rim)
Tower Hill is morphologically the most striking of the Victorian maars because of the height and continuity of the rim deposits, the considerable diameter, and the central cinder cones which form islands in the lake (Fig. 3-5). It is a difficult subject for photography and Stop 9 has been chosen as the most suitable place. The lake is elliptical and 3 x 2 km in plan; plain elevation is 20-60 m ASL and the rim rises from 20 m in the south-west to 100 m on the north-east; the summit of the highest cinder cone is 70 m above lake level. The west-east asymmetry of the maar rim is typical of the subprovince and due to the prevailing wind direction during eruption. The cinder cones obviously postdate maar formation and are aligned along two north-north-west to south-south-east fissures, the south-western of which has 9 cones (Fig. 3-5). The ^{14}C age of Tower Hill is debated, but all data indicate an age of less than 20,000 BP.

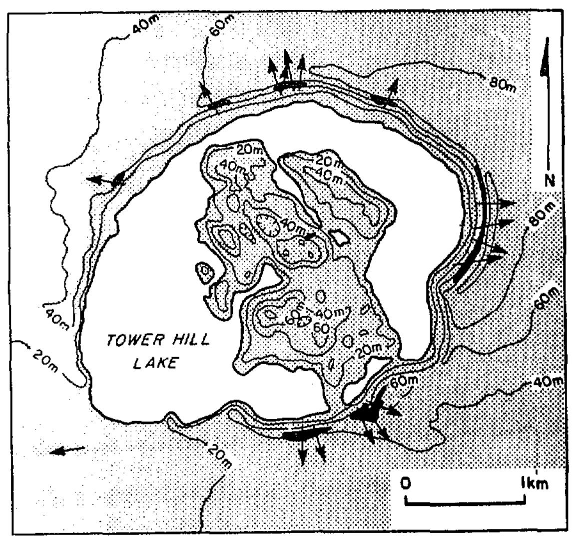

Fig. 3-5: Morphology of the Tower Hill volcanic complex (from Cas and Wright, 1987). Solid black areas are quarries and arrows indicate palaeocurrent directions.

STOP 10: ABANDONED CRB QUARRY IN MAAR RIM
(Warrnambool XC195568 Entrance road to reserve immediately inside gate)
The quarry provides an excellent vertical section through the bedded tuff of the maar rim (Fig. 4-1). The pyroclastics are extremely well-bedded and vary considerably in the proportion of basaltic to limestone debris; the limestone is derived from the underlying Tertiary sequence. Some phases of the eruption were dominantly magmatic, producing cinder-rich horizons and occasionally bombs and blocks. Phreatomagmatic deposits are finer grained and paler coloured due to the contained limestone. Their mechanism of eruption varied from air-fall to base surge as indicated by directional structures. Bomb sags contain blocks of both basalt and limestone.

STOP 11: TOWER HILL RESERVE AND VISITORS CENTRE
This last stop for the day has a variety of activities. A walk to the summit of the highest cinder cone passes a deep crater and gives an excellent internal view of the maar and adjacent coast line. The Visitors Centre has a display on the natural history and regeneration of Tower Hill. The Game Reserve is for native animals. Emus roam the lawn around the Visitors Centre; koalas are said to be common, but usually require a careful search; kangaroos and wallabies are unpredictable in their appearance. Go to it. For those still inclined to geology a visit to a quarry in one of the cinder cones is a more mature pursuit and also a pleasant bush walk past a bird hide.

TOWER HILL TO WARRNAMBOOL 13 km
Tuff derived from Tower Hill blankets the low ground to Warrnambool. On the south side of the highway the ridges are composed of Pleistocene dune limestone (aeolianite) with characteristic large scale aeolian cross-beds.

DAY 4:
WARRNAMBOOL-CAMPERDOWN-WARRNAMBOOL - YOUNG ALKALIC CENTRES OF THE CAMPERDOWN DISTRICT

Topics: Several lherzolite localities; composite maar and cinder cone centres of Mts Noorat and Leura, and Red Rock; detailed examination of maar rim deposits; young stony rise aprons.

WARRNAMBOOL TO NOORAT 62 km
The first stages of the journey cross some of the richest pastoral country in Victoria with the advantages of a basalt-derived soil and substantial rainfall. The road is initially the Princes Highway (Highway 1), the near-coastal route around the continent. A brief tourist digression to Hopkins Falls sets the scene. The waterfall is typical of many on the basalt plains, cascading over an eroded vertical face defined by columnar jointing in a lava flow. Two adjoining maars are passed to the east of the falls before rejoining the highway. The prominent volcano immediately to the north of the Princes Highway is Mt Warrnambool, a nepheline hawaiite cinder cone centred in a maar. The town of Terang is situated on the rim of a maar, the depression visible to the south.

STOP 1: MOUNT NOORAT
(Mortlake XC685724 - permission required for entry)
Mt Noorat is a complex volcano with cinder cones superimposed on, and almost burying a maar. There is no modern description of the volcano, but the basalt itself is a nepheline hawaiite (nepheline basanite according to Irving and Green, 1976). It is a renowned lherzolite locality, the inclusions occurring as either distinct rounded fragments with a thin rind of basalt, or cores to spindle bombs, which are a distinctive feature of the deposit. The inclusion population is dominated by spinel lherzolite, but biotite lherzolite, wehrlite, garnet wehrlite, and websterite are also noted. Megacrysts reported are clinopyroxene and anorthoclase (abundant), and orthopyroxene and ferrokaersutite (rare) (Irving, 1974b). Unfortunately,

fresh exposure,while representative, is very limited as of writing, and Mt Noorat is primarily of interest to the keen lherzolite fancier.

NOORAT TO CAMPERDOWN 27 km

The region ahead is a pleasant landscape of basalt plain studded by numerous isolated volcanic peaks, with its lakes filling the craters of maars or dammed behind lava flows. The plains basalts are hawaiites or transitional hawaiites which form the most extensive area of mildly alkalic rocks in the subprovince. Basalt outcrop is limited given the youth of the volcanoes, in part due to tuff blankets around the many maars. The area is distinctive in several ways: volcanic cones are at their highest density in the subprovince; all cones are distinctly more alkalic than the plains rocks; lherzolite occurrences are at their most frequent; and maars are at their most abundant. Our Warrnambool to Camperdown route lies within the southern boundary zone of the Newer Volcanics adjacent to the Colac Lineament and this entire strip is considered to be geologically controlled by that boundary. In addition, Camperdown marks the intersection between the southern bounding fault and the Mortlake discontinuity (Fig. I-1). The unique aspects of the volcanism are believed to be directly related to the unique tectonic setting such that alkalic volcanism has been favoured by major faults that penetrate the lithosphere.

STOP 2: LAKE GNOTUK MAAR
(Corangamite XC830659)

Stop 2 is located close to the crest of the rim around Lake Gnotuk maar and is a vantage point for panoramic photography. The twin maar craters of Lakes Gnotuk and Bullenmerri have walls predominantly of tuff, though the prominent outcrop around the wall of Lake Gnotuk and part of Lake Bullenmerri is a basalt lava flow. Planar-bedded tuff dipping outward from the crater is visible in the road cutting.

STOP 3: LAKE BULLENMERRI MAAR
(Corangamite XC850650)

The basal layers of the sequence in the maar rim outcrop at the lake edge and comprise bedded tuff and volcanic breccia that dip inward at 30-50^{o}. They contain abundant ultramafic inclusions up to 30 cm in diameter and large blocks of gabbro and basalt. The inclusion population is unique in the province because of the abundance of garnet-bearing lithologies, and has been intensively collected and studied by Hollis (1981), Griffin et al. (1984), O'Reilly and Griffin (1987) and Griffin et al. (1987). The following is a condensation of the abstracts of the last three papers.

> The basanite tuffs enclose abundant xenoliths of spinel lherzolites, many of which contain amphibole±apatite±phlogopite, as well as cumulate wehrlites, spinel metapyroxenites and garnet metapyroxenites. All xenolith types contain abundant large CO_2-rich fluid inclusions. Microstructural evidence for the exsolution of spinel, orthopyroxene, garnet and rare plagioclase from complex clinopyroxenes suggests that all of the metapyroxenites have formed from clinopyroxene cumulates by exsolution and recrystallisation during cooling to the ambient geotherm. Pyroxene chemistry implies that a range of parental magma types was involved. Garnet pyroxenites show a series of reactions to successively finer-grained, lower-P mineral assemblages, which imply a relatively slow

> initial upward transport of the xenoliths in the magma, prior to explosive eruption. The same process has allowed crystallisation of phenocrysts from small patches of interstitial melt within xenoliths of lherzolite, wehrlite and metapyroxenite. Cr-diopside spinel lherzolite xenoliths show metasomatic introduction of amphibole ±mica±apatite at the expense of primary pyroxenes+spinel, accompanied by enrichments in Sr, LREE and other incompatible elements. The metasomatism can be related to fluids emanating from crystallising basaltic magmas now represented by dykes of pyroxenite. Abundant garnet and spinel metapyroxenites are products of an older magmatic episode; igneous-textured wehrlite series xenoliths represent a younger episode.

<u>STOP 4</u>: MOUNT LEURA LOOKOUT
(Corangamite XC887647)
The view from Mt Leura encapsulates the southern section of the plains subprovince and displays much of the route taken today. Over twenty volcanic centres of cinder cone or maar type are visible. From west to east the sites visited by this excursion are Lake Bullenmerri, Lake Gnotuk, Mt Noorat, Mt Shadwell (Day 2, Stops 4-5), Mt Elephant (Day 2, Stops 1-3), Lake Purrumbete and Red Rock- Warrion Hill. Most of the lakes are the result of blocking of streams by the products of eruptions thereby producing an internal drainage. The large lake to the east and north-east is Lake Corangamite. Basement to the volcanic province is exposed in the far distance.

