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EXCURSION GUIDE

NEWER VOLCANICS PROVINCE - PROCESSES AND PRODUCTS OF PHREATOMAGMATIC ACTIVITY

Ray Cas, Carol Simpson and Hiroshi Sato

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Newer Volcanics Province - Processes and Products of Phreatomagmatic Activity

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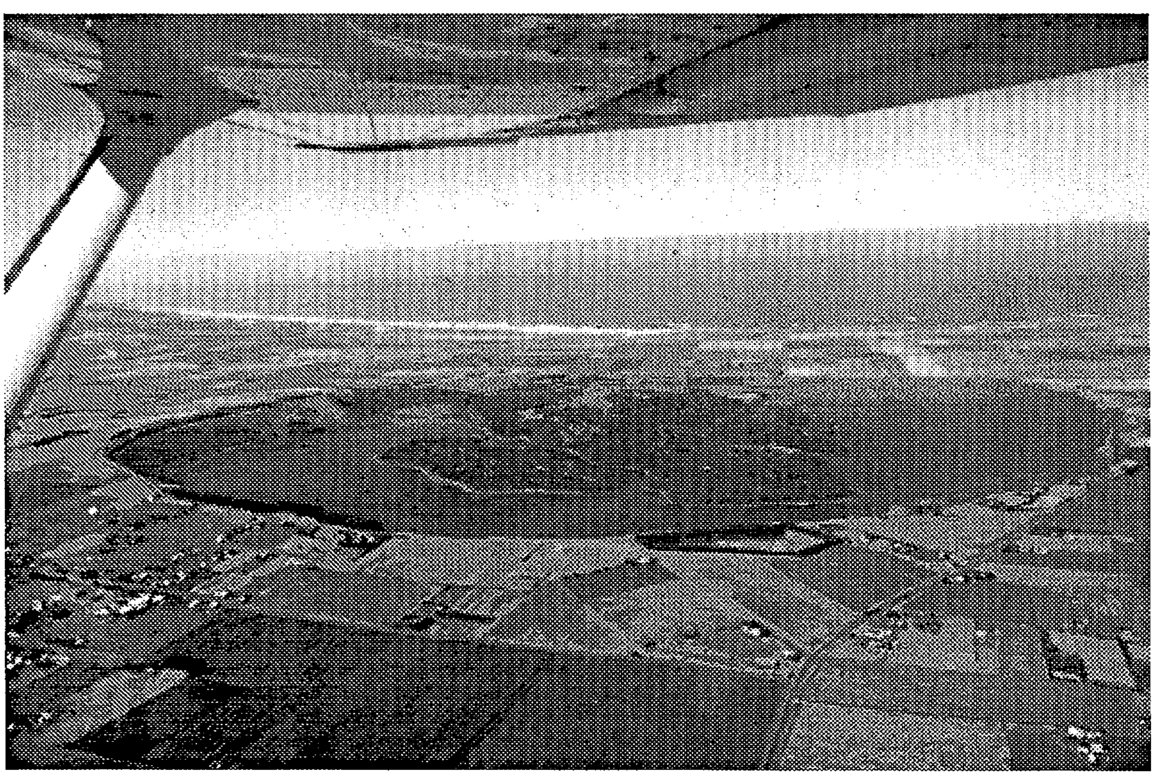

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Frontispiece: Oblique aerial view of the Tower Hill Volcanic Complex, dominated by the 4 km maar lake and the intra-maar scoria cone complex

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1-INTRODUCTION: Regional Setting of the Newer Volcanics Province of Southeastern Australia

GENERAL GEOLOGY AND HISTORY OF VOLCANISM OF AUSTRALIA

The Newer Volcanics Province represents just the most recent episode of volcanism that has affected Australia throughout its geological history. Volcanic rocks are represented in all the rock systems of Australia from the Archean through to the Recent. Komatiitic volcanics are common in the Archean of Australia, with felsic volcanics being of only minor significance. From the Proterozoic onwards, komatiitic volcanics become rare, and conversely, felsic volcanics become more prominent although mafic volcanism remained a significant part of the volcanic record.

As elsewhere in the world, there is on-going debate about the tectonic significance of Australia's ancient volcanic successions, especially for the Archean to mid-Paleozoic volcanics. The common tectonic scenarios that are debated are subduction related arc setting versus rift setting, and plate margin versus intraplate settings. The occurrence of fault bounded mafic-ultramafic complexes ("ophiolitic" complexes) associated with many of these ancient volcanic successions has also fueled the debate on how significant oceanic plate and island arc tectonic settings were compared with continental plate tectonic settings. Lastly, the application of terrane concepts is an on-going process, with considerable work being required to establish the terrane status of crustal blocks of all ages.

In general, the age of basement complexes youngs to the east. Archean belts are almost completely confined to the western one third of the continent, Proterozoic successions are confined to the western two thirds whereas the eastern third of the continent consists of Paleozoic basement complexes. This pattern gives the impression of progressive continental accretion in an eastwards direction by plate margin subduction related processes. The rock record is consistent with numerous orogenic events throughout geologic time that would support such an interpretation, but many uncertainties remain to be resolved were such a simple scenario to be adopted. For example, in eastern Australia, one of the great uncertainties is whether or not the pre-Paleozoic basement was ensialic or ensimatic (Cas, 1983).

From the Carboniferous and Permian on, there is the clearest indication of a plate margin arc setting along the eastern margin of Australia. This arc, originally located in northeastern New South Wales (the New England arc), migrated northeastwards into eastern Queensland during the Mesozoic and earliest Tertiary, and appears to represent the precursor to the modern arc-trench system in the southwest Pacific (New Zea-land-Kermadec-Tonga-Vanuatu-Solomons) that represents the present day eastern margin of the Australian-Indian Plate. Nonetheless, the tectonic significance of the Mesozoic to Tertiary volcanics of the Queensland coastal belt is debatable. They could represent subduction related arc volcanics, or volcanics originating from behind-the-arc rifting associated with the eastwards migration of the active plate margin and the formation of the marginal basins that extend from the east coast of Australia to the current plate margin (e.g. Bryan et al., in press), or both.

From the Jurassic on, Australia's western, southern and eastern margins were subject to rifting associated with the breakup of Gondwanaland. Volcanism was associated with many of these rifted margins (Veevers 1984). In eastern Australia, rifting along the southern margin produced the Otway, Bass and Gippsland Basins along the south coast of Victoria, and rifting and back-arc spreading led to the opening of the Tasman Sea and Coral Sea basins along the east coast (Veevers 1984).

Intraplate volcanism, largely basic in character, has been a notable feature of the geological development of the eastern Australian coastal and highlands belt since the Jurassic (Johnson et al. 1989). Volcanics resulting from this intraplate volcanism are widespread along the eastern margin of the Australian mainland (Fig. 2), and are also known from offshore oceanic settings (Johnson et al. 1989).

GEOLOGY OF SOUTH-EASTERN AUSTRALIA

The exposed basement in southeastern Australia consists of the deformed remains of the early to mid-Paleozoic Lachlan Fold Belt (LFB; Fig. 1). This orogenic belt consists of deformed metasedimentary, volcanic and granitic rocks. The LFB appears to have evolved through the cumulative effects of four cycles of crustal extension and compression from the begining of the Cambrian to the Early Carboniferous (Cas 1983). During the Cambrian to end Ordovician the paleogeography was largely of an open marine basin marginal to the paleo-Australian craton. A number of mafic volcanic belts were active during this time, but there is debate as to whether or not these represent subduction related island arcs or rift related events, and whether or not the basement was oceanic or subsided continental crust (Crawford and Keays 1986; Cas, 1983).