The Mt Leura complex can be traced out from the lookout. The oldest structure is a circular maar 2.5 km in diameter, the tuff rim of which is visible to the north as the slightly elevated surface adjacent to the highway; Stop 5 is located in the quarry there. Several cinder cones are superimposed upon the maar. The lookout is situated on the rim of the largest cone, with its deep crater to the south-west. The crater rim varies considerably in altitude, and is highest on its north-east (Mt Leura lookout) and western (Mt Sugarloaf) sides, probably due to directional lava fountaining (Joyce, CBVWV). Stop 6 is positioned in a quarry on the flank of the main cinder cone, south-east of the lookout.

<u>STOP 5</u>: MOUNT LEURA - QUARRY IN TUFF RING
(Corangamite XC892651 - permission required for entry)
A stratigraphic section of the tuff ring is given in Figure 4-1 and is illustrated in Cas and Wright (1988). The thinly bedded deposit is mainly a pale-coloured lapilli tuff and dips into, and out of, the crater. The upper parts of the sequence are distinctly darker in colour due to a high proportion of basalt fragments. The change in character up-section is equated with a change in eruptive mechanism from phreatomagmatic to strombolian. The following description of the lapilli tuff is taken from Edney and Nicholls (CBVWV).

> The deposits making up the tuff ring are dominated by cross bedded lapilli units which in general pinch and swell markedly and are of base surge origin. The degree of development of cross stratification varies greatly from unit to unit, ranging from forward climbing dune bedforms to highly truncated planar trough cross-sets. ...... Air-fall deposits make up only a minor part of the tuff ring stratigraphy. They are relatively thin deposits of massive ash or diffusely bedded lapilli. The massive air-fall ash deposits often occur mantling cross-bedded lapilli units and as such may be the result of elutriation of fines out of

moving base surge clouds. Accretionary lapilli are almost solely restricted to finer grained air-fall units. The diffusely bedded lapilli air-fall deposits, on the other hand, show no mantling relationship with cross-bedded units and seem to have been deposited during surtseyan-type eruptions with only minor associated surge development, and are discrete units in themselves.

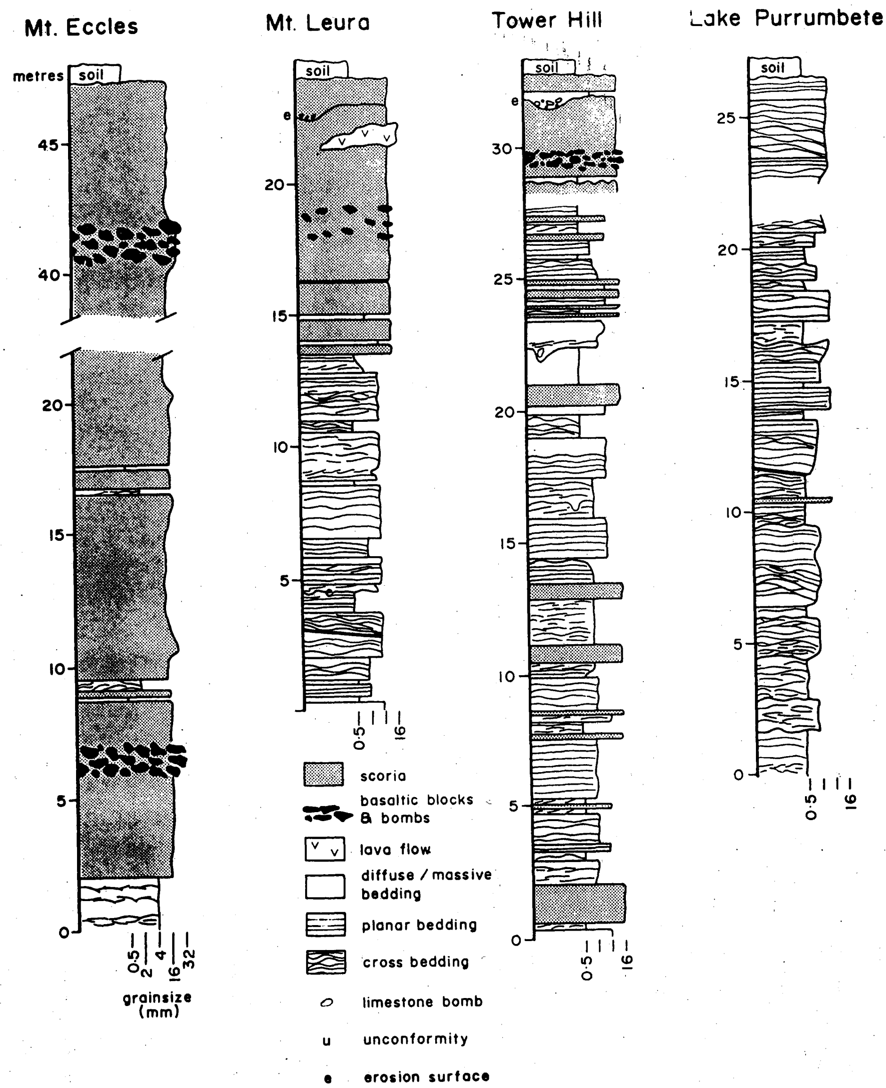

Fig. 4-1: Stratigraphic sections in four centres of the Newer Volcanics (from Cas and Wright, 1988)

STOP 6: MOUNT LEURA - QUARRY IN CINDER CONE
(Corangamite XC892644 - permission required for entry)
The cinder cone at Mt Leura is renowned for xenoliths and megacrysts which have been described in numerous papers. The quarry geology is undistinguished. The host basalt is a nepheline hawaiite (nepheline basanite of Irving and Green, 1976 - Anal 4-1). The most abundant inclusions are spinel lherzolite; reported proportions of other rarer lithologies vary (Irving, 1974a; Ellis, 1976), but the lithologies are wehrlite, plagioclase pyroxenite, dunite, websterite, garnet websterite, clinopyroxenite,

and hornblendite. Anorthoclase and clinopyroxene megacrysts are common, with ilmenite rare.

CAMPERDOWN TO LAKE PURRUMBETE 14 km

Lake Purrumbete is approached from the west and our initial view is eastward across low country to the lake itself, and then beyond to the ridge of tuff on the far side. Hence the tuff ring is decidedly asymmetric and is effectively a crescent-shaped ridge along the eastern side of the lake. The asymmetry is found in other maars in the district and also in dune deposits associated with lakes of non-volcanic origin; it is attributed to transportation of the tuff particles by the prevailing westerly wind.

STOP 7: LAKE PURRUMBETE MAAR - RIM QUARRY
(Corangamite XC963598)

The quarry section cut into the tuff rim deposits of the maar (Fig. 4-1) provides the most comprehensive display of sedimentary structures in the province. The tuff dips gently away from the lake at 3-4^{o} and is fawn-coloured, fine grained and well bedded. Sedimentary structures ascribed to a base surge origin are antidunes, climbing dunes, planar laminations, and low angle truncations.

LAKE PURRUMBETE TO RED ROCK LOOKOUT 42 km

Adjacent to Lake Purrumbete, the road enters the environs of the Mt Porndon volcanic centre. The conical nepheline hawaiite cinder cone is a regional landmark and is superimposed on an extensive basaltic apron of transitional hawaiites ~13 km in diameter. At the edge of the apron flow fronts and stony rises are well exposed. Close to Mt Porndon a very well-preserved flow front is exposed by the road side and has a steep face (~10 m high) weathering into large angular blocks. The front has the blocky appearance of an aa flow, but this interpretation is questioned by Joyce (CBVWV) who notes that many surfaces are made of interlocking blocks rather than rubble. Stonyford is one of the better places to view stony rise terrain because the cleared parts give an impression of the primary volcanic surface. Locally the land surface is so irregular that the original forest is preserved and the difficulty of the topographic barrier that confronted the early settlers is very evident. Road cuttings section the 'rises' of the flows exposing a massive interior of crudely columnar jointed basalt. The Princes Highway is followed to the outskirts of the town of Colac, then a northward leg crosses an extensive hawaiite field that separates Lakes Corangamite (west) and Colac (east). The hills to the north are the objective, the Red Rock-Warrion Hill complex.

STOP 8: RED ROCK LOOKOUT
(Colac YC193632)

The Red Rock lookout provides a dramatic view of a compound volcanic centre with numerous volcanic and geomorphological features on display. Geographically, Camperdown is located 32 km due west at the foot of Mt Leura; Colac is the town 12 km to the south-east. The major lake to the west is Lake Corangamite and that to the south-east is Lake Colac, both of which

formed in response to lava flows blocking drainages. The plain surface is entirely constructed from basaltic lava flows. Lake Purrumbete maar is visible to the south-west, and the cinder cone slightly further south is Mt Porndon. There are four main components to the Red Rock-Warrion Hill complex -
(a) a crudely circular apron of stony rise basalt lava flows approximately 12 km in diameter which is best seen on the low country between Red Rock and Lake Corangamite.
(b) the maars of Lakes Coragulac, Perdiguluc and Gnalinegurk to the east and south of Red Rock.
(c) the relatively small cinder cones of Red Rock and Alvie.
(d) the large cinder cone of Warrion Hill to the north.

Morphologically, the complex is obviously very young and the estimate of its age is 7810±115 BP by ^{14}C on soil carbonate within the volcanics (Gill, 1978).

STOP 9: LAKE PERDIGULUC MAAR - RIM QUARRY
(Corangamite YC187615 - permission required for entry)
The quarry on the south side of Lake Pudiguluc maar provides two excellent sections of the maar rim deposits. The access road to the quarry cuts perpendicularly through the low ridge of tuff and exposes current bedding in profile. The quarry face itself is excavated parallel to the maar rim and has a very varied stratigraphy. The deposits include airfall tuff, base surge, and cinder horizons. Large, isolated, ballistic blocks of basalt in a fine grained host, and bomb sags are distinctive features.

RED ROCK TO WARRNAMBOOL
Subject to the time available, the return journey to Warrnambool will roam informally westward, mainly along minor roads, to provide brief views of additional volcanic features.

PART II: THE OTWAY BASIN

BACKGROUND

Regional Setting

The Otway Basin is one of a series of major east-west trending sedimentary basins along the southern passive margin of Australia. The development of the basin has been most recently reviewed by Magallaa (1986) and Williamson et al. (1987). It was initiated at the very end of the Jurassic, probably as part of a single continuous rift system across the southern part of Australia. The basin covers about 18,500 km^2 onshore with another 26,000 km^2 offshore in Victoria, and continues westwards into South Australia over a total length of 500km. The basin averages about 200 km in width.

The northern boundary of the basin is almost entirely obscured by the thin cover of the Newer Basaltic Province but much of the basin sequence is spectacularly exposed along the south-west coastline of Victoria. The southern side of the basin forms the current continental shelf along much of this section of the Australian coast and is bounded to the south by oceanic crust. At its eastern end however, the basin is surrounded by older continental crust and terminates against a basement high which joins the Mornington Peninsula and King Island in Bass Strait.

The major tectonic elements of the Otway Basin and its regional setting are shown in Figure II-1. The onshore part of the Tertiary basin is divided into a series of sub-basins or embayments separated from each other by basement ridges or structural highs. The excursion will travel across the eastern part of the basin, from west to east over the Warrnambool High, the Port Campbell Embayment, the Otway Ranges High and the Torquay Sub-basin. Offshore the basin is divided into two major tectonic elements, the Mussel Platform and the larger Voluta Trough which extends from the shelf-break to a water depth of about 4000m.

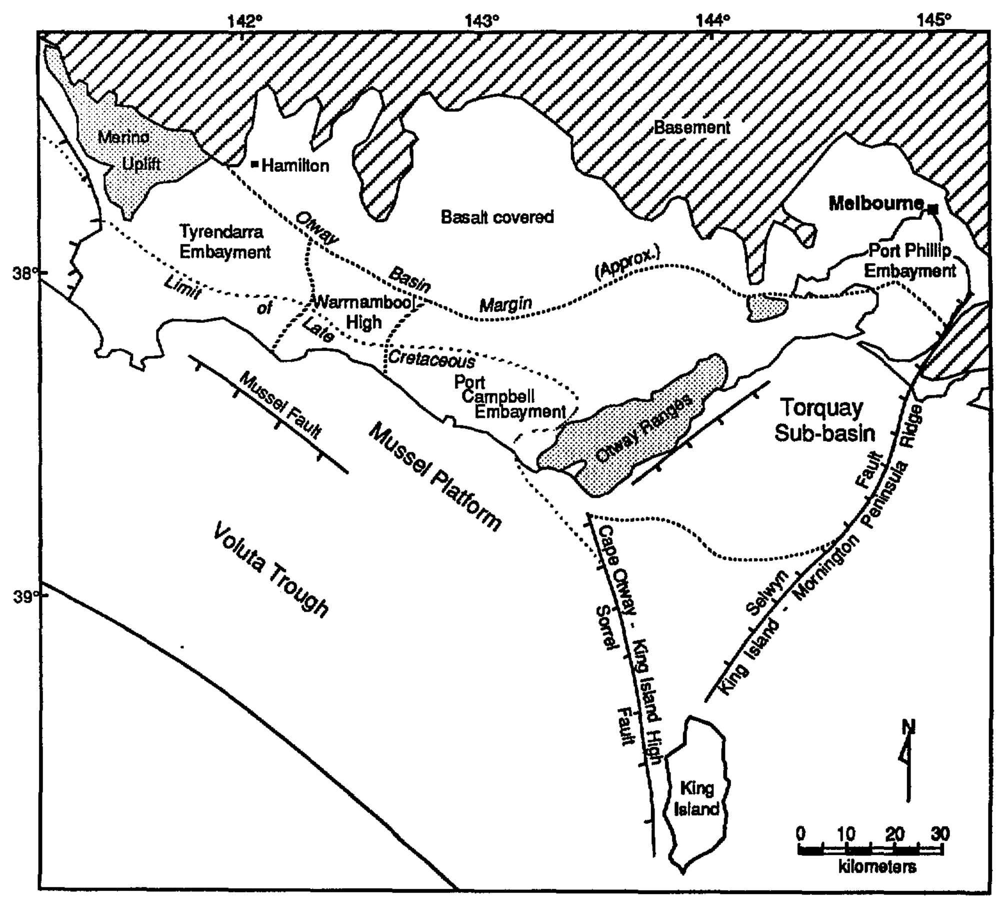

Fig. II-1: Regional setting and major tectonic elements of the Otway Basin in southern Victoria.

Tectonic and structural development

The sedimentary fill of the Otway Basin reaches a maximum thickness of about 10 km in the offshore region. The major structures in this area are controlled by NW-SE trending normal faults, downthrown towards the oceanic side, which displace landward dipping Cretaceous sediments formed during the rift phase of sedimentation. North to south seismic sections indicate that these major faults were extensional and rotational in character producing landward dipping fault blocks with syndepositional wedges stepping down towards the south. The overall pattern of Early Cretaceous rifting in the Otway Basin and its relationship to the Bass and Gippsland Basins to the east is shown diagrammatically in Figure II-2 based on the extensional model of Etheridge et al. (1984).

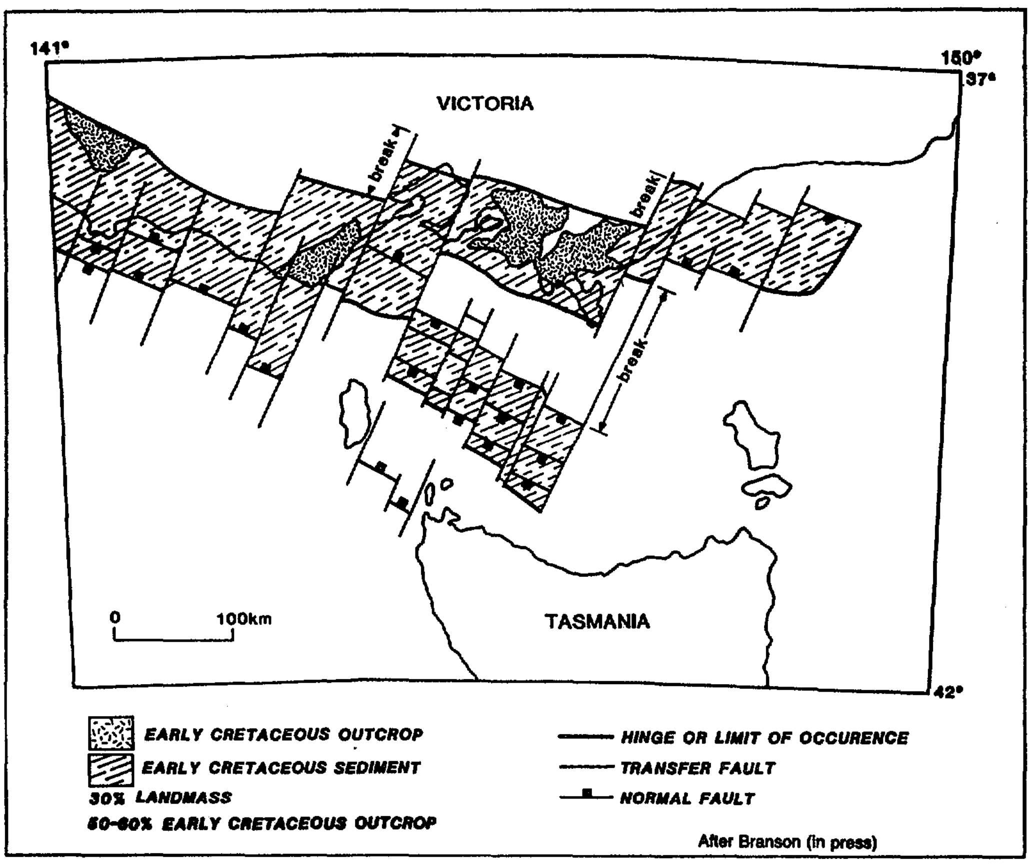

Fig. II-2: Schematic map of the Early Cretaceous extensional basins across Bass Strait (from Megallaa, 1986, after Branson et al. in press)

Rapid tectonic subsidence associated with rifting took place throughout the Early Cretaceous during which time more than 3000 m of non-marine, mostly fluviatile sediments of the Otway Group were deposited. This rift phase continued until about 90 Ma when there was a major re-organisation of the basin associated with the beginning of slow sea-floor spreading to the south (Cande and Mutter 1982). Uplift associated with this event abruptly ended the syn-rift Otway Group sedimentation and began the regional differentiation of the basin into a series of highs and intervening embayments. Compression at this time produced a number of broad open folds and fault blocks plunging to the south. Uplift of the Otway Ranges High cut-off the Torquay sub-basin to the east and the King Island-Mornington Peninsula Ridge divided the Otway from the Bass and Gippsland Basins.

An angular unconformity separates the Lower Cretaceous Otway Group from the overlying Upper Cretaceous sediments which were formed during a period of much slower tectonic subsidence. The Late Cretaceous is characterised by a sequence of transgressive-regressive clastic sediments of the Sherbrook Group which show the first marine influence in the basin. The Upper Cretaceous sediments were deposited in shallow marine to marginal environments and their thickness increases rapidly offshore to a maximum of about 6000 m The Sherbrook Group is relatively thin in the eastern part of the basin and pinches out towards the Lower Cretaceous sediments on the Otway Ranges high. It does not outcrop in the excursion area where the Lower Cretaceous is overlain directly by Tertiary strata.