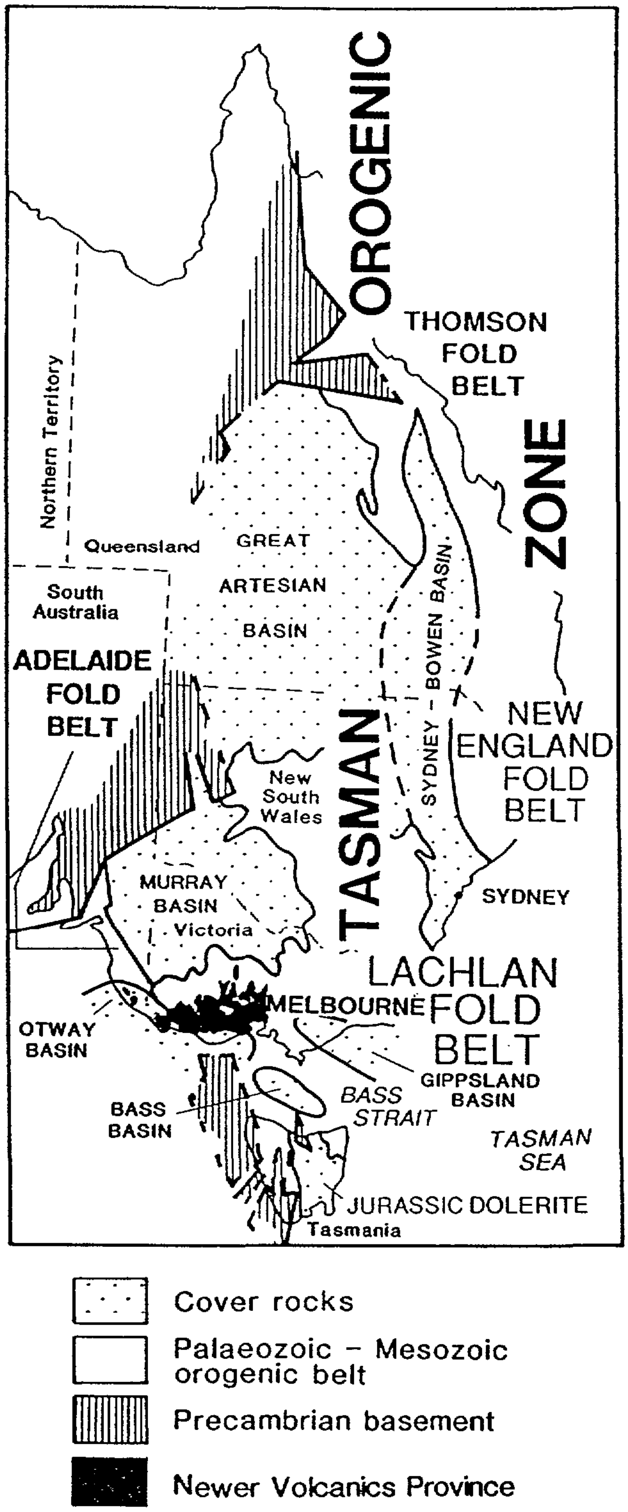


Figure 1: *Principal geological and tectonic elements of eastern Australia (after Cas 1983, Gray 1988).*

By the Siluro-Devonian the the crust was largely sialic based on the widespread occurrence of Siluro-Devonian granites which occupy 25% of the area of the Lachlan Fold Belt. Based on the geochemistry of these granites, and geochemical differences in regionally extensive suites of granitoids as well as the model ages for their source rock successions, Chappell et al (1988) proposed that the LFB shows no evidence of the existence of supracrustal terranes, but appears to show evidence of the existence of the remains of terranes in the lower crust that seem to have amalgamated by the beginning of the Paleozoic. According to this line of reasoning the Paleozoic LFB evolved on a largely sialic basement (Cas, 1983; Chappell et al., 1988). The Siluro-Devonian paleogeography was a mixed marine-subaerial one and the numerous basins of the LFB appear to have originated by extension or transtension, accompanied by voluminous, largely felsic magmatism.

As a result of the mid-Devonian Tabberabberan Orogeny, this paleogeography became almost wholly subaerial. By the Late Devonian another cycle of crustal extension producing rift basins and bimodal volcanism, including major caldera complexes, has reactivate the tectonics of the LFB. During the early Carboniferous Kanimblan Orogeny the crust of southeastern Australia was fully cratonised and stabilised into a sialic crustal complex of deformed metasedimentary and metaigneous rocks ranging from zeolite to greenschist to amphibolite facies metamorphic grades.

Apart from the peripheral effects of the tectonic activity occurring to the northeast in the newly evolving New England Fold Belt (Fig. 1) during the Carboniferous and Permian, tectonically, southeastern Australia remained stable until the latest Jurassic-Early Cretaceous, when rifting associated with the breakup of Gondwanaland led to the formation of the Otway, Bass and Gippsland Basins along the southern margin of Victoria (Fig. 1), the opening of the Southern Ocean between Australia and Antarctica (Veevers 1986), and the subsequent opening of the Tasman Sea along the east coast of the continent.

The Otway, Bass and Gippsland Basins (Fig. 1) were initiated in the latest Jurassic to earliest Cretaceous when the then contiguous land masses of Australia, Antartica and New Zealand began to extend, forming a linear continental rift basin system. The Otway rift basin continued to widen, with breakup (i.e. separation of Australia and Antarctica) occurring about 95 million years ago with the development of a seafloor spreading system in the Southern Ocean (Veevers, 1986). The east-west trending Otway Basin thus represents half of the original rift basin and has evolved into a passive continental margin basin that is open to the ocean. Its basement thus consists of deformed sialic crust of the Paleozoic Lachlan Fold Belt onshore, but offshore this passes into younger oceanic crust. The Otway Basin is still an active basin with both active subaerial and marine erosional and depositional systems. The Bass and Gippsland Basins are failed rift basins, are wholly ensialic, and have led only to the limited separation of the mainland from Tasmania. The Bass

Basin is currently wholly submarine, whereas the Gippsland Basin, like the Otway Basin, has both continental and marine components. They are also both still active basins. After the original continental rift forming phase all basins eventually subsided thermally and isostatically and were transgressed by the sea. Until recently, the Gippsland Basin was Australia's major producer of oil and gas. The Otway Basin has only economic gas resources, and the submarine Bass Basin's potential is still being evaluated.

MESOZOIC-CENOZOIC VOLCANISM IN SOUTH-EASTERN AUSTRALIA

Intraplate volcanism has occurred sporadically from the Jurassic to the Recent in southeastern Australia (Day 1983, 1989). This extended period of volcanism is thought to be related initially to the separation of Australia, Antarctica and the New Zealand-Lord Howe crustal blocks, and subsequently to intraplate mantle activity.

Jurassic volcanism is poorly known, the products are only known from boreholes, and the volcanism is thought to be related to the incipient stages of the rifting that led to the formation of the Otway Basin (Day 1983). The latest Jurassic-Early Cretaceous fills of the Otway, Bass, and Gippsland continental rift basins consist of huge volumes of fluvially deposited volcaniclastic sediment that is up to 4 km thick. Intrabasinal sources have not been identified, and the best suggestion is that the volcanic sources for this sediment are probably extrabasinal, perhaps derived from the then active plate margin arc on the Lord Howe Rise to the east (Veevers 1984). Another possibility for some of the mafic detritus at least is that it is derived from the erosion of the very widespread Jurassic dolerites of Tasmania and the then contiguous Antarctica along the southern margin of the evolving rift basins.