The Tertiary is characterised by marine sediments representing another two transgressive-regressive depositional cycles. Together these reach a thickness of 1000 to 2000 m on the continental shelf which reflects the waning rates of tectonic subsidence and deposition during the drift phase. Within the Tertiary sequence there is an Eocene unconformity which probably corresponds to the beginning of rapid sea-floor spreading at about 45 Ma and separates older terrigenous sediments of the Wangerrip Group from younger carbonates of the Nirranda and Heytesbury Groups. The more minor Nirranda Group does not outcrop and is known only from subsurface intersections in the Port Campbell Embayment.

Since Miocene times there has been continued carbonate sedimentation offshore on the continental shelf with minor continental sedimentation in parts of the onshore basin and along the coast. The northern part of the basin has been progressively covered by the Newer Volcanic field.

The major structural features present in the eastern part of the Otway Basin are shown in Figure II-3. The major pattern of NW-SE trending extensional faults was established early in the basin evolution and controlled the pattern of sedimentation throughout the Cretaceous. Broad NE-SW trending folds were initiated during the mid Cretaceous movements and have been re-activated to varying degrees by renewed compression in a NW direction during the Tertiary.

Stratigraphy

The stratigraphy of the Otway Basin is summarised in Fig. II-4. Only the Lower Cretaceous Otway Group and the Tertiary Wangerrip and Heytesbury Groups will be considered here as they are the only ones to outcrop in the excursion area.

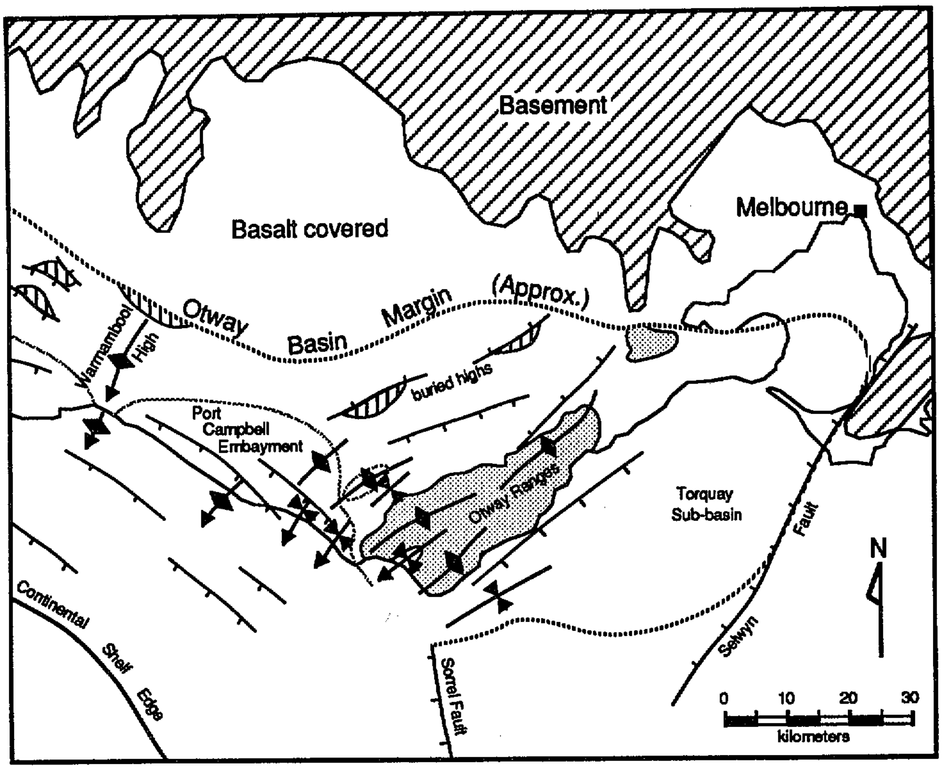

Fig. II-3: Major structures within the eastern part of the Otway Basin

Lower Cretaceous

Sedimentation in the Otway Basin was controlled by the tectonic evolution of the basin. During the Early Cretaceous rift phase more than 3000 m of non-marine sediments known as the Otway Group were deposited in the rapidly subsiding rift zone across southern Victoria. The thick sheet of Otway Group sediments occurs across the whole of the basin area and can be seen in outcrop in two areas (Fig. II-1), the Merino Uplift in the far-west of Victoria and particularly in the Otway Ranges High. The sequence is remarkably uniform both vertically and laterally across the basin, making any internal subdivision of the Otway Group difficult.

The sediments are mostly volcanogenic sandstones and mudstones with some carbonaceous sediments forming minor coaly horizons. Sedimentation rates were high (~120 m/Ma) and the sediments were deposited in fluviatile and lacustrine environments as part of a large braided stream system during a period of active volcanism. The volcanogenic sandstones occur as large massive channel fills interspersed with the finer grained sediments. The greatest thickness was deposited during Aptian-Albian time.

The sandstones contain from 50 to 90% volcanic material in the form of lithic and monomineralic clasts of mostly andesitic or dacitic derivation. The petrology, sedimentology and diagenesis of these sediments has been described in great detail by Duddy (1983). Much of the material was originally glassy and has been extensively altered during diagenesis to form a sequence of zeolite zones, the progressive nature of which can be clearly seen in subsurface well sequences. Early in the diagenesis the clasts become coated with skins of Fe-rich smectite clays later developing into extensive chloritic rims which impart a universal green colouration to the rocks when fresh. Pore spaces were progressively infilled by the zeolite mineral heulandite before extensive replacement by laumontite and albite which characterises most of the outcrop of the Otway Group. Another feature of the diagenetic alteration of the sediments is the widespread occurrence of early formed carbonate concretions which can preserve the primary mineralogy and structures of the rocks.

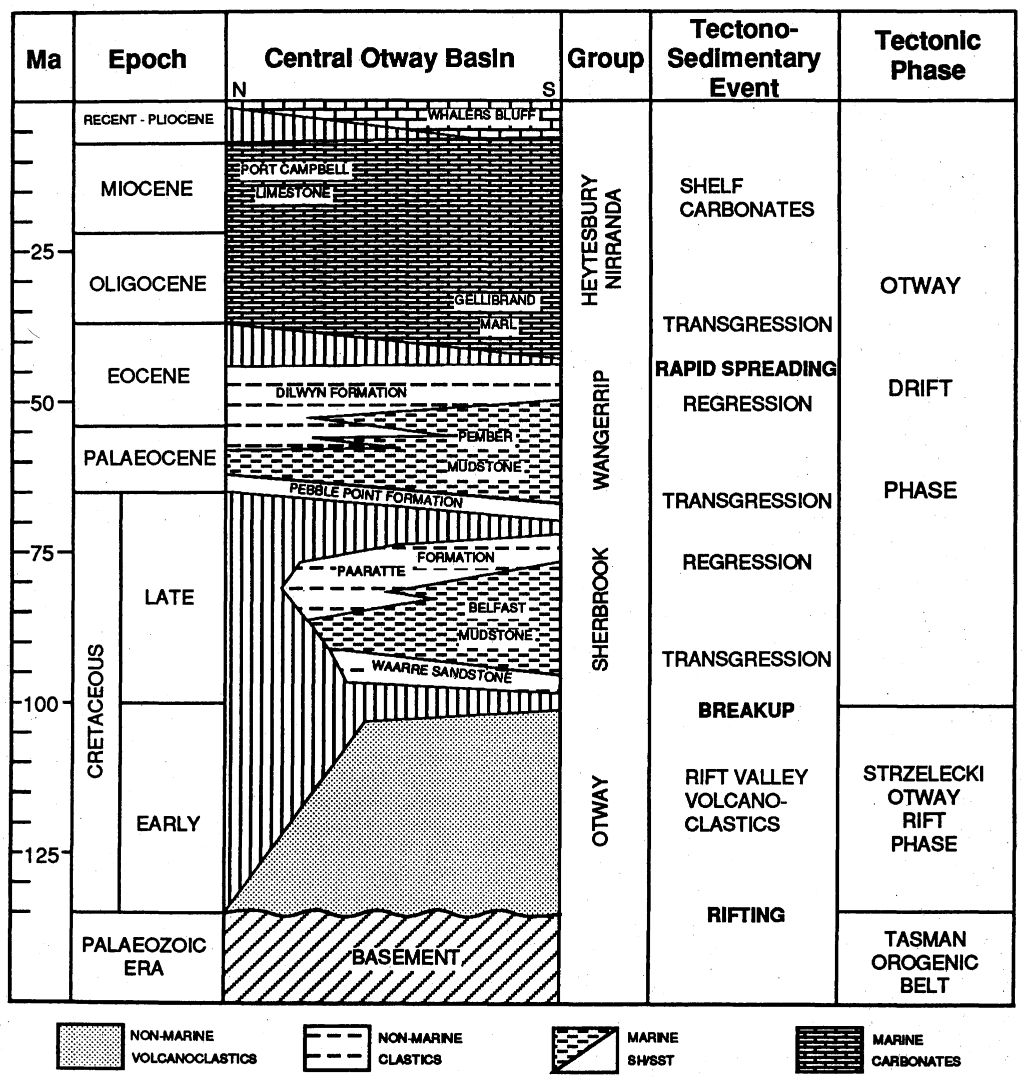

Fig. II-4: Generalised stratigraphy of the Otway Basin (after Holdgate et al., 1986)

The source of the volcanic detritus is not clear as no volcanic rocks of Cretaceous age are known in Victoria. Several alternative provenances have been suggested including derivation from extensive Upper Devonian acid volcanics in central Victoria, a contemporaneous magmatic arc to the east and volcanoes along the developing rift itself. The large volume of volcanogenic material deposited across the three Bass Strait basins (>100,000 km^3), however, requires a particularly abundant source of probably fragmental material. Despite this dominantly volcanogenic character, the Otway Group sediments contain no tuffaceous material or volcanic rocks within the sequence. The supply of volcanogenic detritus was cut off abruptly by the movements at the end of the Early Cretaceous and this material is absent from the later sediments in the basin.

In addition to the abundant volcanogenic detritus the Early Cretaceous sediments also contain minor amounts of normal terrigenous detritus, especially near the basin margins. This detritus was probably derived from the Palaeozoic and Proterozoic basement rocks on the northern and southern flanks of the basin, but its minor occurrence shows that most of the sediment was being transported along the rift system.

An important feature of the Otway Group sediments is that the basin was entirely within the Antarctic Circle during the Early Cretaceous. Palaeomagnetic evidence shows that this area would have remained at 75-80° South for most of the Cretaceous (Embleton, 1984). The rocks contain an abundant record of the plant life which existed at these polar latitudes during this time (Douglas 1986) and have recently yielded important dinosaur remains (Rich and Rich, 1988). The plant macrofossils and microfossils are used for correlation and subdivision within the monotonous Otway Group sequence. The distribution of some of the important polar dinosaur and plant fossil localities is shown in Figure II-5. The Otway Group and related sediments elsewhere in Victoria thus provide a remarkable opportunity to study the Cretaceous polar environment and the adaptation of life to the conditions which prevailed there.

Upper Cretaceous - Tertiary

The Upper Cretaceous to Lower Tertiary part of the Otway Basin consists of two major deltaic sequences formed during the initial opening phase of the Southern Ocean (Holdgate et al. 1986). Major subsidence occurred at this time due to post-rift cooling of the basement and flexure under the increasing sediment load of the Sherbrook and Wangerrip Groups.

The Late Cretaceous Sherbrook Group does not outcrop along the route of the excursion but was deposited unconformably over the Otway Group sediments as a thick deltaic sequence sourced mainly from the north and west of the basin. The base of the group is represented by the fluvio-deltaic sands of the Waarre Sandstone which occurs in depressions in the Otway Group terrain. This is conformably overlain by thick prodelta shales of the Belfast Mudstone which increases in thickness in the offshore areas to the south and is interfingered with the associated fluvio-deltaic sands and shales of the Paaratte Formation.

The second major deltaic cycle is represented by the Early Tertiary Wangerrip Formation which began during rising sea-levels in the Early to Middle Palaeocene resulting in transgression over the underlying Sherbrook Group and exposed Otway Group sediments. The transgressive phase is represented by a basal conglomeratic sandstone unit known as the Pebble Point Formation deposited mostly in a restricted shallow marine environment. Rapidly increasing water depths produced open marine conditions across much of the basin and the coastline became the site of a number of overlapping deltaic accumulations. A major prodelta sequence of fine-grained sediments, known as the Pember Mudstone, interfingers and grades up into a deltaic sandstones, siltstones and shale sequence, the Dilwyn Formation. A lignite-rich equivalent of the Dilwyn Formation was deposited as the Eastern View Formation in the Torquay sub-basin across the Otway Ranges High to the east.

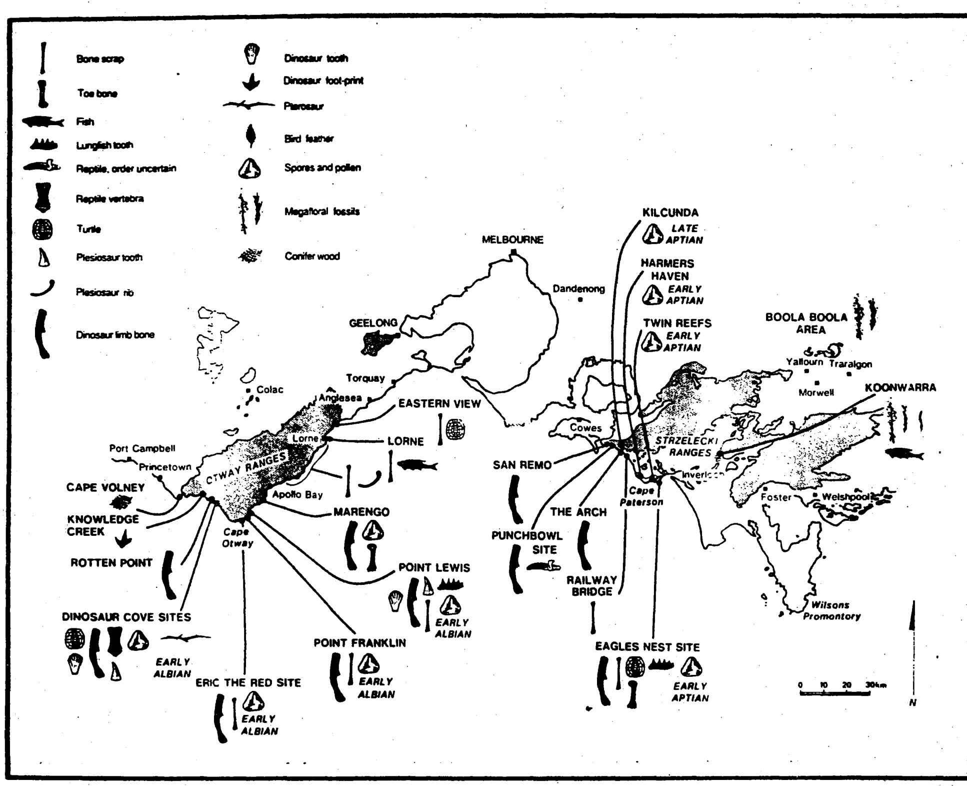

Fig. II-5: Early Cretaceous vertebrate and plant fossil localities in southern Victoria (after Rich and Rich, 1988

A regional unconformity separates the Wangerrip Group from the overlying transgressive sequences of the Nirranda and Heytesbury Groups which are an extensive suite of marls and shelf limestones deposited in an open marine environment. The unconformity was probably caused by a drop in sea-level and uplift of the Palaeozoic basement to the north. Subsidence slowed during this final sedimentary cycle and deposition is characterised by a relatively stable, slowly subsiding shelf environment with the carbonates prograding rapidly seawards. Open marine conditions prevailed with prolific growth of shelly organisms supplying most of the sediment. There was a relative absence of terrigenous detritus compared to the previous deltaic sequences. The finer grained carbonate sediments of the Gellibrand Marl were deposited in an inner to mid-shelf environment and pass vertically and laterally into the calcarenites of the Port Campbell Limestone deposited in a high energy shallow water environment. An equivalent carbonate sequence, the Torquay Group, was deposited in the Torquay sub-basin to the east. Along the southern coastline of Victoria the Port Campbell Limestone and the underlying Gellibrand Marl have been eroded to produce a number of spectacular coastal landforms which will be visited on the excursion.

Fission Track Thermochronology of the Otway Basin

Studies of detrital minerals from the Otway Basin have made a particularly significant contribution to the development of fission track thermochronology over the past ten years for a number of reasons:

- the uniformity of the Otway Group sediments across the basin and in depth throughout the Early Cretaceous section.
- the volcanogenic nature of the detritus so that apatites were deposited in the basin with essentially no inherited tracks.
- the abundance of detrital apatite (and other minerals) in the volcanogenic sandstones
- the availability of a large number of exploration wells intersecting the Early Cretaceous sediments.
- the existence of a well-controlled basin stratigraphy enabling detailed modelling of subsidence and thermal histories.
- the accessibility of suitable rocks around the basin margins for examining the regional context within which basin development occurred.

Basement Thermochronology on the Basin Margins

Fission track dating of basement granitic rocks along the northern margin of the Otway Basin in Western Victoria has been reported by Gleadow and Lovering (1978a) and from King Island on the southern margin by Gleadow and Lovering (1978b). Sphene ages in Western Victoria are generally concordant with known independent ages for the Palaeozoic rocks. However in both areas apatite apparent ages are invariably much younger than the emplacement ages reflecting a prolonged cooling history. On both basin margins the youngest apparent ages are broadly Early Cretaceous suggesting a significant thermal disturbance or rapid denudational cooling during the early stages of rifting and basin formation.

In western Victoria, the oldest apparent ages are about 340 Ma and the youngest 125 Ma, although none of the granitic plutons are younger than about 360 Ma. More recent work on the track length distributions and the apparent apatite ages are shown in Fig II-6 for this area. There is an obvious decrease in apparent age along the southern edge of the basement outcrops and an increasing breadth and bimodality in the length distributions as the basin is approached from the north. The youngest apatite ages occur in the Lismore area which is only about 10 km from the basin margin as defined by the limit of thick Early Cretaceous sedimentation (Fig. II-1). On King Island (Fig II-7) a pattern of severe resetting of apatite ages is apparent with the youngest ages of 110-130 Ma having narrow unimodal length distributions close to volcanic type patterns.