From the Late Cretaceous through the Tertiary, intraplate volcanism was widespread not only throughout southeastern Australia but along the whole eastern part of Australia (Johnson 1989; Fig. 2). Although the Cenozoic volcanism of eastern Australia was no longer associated with a plate margin, it is thought to have resulted from intraplate "hot spot" or "hotline" activity in the mantle, and in some cases may have been localised along the crustal extensions of oceanic transform faults. In some parts of eastern Australia "hot spots" or east-west orientated "hotlines" are thought to have sourced southward younging lines of central volcanoes that record the northward passage of the Australian-Indian Plate over the sublithospheric mantle (Wellman and McDougall 1974, Wellman 1983, Sutherland 1985, Johnson et al 1989).

The known relicts of Late Cretaceous-Quaternary volcanism are widespread throughout Victoria, both in surface exposure and in the subsurface. Examples are known from the Otway and Gippsland Basins and outside these basins, scattered throughout the Paleozoic basement areas of the LFB. Most of the known occurrences of Tertiary volcanism are in the eastern half of the state, whereas latest Tertiary-Quaternary volcanism occurred in the western half. The volcanism occurred in both subaerial settings and, in the Otway and Gippsland Basins, in submarine settings as well. The volcanism ranging from the Late Cretaceous through to the Quaternary has been divided into three groups:

-The Older Volcanics (95-19 Ma)
-The Macedon-Trentham group (7-4.6 Ma)
-The Newer Volcanics (4.6- Ma)

Day (1983, 1989) subdivided the Older Volcanics into fourteen provinces based on age and compositional character, and then grouped these into four groups based on age range, distribution and composition. Most of the remains of the Older Volcanics are eroded, weathered lava fields, valley fill lavas and lava cones. However, in the Otway Basin at least, local occurrences of pyroclastic cones are preserved (Stops 28, 29). The compositions vary from nephelinites to *qz*-tholeiites (Day 1983,1989). According to Day (1989, p.133): " ... relative proportions differ widely between volcanic fields and, regionally, there is no correlation between basalt type and either age or location. However, six fields became more alkaline or increasingly fractionated during their lifespan."

The Macedon-Trentham group of volcanics represents the only felsic group of Cenozoic volcanics in Victoria, consisting of subaerial trachytic lava flows, domes and plugs (Knutson and Nichols 1989). They are very restricted in occurrence and specific rock types include a range from K-rich basanite, alkali basalts, hawaiites, and *ne*- and *qz*- trachytes (Knutson and Nicholls 1989).

The intraplate volcanism represented by the Newer Volcanics represents the latest phase of largely basaltic volcanism that has occurred in southeastern Australia since the Jurassic. The Newer Volcanics have an age range from 4.6 Ma to about 4,500 years, and they extend from Melbourne westwards to southeastern South Australia. The province is well preserved because of its youth and is characterised by lava plains and scattered point source lava shields, strombolian scoria/cinder cones and maars. The rock types range from subalkaline ol- and qz-normative tholeiites and icelandites to alkaline suites such as hawaiites And basanites (Nicholls and Joyce 1989).

GEOLOGICAL SETTING OF THE NEWER VOLCANICS PROVINCE

The Newer Volcanics Province has an east -west orientation, extending about 400km westwards from the longitude of Melbourne to a longitude just west of Mt. Gambier in southeastern South Australia. It spans the east-west trending northern margin of the Otway Basin and overlaps onto the Paleozoic basement of the Lachlan Fold Belt exposed to the north (Fig. 3). The east-west trend of the province almost certainly reflects the influence of east-west basement faults associated with the formation of the Otway Basin.

The stratigraphy of the Otway Basin is illustrated

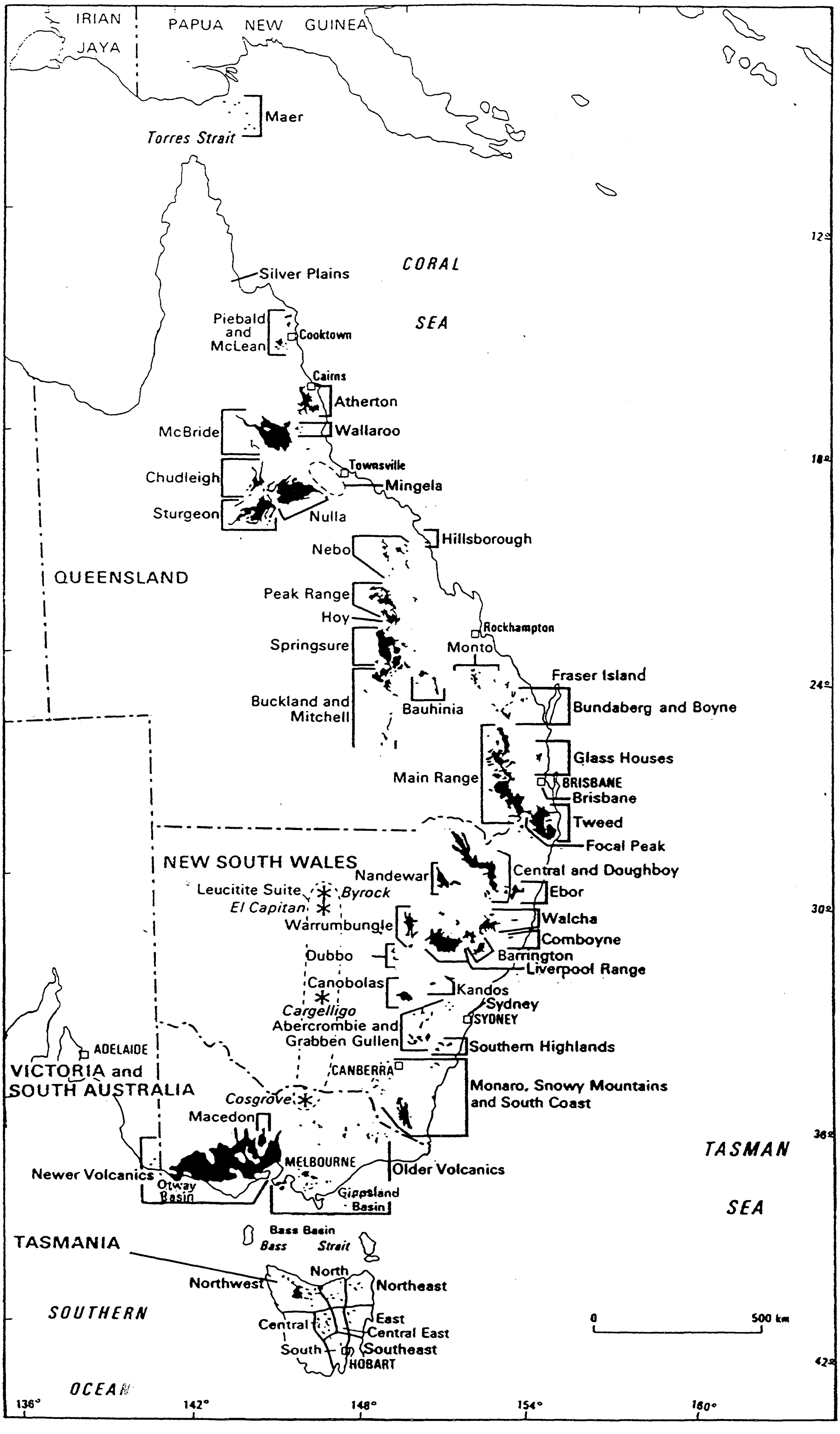


Figure 2: *Distribution of Jurassic-Quaternary eastern Australian intraplate volcanism (after Johnson et al. 1989).*