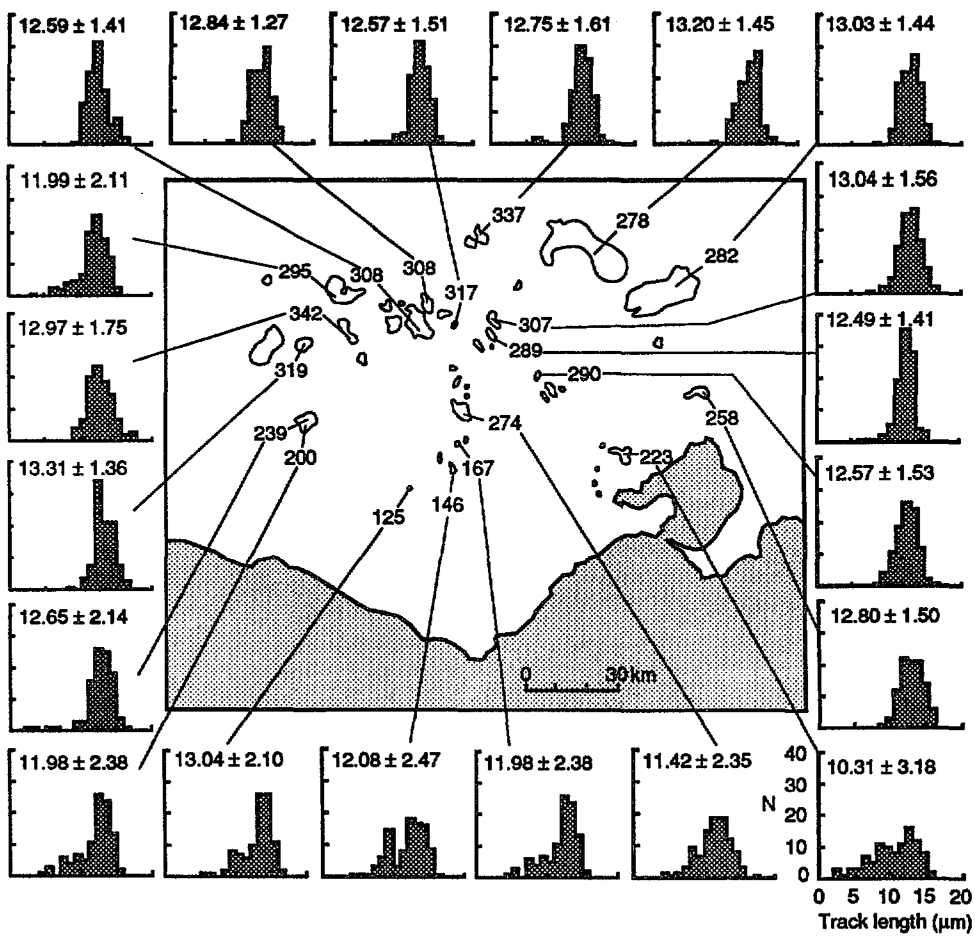

Fig II-6: Distribution of fission track ages and confined track length distributions for apatites from granitic rocks in the Palaeozoic basement of western victoria. The granitic plutons are shown in outline. Apatite ages are in Ma and track lengths are in µm.

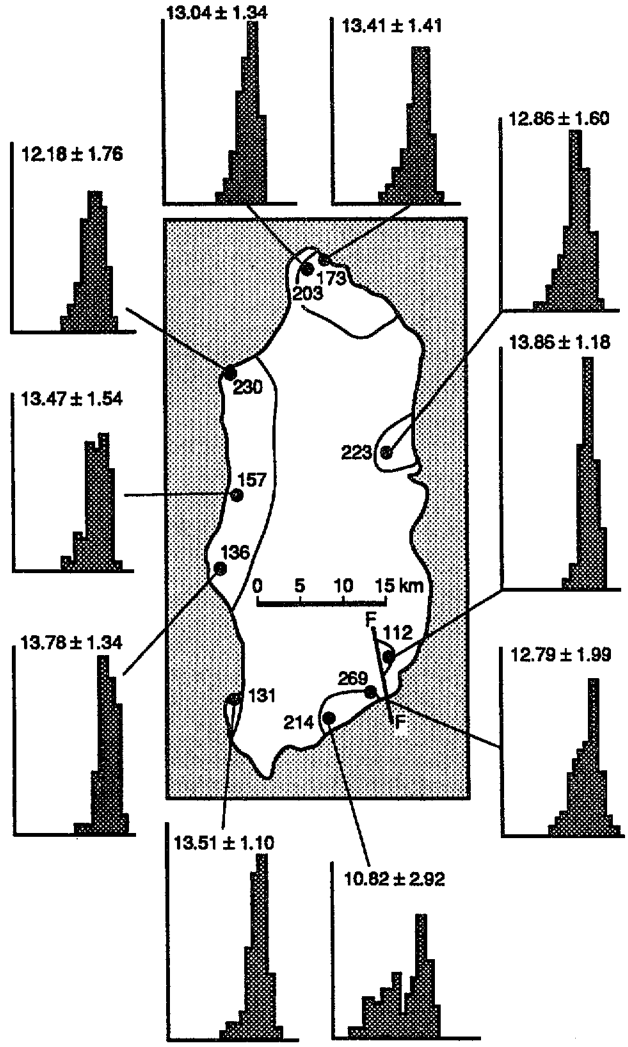

Fig II-7: Apatite fission track ages and confined track length distributions for granitic rocks from King Island in Bass Strait. Apatite ages are in Ma and the length distributions are in microscope scale bar units of 0.934 µm. Mean lengths and standard deviations are shown on each histogram in µm.

Provenance of the Otway Group

The Provenance of the Otway Group volcanogenic sediments has been discussed by Gleadow and Duddy (1981a) and Gleadow et al. (1983). Concordant fission track ages on apatite, sphene and some zircons range between 100 and 125 Ma, broadly matching the stratigraphic ages of the sediments determined on palaeontological grounds. These results show clearly that the volcanogenic detritus was derived from a contemporaneous volcanic source and not as some have suggested from an older Devonian volcanic source. Some older Palaeozoic zircon ages are also preserved, reflecting the minor amounts of basement derived detritus which is mixed with volcanogenic material in the Otway Group, especially towards the basin margins. The location of this contemporaneous volcanic source is still not clear. Gleadow and Duddy (1981) argued that the volcanics may have originated along the developing rift itself based on the apparent freshness of the volcanolithic clasts when first deposited and the distribution of volcanogenic sediment in the whole Bassian rift system.

However the intermediate compositions of most of the original volcanic rocks fragments (andesites to dacites) and the complete absence of any air-fall tuffs in the basin argue for a more distant source. Jones and Veevers (1983) has suggested that this might be a magmatic arc on the convergent plate boundary to the east.

Well Profiles in the Otway Basin

A number of papers have described the natural annealing effects observed in apatites from the Otway Group in deep drillhole samples in the central part of the Otway Basin (Gleadow and Duddy, 1981b; Gleadow et al. 1983; Gleadow et al. 1986a; Green et al. 1989). These studies have concentrated on a group of wells from areas of the basin with thick Late Cretaceous and Tertiary sedimentation. For such wells, thermal modelling shows that the temperatures should now be at a maximum and that this conclusion is insensitive to higher heat flow which probably occurred during the Early Cretaceous rift phase. Two of these reference wells, Flaxmans#1 and Port Campbell#4 occur within the Port Campbell Embayment. Fig II-8 shows the distribution of apparent apatite ages and mean confined track lengths with corrected downhole temperature in these reference wells. Other wells in areas which have not experienced as much later burial have shown the effects of rapid cooling during uplift at the close of the Early Cretaceous around 95 Ma ago. Two examples are the Fergusons Hill#1 well, drilled on a broad domal structure north of the Gellibrand River mouth, and the Olangolah#1 well drilled on the crest of the Otway Ranges High near Beech Forest.

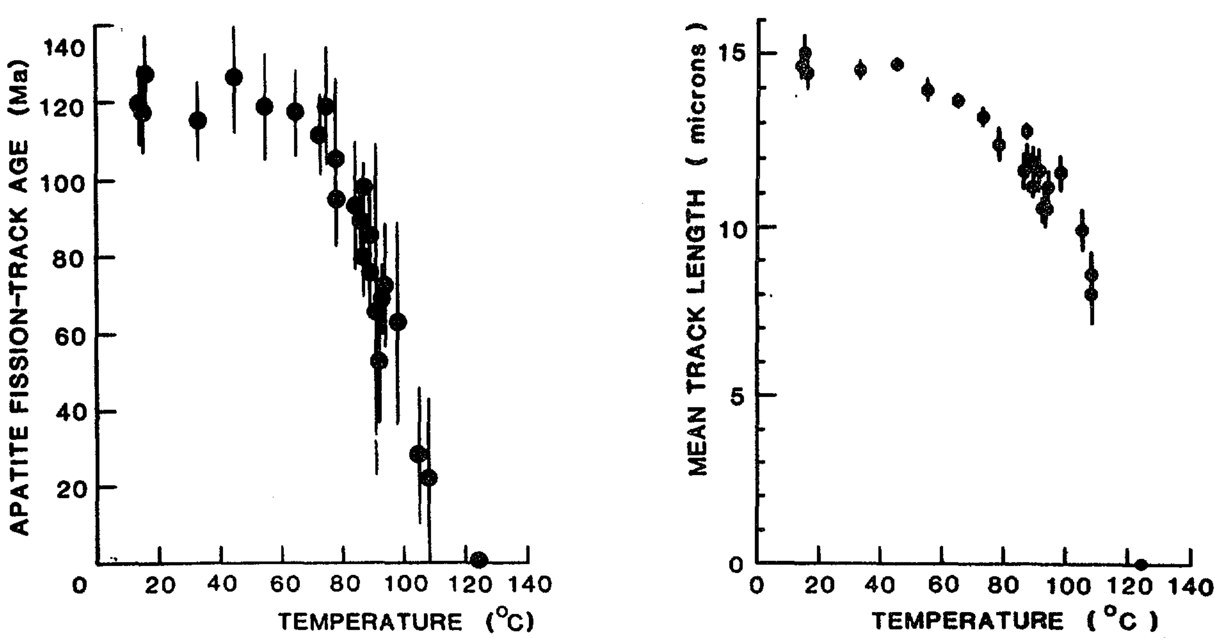

Fig II-8: Variation of Apparent fission track age (left) and mean confined track length (right) in apatites from the Otway Group against corrected downhole temperature for four selected wells in the Otway Basin. Error bars are shown as 2σ.