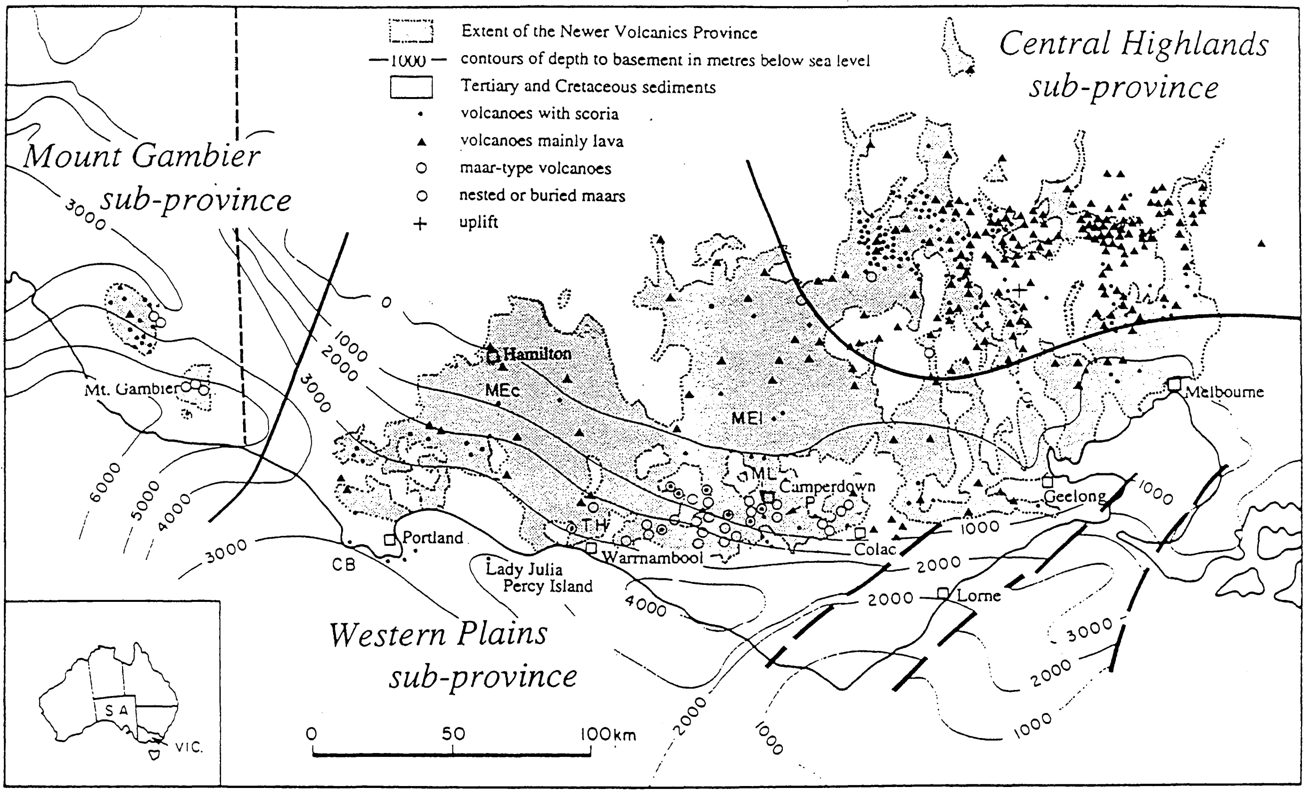


Figure 3: *The latest Tertiary-Quaternary Newer Volcanics Province of Victoria and South Australia, showing the extent of the lava plains, the distribution of known point source volcanoes and volcanic centres, and the sub-division into sub-provinces (after Joyce 1975, Cas & Wright 1987).*

in Figure 4. Although the details are unimportant from the point of view of this field trip, there are several significant points to be made. The initial fill of the Otway Basin is represented by the Otway Group and consists of huge volumes of volcaniclastic sediment deposited in high latitude fluvio-lacustrine environments. No intrabasinal volcanic source is known. According to Smith (1988) continental sedimentation continued until the Late Cretaceous when transgression of the sea produced offshore marine to deltaic environments (Sherbrook Group). Marginal marine environments are represented by the Wangerrip Group and a major transgression by the Nirranda Group in the late Eocene and Oligocene. During the Miocene marine conditions persisted in the Otway Basin, represented largely by temperate climate bioclastic carbonate successions, the most prominent being the Miocene Port Campbell Limestone and its lateral equivalents the Gellibrand Marl and Torquay Group. These limestones are major aquifers and have played a dynamic role in the phreatomagmatic volcanism that has been a significant factor in the history of the Newer Volcanics Province (Joyce 1975; Edney 1984). Final regression of the sea began in the late Miocene.

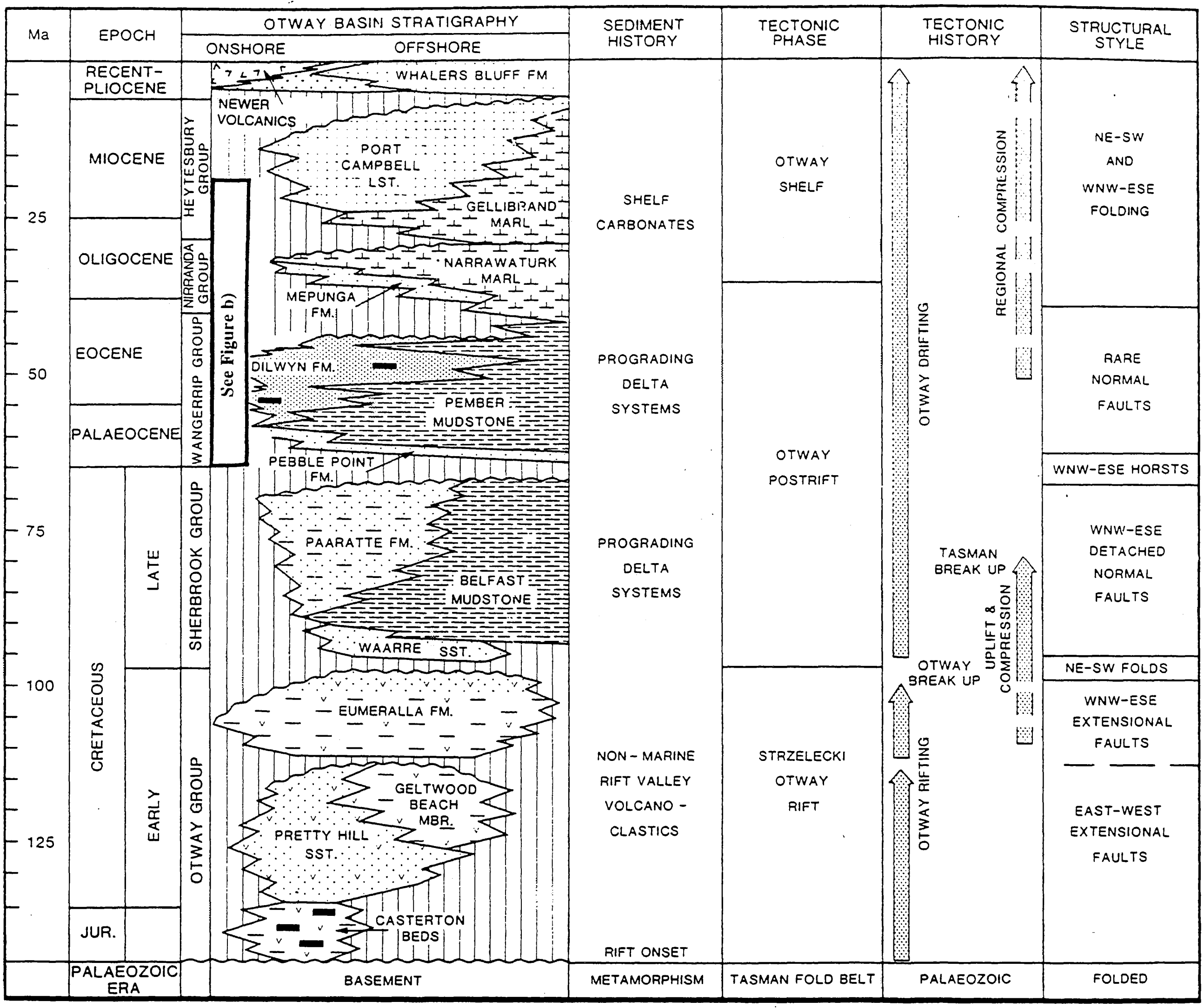
Intrabasinal volcanism has not been a major influence in the history of the Otway Basin although occasional pulses of basaltic volcanism are preserved. The basaltic volcanism represented by the Eocene-Oligocene Angahook Member of the Demon's Bluff Formation (Stops 28, 29) is a good example. It occurred during a marine transgressive phase in the Eocene-Oligocene, and produced a shallow marine surtseyan volcanic complex, the remains of which will be examined during this trip.