Studies on Otway Basin well sequences have also given insights into other aspects of fission track annealing and showed for the first time that apatite composition has an influence on its fission track annealing properties. These studies also provided the first evidence that the most important compositional factor was probably the concentration of the halogen anions Chlorine and Fluorine in the apatite molecule. The Otway Group apatites have an unusually wide spread of apatite compositions so that the slight variations in annealing rates leads to an much greater spread of single grain ages than would be expected purely from statistical variations. This slight variability of annealing properties also has a characteristic effect on the track length distributions.

EXCURSION ITINERARY
DAYS 5-6, SEPTEMBER 21-22, 1990

DAY 5:
WARRNAMBOOL TO PETERBOROUGH - A STRATIGRAPHIC TRAVERSE THROUGH THE OTWAY BASIN

Topics: Tertiary stratigraphy of the Otway Basin - the Heytesbury and Wangerrip Groups; petroleum exploration wells of the Port Campbell Embayment; coastal geomorphology of the Port Campbell Coast; regional subdivisions of the Otway Basin; sediments of the Moonlight Head Member of the Otway Group; the Johanna Syncline and structures in the Otway Ranges High.

WARRNAMBOOL TO PETERBOROUGH 51 km

The route follows the Princess Highway east from Warrnambool and then southeastwards to connect with the Great Ocean Road which will follow some of the most spectacular coastal scenery in Australia over the next two days. In Warrnambool itself local cuttings expose strongly cross-bedded Pleistocene dune deposits assigned to the Bridgewater Formation and persisting for some distance eastwards along the coast. The Princess Highway initially travels closely along the southern margin of the Newer Volcanics Province with basalt plains to the north and the Tertiary Heytesbury Group to the south. The route then follows the relatively flat coastal plain of the Otway Basin towards the southeast, firstly across the flat lying shelf carbonates of the Port Campbell Limestone and then over minor Pliocene sediments of the Parilla Sands. The terrain is rather featureless and few outcrops are seen except where the plain is youthfully dissected by the valleys of the Hopkins, Curdies and Gellibrand Rivers and their tributaries. To the south of Nirranda a low hill may be seen which defines a slight domal feature on which the Flaxmans#1 petroleum exploration well was drilled.

From the Peterborough area to Princetown the coastal plain ends abruptly and spectacularly in the vertical cliffs of the famous Port Campbell coastline. Driving eastwards on the Great Ocean Road these cliffs may be seen for the first time near the Bay of Islands about 5 km west of the coastal town of

Peterborough. Continuing to the east from Peterborough the road follows close to the cliff tops with many spectacular coastal views.

STOP 1: LONDON BRIDGE

Erosion of the Oligocene-Miocene Port Campbell Limestone along the coastline east and west of the town of Port Campbell has resulted in spectacular cliffs, bays, islands, natural arches and rock stacks. The cliffs are mostly about 30 m high and near-vertical, cut into the flat-lying shallow marine calcarenite. The top of the Port Campbell Limestone occurs near Peterborough and travelling eastwards the coastal section gradually exposes deeper levels of the Heytesbury Group for which this coastline forms the type section. Thus the top of the cliff at London Bridge is near the top (Upper Miocene) of the Limestone sequence. Until early this year London Bridge was a magnificent example of a natural arch which could easily be crossed to the rock stack beyond. One day in February it collapsed without warning, stranding two visitors on the far side. Fortunately no-one was injured and the two were rescued by helicopter.

Numerous petroleum exploration wells have been drilled in this central part of the Port Campbell Embayment and several of these have been used in fission track studies. The Port Campbell#4 well was drilled about 10 km due north of London Bridge near the Paaratte. The only commercial hydrocarbon discoveries in the Otway Basin, the small North Paaratte, Wallaby Creek and Grumby gas fields are also in the same area. These fields produce natural gas from the Waarre Sandstone at the base of the Sherbrook Group and supply the town of Warrnambool.

The importance of this central part of the Port Campbell Embayment for fission track thermal history studies is that deposition has been relatively continuous until late Miocene times. Thermal modelling (Gleadow et al. 1986a) shows that the that Early Cretaceous samples from the deep wells here (e.g. Flaxmans#1 and Port Campbell#4) are now at their maximum temperatures.

STOP 2: LOCH ARD GORGE.

This part of the coastline is heavily indented with numerous deep bays and canyons cut into the soft limestones. The erosion proceeds by undercutting the base of the cliffs, usually enhanced where there is jointing or some other local weakness in the rocks. The roughly parallel sides of the narrow canyons and bays cut into the cliffs in this area indicate a structural control on the erosion. Continual undercutting by the sea has produced first caves and then tunnels at this locality, which have later collapsed to form the narrow canyons and bays. Evidence of the existence of earlier caves can still be seen at the head of the Loch Ard Gorge where stalactites and other cave deposits line overhanging cliffs above the beach. Nearby the the collapse of part of the roof of one of these tunnels has produced a spectacular 'blowhole' where the sea surges underground for 100 m and then erupts through a huge hole 40m across and 17m deep.

This locality takes its name from the three-masted iron clipper *Loch Ard* which was wrecked here in 1878 with the loss of 52 lives. There were only two survivors and four of the victims of this wreck were buried at the cemetery above the cliffs nearby. The *Loch Ard* was just one of many ships wrecked along this rugged coast, particularly during the 19th century.

STOP 3: THE TWELVE APOSTLES

Perhaps the most striking locality along this coastline is the group of rock stacks known as the Twelve Apostles. As the name implies there are twelve of these stacks, although only eight can be seen from the lookouts. They represent residual areas of harder rock capped by the Port Campbell Limestone with Gellibrand Marl at the base. A slight darkening of the rock about halfway down the stacks marks the transition to the slightly deeper-water marl deposits. This area is stratigraphically deeper in the section than the upper part of the Port Campbell Limestone seen near Peterborough.

Looking northwards from the carpark at this locality you can see the broad dome of Ferguson's Hill which is a domal structure just west of the Otway Ranges High. The Fergusons Hill#1 well was drilled on the crest of this structure and has yielded fission track evidence from the Otway Group sediments of significant cooling at the end of the Early Cretaceous.

TWELVE APOSTLES TO MOONLIGHT HEAD 25 km

Travelling east from the Twelve Apostles the route passes down from the base of the Heytesbury Group into the underlying Wangerrip Group near the mouth of the Gellibrand River. From Princetown the road climbs back up onto the coastal plain and passes a number of cuttings which expose the deltaic and prodelta sediments of the Dilwyn Formation and Pember Mudstone before steeply descending to cross the Gellibrand River once more. Near the bottom of this descent outcrops of basal transgressive phase of the Wangerrip Group, the Pebble Point Formation, can be seen in road cuttings on the left just before the bridge The Pebble Point Formation consists of yellowish brown sands and conglomeratic sands with discontinuous lenses of white quartz pebbles.. At the river crossing at Lower Gellibrand the road passes the basal Tertiary unconformity into the underlying Early Cretaceous Otway Group.

After the turnoff to Moonlight Head some landslide scars may be seen in cleared land to the right of the track. Such features are common on cleared areas of the Otway Ranges throughout the outcrop area of the Otway Group and reflect the weakness of these sediments due to the rapid and deep weathering of the volcanogenic material.

STOP 4: MOONLIGHT HEAD

A steep climb down to beach level near Moonlight Head shows the magnificent exposures of the greenish volcanogenic sandstones and finer sediments of the Early Cretaceous Otway Group which are characteristic of the coastal exposures. Away from the coast the exposures of the Cretaceous sediments are generally very poor indeed due to their labile character. This locality is stratigraphically near the top of the Lower Cretaceous and is one of the few places where a separate formation, the Moonlight Head Beds, can be distinguished within the otherwise very monotonous Otway Group.

This locality is also on a structural high being near the crest of a broad southwards plunging anticline.

The upper part of the cliffs at Moonlight Head is composed of the overlying Pebble Point Formation in the basal Wangerrip Group. These Early Tertiary sediments are flat lying and rest with sharp angular unconformity on the underlying Early Cretaceous sediments which dip at about 30-40° westwards. Occasional large blocks of heavily ferruginised grits and conglomeratic sands from the Pebble Point Formation have fallen down the cliffs from these deposits and can be seen scattered along the beach.

The exposures at beach level and in shore platforms reveal a sequence of cross-bedded fluviatile volcanolithic sandstones with very little of the honeycomb weathering that characterise so much of the coastal outcrop of the Otway Group. The rocks have a characteristic greenish colour and speckled, 'salt and pepper' texture caused by mixed light and dark coloured clasts. The clasts consist of fresh volcanic rock fragments, feldspar, quartz and some hornblende and biotite. The feldspars are most commonly andesine in composition and the lithic clasts mostly of andesitic and dacitic origin. Particles and larger fragments of coalified wood are also quite common in the sediments. The rocks of the Moonlight Head Beds are much less altered than other parts of the Otway Group. The universal green chlorite cement is well developed and heulandite is the only zeolite present, partially filling primary pore spaces in the sandstones.

The Moonlight Head Beds contain plant fossils of the youngest floral zone in the Early Cretaceous and yield the youngest primary fission track ages of any rocks in the Otway Group. Fission track ages on apatite (102 ± 4 Ma) and sphene (104 ± 3 Ma) are confirmed by K-Ar ages on hornblende of 102 ± 2 Ma (I. McDougall, pers. comm.). The confined track lengths in apatites from these rocks are typical of undisturbed volcanic rocks (Gleadow et al, 1986b) with a mean and standard deviation of 15.69 ± 1.09 μm. In addition to being relatively unaltered, the rocks at Moonlight Head are also particularly rich in volcanogenic material suggesting an influx of new volcanic material into the basin towards the end of Otway Group deposition.

STOP 5: SCENIC LOOKOUT TOWARDS CAPE OTWAY

Back on the Great Ocean Road about 2.3 km past the Moonlight Head turnoff a lookout gives excellent views along the coastline past Lion Headland, across the embayment of the Johanna Syncline, to Rotten Point and finally Cape Otway, the southernmost point of this coastline.