The Newer Volcanics Province (NVP) represents one of the youngest stratigraphic components of the Otway Basin. However, the northern margin of the NVP extends beyond the northern margin of the Otway Basin, overlapping the uplifted Paleozoic basement that is exposed to the north of the east-west trending Otway Basin.

GEOLOGY OF THE NEWER VOLCANICS PROVINCE

The Newer Volcanics Province (NVP) is an intraplate continental basaltic volcanic province of the plains type as defined by Greeley (1977, 1982). It occupies approximately 15,000 km^2 in western Victoria and southeastern South Australia (Fig. 3) and the eruptive products have a volume of about 1300 km^3. The province extends about 400km from the longitude of Melbourne to just west of Mt Gambier in southeastern South Australia.

Newer Volcanics volcanism began about 4.6 million years ago, and the latest dated eruption was at Mt Gambier about 4,500 years ago (Blackburn et al., 1982, 1984; Nicholls 1989). Nearly 400 eruption points are known (Joyce 1975). Clearly given the youth of the province, the recency of the last eruption, and a minimum guestimated average eruption frequency of every 11,500 years (4.6ma divided by 400 eruption points further eruptions can be expected, either on land or offshore. Natural



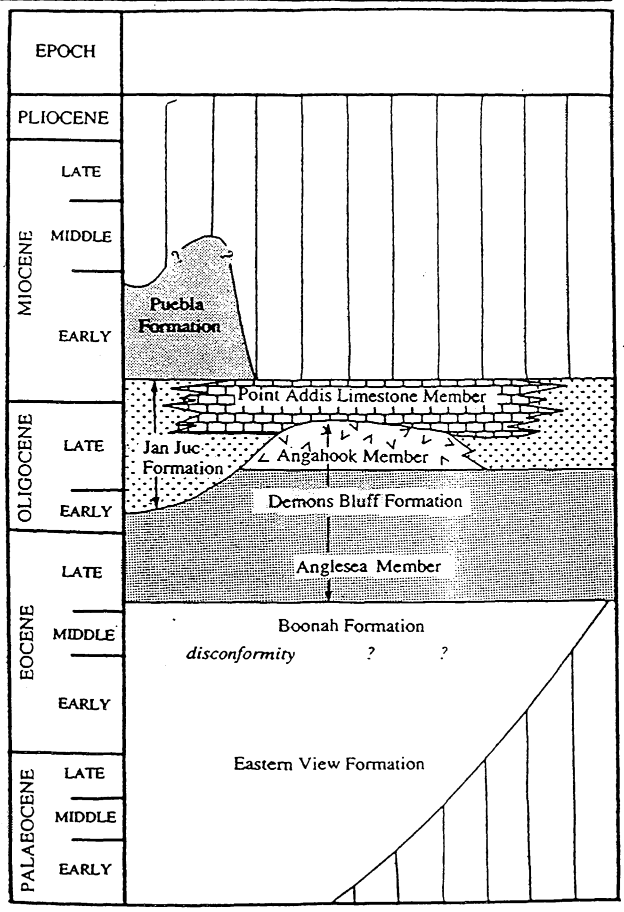


Figure 4: *(a) Stratigraphy and principal geological events of the Otway Basin (from Smith 1988)*
(b) Stratigraphy of the Torquay Embayment sub-basin.

water springs around the Daylesford area, and natural carbon dioxide production form the Mt. Gambier area (Chivas et al. 1987) may be a representation of continued magmatic activity.

The NVP can be subdivided into several distinct subprovinces, these being the Central Highlands Sub-province to the north, the Western Plains Sub-Province, and the Mt. Gambier Sub-province in the far west (Joyce 1988; Nicholls and Joyce 1989). The Central Highlands Sub-Province occurs along the northern margin of the NVP where the province laps onto highlands consisting of exposed Paleozoic basement. The sub-province consists of at least 250 eruption centres, mostly scoria cones and lava shields, and valley fill lava flows scattered through the hilly topography of basement exposures. The geochemistry of the products indicates roughly equal proportions of subalkaline (*ol*- and *qz*- normative tholeiites and icelandites) and alkaline (hawaiites and basanites) compositions (Nicholls and Joyce 1989).

The small Mt. Gambier Sub-province consists of clusters of central scoria cones and maars, with minor associated lavas (Sheard, 1990 ; this volume), and is separated from the main part of the NVP, lying 60-80 km to the west of it. Many of the cones in the Mt. Burr Range area are aligned along northwesterly trending basement fractures (Sheard 1990). The compositions of the volcanics are largely alkaline (Nicholls and Joyce 1989).

The main part of the NVP, the Western Plains Sub-province, is dominated by an extensive plains forming lava field with interspersed central vent eruption centres, many of which are aligned along inferred basement lineaments. The flat topography in large part mimics the flat depositional topography of the underlying Otway Basin succession, but also the topogrphy filling and blanketing nature of the lava flows. Scoria cones, maars, lava shields and complex centres are dispersed throughout the sub-province (Fig. 3). Lakes are also a commmon feature of this sub-province. Whereas some lakes are maar crater lakes up to 3 km in diameter, others are large interior drainage lakes ponded in the flat plains topography (e.g. Lake Corangamite, the largest wet lake in Australia). Lavas have in many cases disrupted and displaced drainage systems (Ollier 1969, 1985). The older plains lavas of the Western Plains Sub-province are predominantly subalkaline, with mildly to strongly alkaline flows being subordinate. By contrast the majority of the younger eruptive centres are alkaline, with less than 10% subalkaline products (Price et al. 1988; Nicholls and Joyce 1989).

Phreatomagmatic eruption centres are almost exclusively confined to the Western Plains and Mt. Gambier Sub-provinces (Fig. 3), a distribution pattern which can be attributed to the existence of Tertiary sedimentary successions of the Otway Basin, including aquifers, in the subsurface below these two sub-provinces. By contrast, the almost complete absence of phreatomagmatic volcanic centres from the Central Highlands Sub-province corresponds with the absence of significant aquifers in the Paleozoic basement below (Joyce 1975).

Although the Newer Volcanics Province is considered to be a continental basaltic volcanic province, shallow marine eruptions have also occurred. Lady Julia Percy Island which lies 10 km offshore between Portland and Warrnambool consists of a lower succession of pillow lava, hyaloclastite and the remains of a phreatomagmatic, surtseyan tuff cone that is capped by a flat topped subaerial lava (Joyce 1988). Small islands offshore from Portland may also record marine volcanism. The dissected remains of several superimposed surtseyan tuff cones capped by a lava shield forming succession of lavas are preserved at Cape Bridgewater and Cape Duquesne (Stops 15 and 16). Although the exposures are now connected to the mainland by a Quaternary sand dune spit, the remains of foraminifera in some of the tuff specimens indicate that the tuff cone forming eruptions took place in a marine environment.

The most comprehensive summaries of the aspects of this province are those of Ollier (1967a), Joyce (1975), Ollier and Joyce (1967), Nicholls and Joyce (1989), Sheard (1990), and of course this volume.

II VOLCANOLOGY: Volcanic processes and problems

VOLCANOES OF THE NEWER VOLCANICS PROVINCE

Nearly 400 volcanoes have been recognised in the the Newer Volcanics Province (Ollier & Joyce 1964; Ollier 1967q; Singleton & Joyce 1969; Joyce 1975; Fig. 3). These can be subdivided into lava volcanoes or lava shields, strombolian scoria or cinder cones, composite volcanoes, maars and tuff rings, tuff cones and volcanic complexes. The preserved volcanic centres represent only the youngest phases of eruptive activity, and in general contributed relatively few lavas to the plains volcanic province. The nature of the source eruptive centres for the bulk of the older plains lavas is unknown, and are presumed to be fissure style vents, or buried, degraded small central vent type centres such as those that are currently preserved.

Lava shields and cones are especially common in the Central Highlands Sub-province and in the eastern part of the Western Plains Sub-province (Joyce 1975). Unlike the very large Hawaiian shield volcanoes and the large Tertiary shield centres of New South Wales and Queensland, the NVP shields are typically small with maximum diameters of 4-5 km, and maximum heights above the surrounding plains of 100-200m (e.g. Warrion Hill north of Colac). Some have multiple craters, and some have evolved from shields to strombolian scoria cones, i.e. into composite volcanoes (e.g. Mt. Napier). Almost no lava shields are sufficiently dissected to expose the internal stratigraphy of these volcanoes. However, coastal exposure at Cape Duquesne (Stop 16) has exposed a succession of at least 30m of pahoehoe lava flows, with flows varying from 1m to several metres thick each. Rare ropey textures are preserved on the surfaces of some flows. Similarly within the walls of the fissure vent system at Mt. Eccles (Stop 21) lavas 1-3m thick are common in the 30m thick exposed sequence. At Warrion Hill, north of Colac, the hummocky, lobate topography is evidence of a succession of overlapping lobate flows.

Although short lavas contributed to the growth of the lava shields, far flowing lavas are also known. The Harman Valley flow from Mt. Napier is 25km long valley-confined lava (Ollier & Joyce 1973). The Tyrendarra lava flowed 50km southwards from Mt. Eccles, prhaps entering the sea which at that time was lower (Ollier 1964; Orth 1988). Similarly the Mt. Rouse flows flowed at least 60km perhaps also to the sea (Ollier 1985).

Strombolian scoria cones are widespread throughout the Newer Volcanics Province. In some cases they occur as isolated single event edifices (e.g. Mt. Elephant, the largest scoria cone in the province, and Smeaton Hill), in other cases they occur in association with other volcano types in composite centres (e.g. Mt. Napier which has a scoria cone superimposed on top of a basal lava shield) or as part of volcanic complexes (e.g. the Red Rock Volcanic Complex- Stops 1-3; Mt. Leura Volcanic Complex -Stops 4-6; Tower Hill Volcanic Complex - Stops 23-25; Mt. Eccles Volcanic Complex - Stops 21-22; Mt. Noorat Volcanic Complex - Stop 26).

The largest scoria cone in the NVP is Mt. Elephant, which has a basal diameter of 1.3 km and is 240m high. The deposits of Mt. Elephant are internally massive apparently without any breaks, suggesting a short lived maintained eruption. This is consistent with the findings of Wood (1980) who found that scoria cone heights may reach 100m in one day during high discharge maintained eruptions. Wood (1980) also found that although the eruptive life could be as long as 15 years, the median was 30 days based on the activity of 42 centres. 93% ceased activity in a year. The deposits consist of massive vesicular basaltic scoria lapilli, bombs, blocks and spatter. Whereas some cones, like the large Mt. Elepant cone, are largely scoria or cinder cones, others, like the small cones at Mt. Eccles are largely spatter cones. Some scoria cones are internally stratified, and some even contain finer phreatomagmatic ash horizons indicating not only a change in eruption style, but perhaps even breaks in the eruption (e.g. the largest cone at Mt. Eccles; Edney 1984).

Although scoria is the principal product, some scoria cones have also produced lavas, generally from base of cone fissures.

The term **composite volcanoes** is used here for volcanoes which have evolved from one volcano type to another, and therefore consist of two superimposed volcanoes. Mt. Napier, as discussed above is a typical example, with a basal shield superimposed by a scoria and spatter cone. The change from one to another must coincide with a change from gas poor to gas rich magma.

Phreatomagmatic/phreatic **maars and tuff rings** (Ollier 1967b, 1974; Lorenz 1973, 1986; Wohletz and Sheridan 1983; Cas and Wright 1987) are common in the southern half of the Newer Volcanics Province (Joyce 1975), this coinciding with the occurrence of aquifers in the underlying Tertiary sequence of the Otway Basin. About 40 are known (Joyce 1975), extending from the

Colac region west to Mt. Gambier. Explosive activity that produces maars is considered to occur below ground surface level through the explosive interaction of hot magma and subsurface ground water (Ollier 1967; Lorenz 1973). As a consequence, the subsurface structure of maars is likely to consist of breccia pipes and diatremes (Lorenz 1986). By contrast the explosive focus of tuff rings (sensu stricto) is thought to occur at ground level (Cas and Wright 1987), a situation most likely through the explosive interaction between rising magma and significant surface water or very shallow groundwater.

The two biggest maars in the NVP are Tower Hill and Purrumbete, which are 4km and 3km respectively in diameter.

Although some simple maars occur in the NVP (e.g. Purrumbete, Ecklin), others have been associated with a more complex eruptive history and are part of volcanic complexes as discussed below. These may involve maars or tuff rings which have evolved into scoria cone complexes (e.g. Mt. Leura - Stops 4-6, Mt. Noorat - Stop 26), presumably as a result of the magma conduit becoming impermeable to water during the eruption. In other situations maars are parts of multiple eruption point volcanic complexes, which could include multiple maars, scoria cones and tuff cones (e.g. Red Rock Volcanic Complex - Stops 1-3).