MOONLIGHT HEAD TO APOLLO BAY VIA JOHANNA 70 km

The drive eastwards will now climb along a ridge defining the broadly essentially anticlinal structure of the Crowes Anticline towards Lavers Hill. Just after Lavers Hill the road, after travelling northeastwards, turns to the southeast and passes through road cuttings with some of the best exposures of the Early Cretaceous sediments in the Otway Ranges. The overall structure of the Otway Ranges High is essentially an anticlinal dome plunging both to the southwest and north east. Dips along the western flanks of the range are generally westwards and along the eastern coastline, most commonly eastwards. Mostly dips in the Otway Group are relatively gentle but in places they become near vertical along some of the more major structures. One such place is on the eastern limb of the Crowes anticline where very steep dips are seen in road cuttings on the road to Johanna Beach. The Johanna area is a broad southwesterly plunging syncline which is filled with an outlier of Early Tertiary sediments which are broadly correlative with the Wangerrip Group. The road traverses these reddish brown sandy sediments before climbing back up to the Great Ocean Road.

From Glenaire, near Rotten Point, to Apollo Bay the road passes through some magnificent stands of the original wet eucalypt forest which once covered much of the Otway Ranges. These thick forests are supported by a rainfall of 1520 mm/year. The tallest trees in the forest include the largest of all the Eucalypts, the Mountain Ash (*Eucalyptus regnans*, up to 95 m tall) and the Blue Gum (*Eucalyptus globulus*, up to 60 m). Scattered remnants of an earlier temperate rainforest occur in some of the wet valleys in the ranges which are protected from forest fires. These are dominated by one of the antarctic beeches (*Nothofagus cunninghamii*) with an understory of the soft tree fern (*Dicksonia antarctica*). If time permits a stop will be made at Mait's Rest to see one of these rainforest areas which have survived with little change from an original Gondwana flora.

DAY 6 - APOLLO BAY TO MELBOURNE

Topics: Lower Cretaceous sediments of the Otway Group; early formed concretions and oxygen isotope records; diagenesis and zeolites; sedimentary environments and structures; provenance of the volcanogenic sediments; Tertiary sediments of the Torquay sub-basin.

STOP 1: SKENES CREEK SHORE PLATFORM

The shore platform at Skenes Creek is a typical example of the coastal outcrop of the Otway Group along the eastern coast of the Otway Ranges. The rocks show the typical cross-bedded fluviatile sandstones in lenticular channel deposits with some finer grained sediments and occasional lenses rich in coalified plant remains. The sediments are heavily zeolitised with primary porosity completely filled by laumontite and some of the primary minerals replaced by laumontite and albite. The resulting rock has almost no remaining porosity and in places has a characteristic mottled texture. Also seen at this locality are some examples of the mud-chip conglomerates which are common throughout the Otway Group sediments. These conglomeratic layers containing pebbles of locally derived finer-grained sediments further demonstrate the relative lack of normal detritus. However, at this locality a few small elongated lenses do contain a significant proportion of coarse angular granitic quartz grains, presumably derived from the southern basin margin. The amount of such basement derived detritus tends to increase towards the margins of the basin.

SKENES CREEK TO ARTILLERY ROCKS 29 km

Travelling northeast along the Great Ocean Road reveals not only spectacular coastal views, but numerous road cuttings and natural outcrops of the Otway Group sediments. The road winds along the coast around a succession of headlands and intervening bays and across the mouths of a number of streams draining the eastern slopes of the ranges.Along most of this road the sediments dip at relatively moderate angles to the east and the bedding planes often control the slope of the hillsides descending towards the sea. Where the dips are gentle the slopes tend also to be gentle and where they are steep the slopes can be precipitous. This is not universally the pattern however, and in places the beds are dipping inland.

Going northeast from Skenes Creek the road crosses a succession of creek valleys several of which are very youthful in character reflecting rejuvenation of uplift on the Otway Ranges high since Pliocene times. At Smyths Creek, outcrops of two particularly large channel sandstone lenses produce massive outcrops and cliffs on the hill sides and the dark-coloured bedded mudstones can be seen in between along the roadside. The slope of the hillside here is clearly a dip slope controlled by the bedding in the massive sandstone. Further north at Cape Patton the lookout high above vertical cliffs gives magnificent views along the coast to the south. The bedding here is nearly horizontal and the steep slope is controlled by vertical jointing in the sandstones. The cutting opposite the lookout shows both the fine grained mudstones and coarser sandstones.

STOP 2: ARTILLERY ROCKS

The shore platform at Artillery Rocks is the best locality for examining two important characteristic features of the Otway Group sediments, the carbonate concretions and the honeycomb weathering. Examples of these features are present at most of the localities visited so far, but nowhere are they displayed as well as here. The carbonate concretions are seen as the obvious spherical 'cannonball' features and as elongated structures forming along bedding planes and some joints. Many of the concretions lie parallel to bedding planes and were formed when the beds were horizontal and still contained significant primary porosity. The concretions contain up to 20% of secondary calcite cement, and sometimes a later growth of siderite. A later generation of secondary mineral deposition can often be seen forming as post-tectonic joint fills of carbonate. Primary structures such as bedding laminations are often preserved and resist subsequent compaction which may be seen occurring differentially around them.

This evidence of formation very early in the history of diagenesis is confirmed by petrographic studies showing that the concretions preserve the primary mineralogy of the sandstones intact when the surrounding matrix has been completely zeolitised. For example labile andesine, pyroxene and amphibole may be found in concretions where the matrix is extensively converted to laumontite and albite.

Oxygen isotope studies on the carbonate cements from these early formed concretions (Gregory et al., 1989) shows that they were probably derived from meteoric fluids with extremely low $\delta^{18}O$ soon after burial. Fluids with $\delta^{18}O$ as least as low as -15 ‰ and probably as low as -20 ‰ were involved in the early calcites. These values suggest that the river system that deposited these sediments had a cold high-latitude climate with mean annual temperatures of <5°C and possibly below freezing. These are consistent with the presence of permanent snow and ice in the local catchment area and cast doubt on previous ideas the the Cretaceous poles may have been essentially ice free.

Honeycomb weathering and the more enlarged cavernous weathering or tafoni are a feature of most of the coastal exposures of the Otway Group and are particularly well displayed at this locality. This weathering pattern is best displayed in the spray zone above the water line and is absent on low-lying parts of the shore platform where it is rapidly removed by abrasion in the waves. In the Otway group this type of weathering seems to be best developed on the completely cemented rocks of the laumontite-albite zeolite zone and is relatively poorly formed in the much less zeolitised rocks of the Moonlight Head Beds. The mode of origin of honeycomb and cavernous weathering is not well understood but it is particularly common in areas affected by salt spray along the coast. However, fresh water varieties also occur as will be seen at Swallow Cave.

STOP 3: CUMBERLAND RIVER

The Cumberland River gorge is eroded along the line of the Cumberland fault which cuts the coastline and trends inland at this point. Some very large sandstone channels form prominent cliffs up the sides of the valley. The base of one of these major fining-upwards sequences is seen in the undercut river bank across the river from the camping ground. The scoured base of the major sandstone unit is seen where it has eroded down into the underlying dark mudstones representing earlier overbank deposits. Progressive undermining of this bank by the rover leads to collapse of the overlying sandstone along joint planes and maintains the vertical cliff. An example of a recent rock topple produced by this undermining of the fine-grained sediments can be seen across the river.

STOP 4: SHEOAK RIVER-SWALLOW CAVE

A walking track of about 1 km beside the Sheoak River leads to two waterfalls which have formed where the river descends across two massive sandstone channel deposits. Two similar caves have developed beside both of these waterfalls on their southern sides in the zone where the rocks have been affected by water spray from the falls. Both these caves show a cavernous weathering in the massive cross-bedded sandstones similar to that seen along the coastal exposures, but here they obviously can not be affected by sea spray. The weathering pattern must be forming in a fresh water environment at this locality, although it is worth noting that pore fluids from the Otway Group in a number of deep oil wells have been shown to be extremely saline . The walk beside Sheoak River passes through much more open woodland of the southern blue gum than that seen on the much wetter southern slopes of the Otway Ranges.

LORNE TO ANGLESEA 31 km

About 9 km north of Lorne the road leaves the Otway Group and passes the basal unconformity into the Tertiary Sediments of the Torquay sub-basin on the eastern side of the Otway Ranges High. The route passes first through the continental sediments of the Eastern View Formation which are broadly correlative with the Wangerrip group in the Port Campbell Embayment. Some typical clastic sediments of this sequence can be seen long the road near Eastern View. The sequence includes interbedded clay and silt, cross-bedded sand and gravel and locally seams of lignite which are usually less than 10 m thick. The Eastern View Formation is in turn overlain by a marine shelf carbonate sequence of the Torquay Group which is the equivalent of the Heytesbury Group farther west. Sediments of the Torquay Group can be seen on the right forming the headland of Point Roadknight on the approach to the town of Anglesea. These sediments all have a regional seawards dip to the southeast, mostly at low angles.

STOP 5: ANGLESEA BROWN COAL MINE

An excellent exposure of the Eastern View Formation including a 30 m thick seam of lignite can be seen at the Alcoa brown coal mine about 1.5 km inland from Anglesea. The seam is near the top of the Eastern View Formation and the overburden consists of sand and clay and varies considerably in thickness. The sediments are Late Eocene in age and include clay lenses that have yielded well-preserved plant remains indicative of lush sub-tropical rainforest vegetation. The coal is used to fire the small 150 MW power station nearby which produces electricity for the Alcoa aluminium refinery at Point Henry near Geelong.

ANGLESEA TO MELBOURNE 112 km

The route now rejoins the highway to Geelong and then back to Melbourne passing again over the Werribee basalt plain on the western side of Port Phillip Bay.

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