The deposits of the maars and tuff rings vary enormously in their character, a theme which will be a principal one of his field trip. The deposits of simple maars, such as Purrumbete (Stop 27), are dominated by gently outward dipping (<10^{o}) pyroclastic (base) surge deposits with spectacular dune-form bedded lapilli-tuffs, co-surge fall deposits, and minor fall deposits. Others consist of a huge variety of deposits, including dune-form bedded lapilli-tuffs, massive to diffusely bedded lapilli-tuffs, bedded fine tuffs, often with ballistic impact sags, and not uncommonly interbedded strombolian scoria beds (e.g. Purdigulac/Coragulac maar, Red Rock - Stops 1-3; Tower Hill maar - Stop 25).

Tuff cones (Thorarinsson 1967; Verwoerd and Chevallier 1987; Cas et al. 1989; Sohn and Chough 1989; Chough & Sohn 1990), are uncommon in the NVP. Tuff cones, like scoria cones are conical in form and have steep slopes. Tuff cones are most commonly associated with phreatomagmatic shallow marine explosive ("surtseyan") eruptions such as the eruptions of Surtsey in 1963-67 (Thorarinsson 1967). The remains of surtseyan type cones are preserved in the lower cliff exposures of Lady Julia Percy Island (Fig. 3; Joyce 1988) and in the coastal cliffs of Cape Bridgewater (Stop 15) . In both cases they are capped by subaerial shield lavas. In addition, a tuff cone complex is also preserved in the Older Volcanics in an Eocene-Oligocene Surtseyan complex of the Otway Basin near Airey's Inlet (Stops 28-29).

The deposits of tuff cones are diffusely bedded, planar bedded, wavy bedded, and dune-form bedded lapillli-tuffs, tuffs, bomb and block beds, and even locally spatter beds. Dips are steeper than in maar and tuff rings, generally being 15-20^{o}. In the Red Rock Volcanic Complex there are cones that appear to consist of both scoria and phreatomagmatic tuff.

Volcanic complexes are the most spectacular volcanic centres in the NVP. They consist of multiple eruption point, often multiple volcano complexes. They vary at one extreme from the largest maar in the NVP, the Tower Hill maar which has a scoria cone complex in the centre of the maar (Stops 23-25), to multiple nested maar and scoria cone complexes (e.g. Red Rock Volcanic Complex - Stops 1-3; Mt. Gambier - Stops 7-10), to fissure vent and spatter cone complexes (e.g. Mt. Eccles - Stops 21-22). In some of the simpler of these complexes there appears to have been a progression from maar eruptive activity to scoria cone activity. For example at both the Mt. Leura (Stops 4-6) and Mt. Noorat volcanic complexes maars and tuff rings are partially buried under a younger scoria cone complex. In other complexes, there appears to have been a fluctuation between phreatomagmatic and strombolian explosive eruptive activity during the history of the volcanic complex (e.g. Red Rock - Stops 1-3; Tower Hill -Stops 23-25).

The deposits of volcanic complexes can be extremely complex, varying from successions of interbedded phreatomagmatic and magmatic pyroclastic deposits that are mainly surge in origin (e.g. Tower Hill), to those with basal phreatomagmatic successions resulting from initial maar/tuff ring activity to younger strombolian scoria deposits, resulting from a late stage change to strombolian activity (Mt. Leura, Mt. Noorat).

MODES OF FRAGMENTATION

Fragmentation processes in basaltic volcanic terrains can be subdivided into three general categories: pyroclastic, autoclastic and epiclastic (Cas & Wright 1987; Cas 1989b). **Pyroclastic processes** include magmatic explosions, phreatic explosions and phreatomagmatic explosions. **Magmatic explosions** (Sparks 1978) are entirely driven by the explosive expansion of exsolving magmatic volatiles. The intensity of the explosive activity is directly related to the volatile content, especially H_2O and CO_2, and the rate at which these exsolve. The higher the volatile content, the greater the vapour pressure exerted by the volatile component, and therefore the sooner that it begins to exsolve during the ascent of the magma. Counterbalancing exsolution is the confining pressure affecting the magma in the subsurface, which may be any combination of magmastatic, hydrostatic and lithostatic. As gas bubbles grow they rapidly expand. They eventually impinge on each other and cease to grow. However if the total fluid pressure in the magma significantly exceeds the ambient atmospheric pressure in an open vent, then explosive disruption of the magma will occur. The products will be highly vesiculated scoria and cuspate shards (burst bubble walls).

Scoria is the product of magmatic explosive eruption of basaltic magma. The scoria cones in the Newer Volcanics Province, as well as the more dispersed layers of scoria occurring beyond the limits of cones, represent prolonged magmatic explosive episodes, usually of the strombolian type, as discussed below. Even scoria cones, however, may experience intervals of phreatomagmatic activity (eg. Mt. Eccles), and vice versa, phreatomagmatic centres may experience intervals of magmatic explosive activity (eg. Tower Hill, Leura, Red Rock), producing complex eruptive stratigraphies.

Phreatic explosions are essentially just steam explosions resulting from the superheating of groundwater or surface water by magma. The exploding steam is essentially external water, not magmatic water, although some of the latter may also be involved. Where solids are erupted, they are fragments of country rock, and little or no primary magmatic component is erupted. No phreatic deposits sensu stricto are known in the Newer Volcanics Province.

Phreatomagmatic explosions are hybrids between the former two explosion types. When magmas come into contact with groundwater or surface water, the water is superheated, volatilises, and given a confining pressure and strength of overburden country rock (relevant in the subsurface situation) that are lower than the gas pressure in the superheated steam, explosive expansion of the steam may occur. The magma in contact with the water will almost certainly be fragmented. Simultaneously, the magma that is in contact with the water will be quench shattered (see below). Both processes open up fractures that give further access to water into the magma body. This sets up a self-sustaining system called fuel-coolant interaction involving repeated, closely spaced collapse of a steam film that develops between the magma and the liquid water leading to direct contact and explosive superheating of the water (Colgate & Sigurgeirsson 1973, Peckover *et al.* 1973, Wohletz 1983, 1986).

The products will be dominated by variably vesiculated fragments of varying sizes (Heiken & Wohletz 1986; Houghton & Wilson 1989), depending on the degree of vesiculation of the magma prior to its interaction with external water. The size of the debris depends on the efficiency of the explosive activity. The efficiency of the explosive activity is controlled largely by the water to magma mass ratio, and is at a peak where the ratio is about 0.3 (Sheridan & Wohletz 1981, Wohletz 1983; Heiken & Wohletz 1986; Fig. 5), producing extremely fine fragmentation, and usually very wet ashes (e.g. some of the Tower Hill ashes). Where explosive efficiency is less coarser, "drier" deposits are produced. In some instances, initial fragmentation may be caused by magmatic explosions, followed by secondary phreatomagmatic fragmentation. However, there are also some deposits which contain both highly vesiculated and poorly vesiculated juvenile debris (e.g. Cape Bridgewater), which require more complex explanations.

Some of the most spectacular volcanic landforms

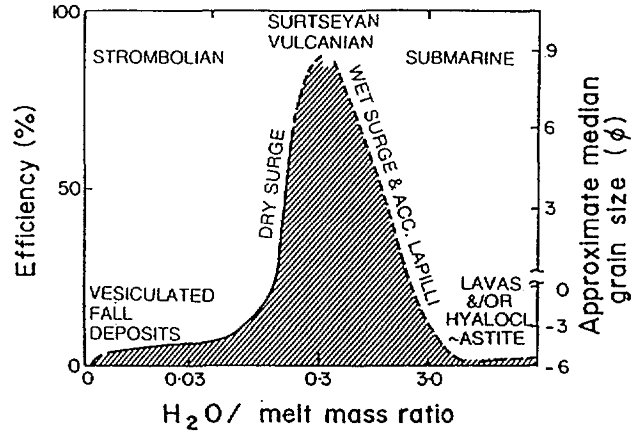


Figure 5: *Efficiency of explosive activity as a function of water: magma mass ratio, with an estimation of the fields appropriate to different eruption styles.*

in the Newer Volcanics Province, such as Tower Hill and the Mt. Gambier centre, are phreatomagmatic volcanic centres. Although some centres preserve only phreatomagmatic deposits (e.g. Purrumbete), others also record, short-lived, but repeated changes to magmatic explosive activity (eg. Tower Hill, Leura; Edney 1987), producing complex stratigraphies.

In the Newer Volcanic Province, phreatomagmatic explosive activity appears to have been sourced by dynamic subsurface explosive interaction between rising basaltic magmas and groundwater aquifers (especially limestone units) in the Tertiary succession of the Otway Basin. However, given that this continental basaltic province interfaces directly with the sea, it would be surprising if some shallow marine phreatomagmatic tuff cones like Surtsey had not formed through explosive interaction between basaltic magma and seawater. The Cape Bridgewater volcano near Portland appears be one such centre, and the Eocene-Oligocene Angahook Member of the Demons Bluff Formation of the Otway Basin is another.

Autoclastic processes include **autobrecciation** and **quench fragmentation**. In the former a solidifying lava, or outer crust of a lava breaks into slabs and blocks under the influence of continued flow within the lava. Intrusives may also be autobrecciated. Quench fragmentation involves the shattering of glass as it comes into contact with cold water. It chills, contracts, and shatters into splinter-shaped fragments, aggregates of which are called hyaloclastites.

Epiclastic processes are common in all volcanic terrains, and can be responsible for both the fragmentation and transportation of significant volumes of volcaniclastic debris. Processes include gravitational collapse and erosion from the influences of water, wind and ice. Isolated resedimented deposits are known at Tower Hill in the scoria cone complex, as well as at Cape Bridgewater. However, basaltic terrains do not produce large volumes of epiclastic debris due to the high weatherability of basaltic glassy material, especially in temperate to tropical climates. Exceptions to this occur in cold climates such as Iceland. Although some deeply entrenched streams drain the Newer Volcanics Province, their beds contain little clastic debris, implying major transport of material in solution. *In situ* soil formation is a major process.

ERUPTION STYLES AND PYROCLASTIC FALLS

Eruption styles can be subdivided into effusive eruptions that produce lavas, and explosive ones that produce pyroclastics. The greatest volume of basaltic products are produced by effusive eruptions. Explosive basaltic products are volumetrically minor in comparison, which is a reflection of the generally low volatile content of basaltic magmas. Of the common eruption styles (Cas & Wright 1987) those represented by deposits in the Newer Volcanics Province include hawaiian, strombolian, vulcanian and surtseyan-phreatomagmatic.

In **hawaiian activity** the eruption column is essentially a lava 'fire' fountain formed when jets of disrupting magma are released, almost continuously in some cases, through the vent. Generally lava fountain heights are less than about 200m (MacDonald 1972) and in such cases magma would be ejected at velocities of a few tens of metres per second (Wilson & Head 1981). The predominant products of these lava fountains are large spatter pieces which fall back around the vent area. These may form discrete spatter deposits or agglutinates (e.g. Mt Eccles), or reconstitute into lavas, including near-vent clastogenic lavas (e.g. Cape Bridgewater) which preserve some fragmental character. Poorly developed convective plumes above lava fountains may take the smallest ash-sized particles derived from lava spray up to heights of a few hundreds of metres, but all coarser fragments will already have fallen out of the column. Hawaiian deposits have low D and F characteristics (Walker 1973).

Although hawaiian eruption style is almost universally considered to be a pyroclastic style of volcanism, is this necessarily so? Fire fountaining is indicative of the eruption of low viscosity magma under the driving force of a high total fluid pressure. Although this may include in part a gas fluid pressure component, this need not be a dominant component if the intial lithostatic pressure on the rising magma is high enough. This may in itself be enough to generate a fountain, and the fragmentation mode in such a fountain may simply be extension and air induced quenching as the fountain above the vent spreads as it loses momentum. Explosive expansion of volatiles (pyroclastic sensu stricto) need not be a fundamental or universal fragmentation process in fire fountains. The occurrence of spatter deposits on the deep sea floor, below the maximum depth for explosive volcanism suggests that non-explosive fire foutaining can be a sginficant eruptive style in both subaerial and subaqueous settings (Cas 1991).

The mechanisms and dynamics of **strombolian activity** have been discussed by Blackburn *et al.* (1976), Wilson (1980) and Wilson and Head (1981), and have been summarized by Cas and Wright (1987) and Cas (1989b). Eruptions consist of a series of discrete, time transient explosions separated by periods of less than 0.1 seconds to several hours. Explosions are thought to be generated when one or a number of large gas bubbles (<1 to >10m in diameter) burst the magma surface of a lava lake in the vent in a low viscosity magma (Blackburn *et al.* 1976). When each bubble bursts the fragmented remains of the magma which formed the upper skin of the bursting bubble (Blackburn *et al.* 1976, Wilson 1980) are blasted out as pyroclasts. If there is a pause in activity, and/or as in the waning stages of an eruption, a crust has time to form on the magma surface, this may be ejected during renewed bubble burst events. This mechanism may account for the slabby lava blocks found in some deposits.

If explosions occur in rapid succession (e.g. every 1-2 seconds), a maintained eruption column, driven by convection, could reach heights of 5-10km, as observed in the 1973 Heimaey eruption (see Blackburn *et al.* 1976), and deposit a thick massive scoria deposit close to vent, such as those making up the scoria cones of the Newer Volcanics Province (eg. Mt. Elephant, Leura Tower Hill, Gambier cone complexes), as well beyond on the surrounding landscape. D-F characteristics of strombolian deposits are also low (Walker 1973).

Vulcanian pyroclastic fall deposits from individual eruptions are thin, small volume (<1km^3), stratified ash deposits which contain large ballistic bombs and blocks near-vent, sometimes with breadcrusted and jointed surfaces. In composition they are usually intermediate (basaltic-andesite, andesite, dacite) but basaltic ones are also known (e.g. Tower Hill).

Activity during vulcanian eruptions proceeds as discrete cannon-like explosions at intervals of commonly tens of minutes to hours, producing a series of small eruption columns (<5-10km) with plumes strung out downwind of the volcano. Pyroclastic fall deposits are fine-grained with a wide dispersal. Larger fragments in the column simply fall back around or into the vent to be further fragmented and abraded. Commonly, the material ejected with each explosion includes a large fraction of country rock as accessory lithics. At the onset of an eruption a plug of older, pre-existing lava may first be exploded out. However, coarser grained scoria fall deposits of more limited dispersal, can also be produced during periods of more intense, maintained explosions with continuous gas-streaming. Eruption columns reach heights >10-20km. Hence two types of fall deposit are formed during eruptions which have overall been termed vulcanian. Small-volume pyroclastic flows are also frequently generated during vulcanian eruptions when large amounts of ejecta fall back around the vent, and a dense aggregate of debris. Vulcanian fall deposits may have moderate D-F characteristics (Walker 1973).

The term **'surtseyan'** was used by Walker (1973) to describe the type of air-fall deposit which would result from similar activity to that observed during the eruption of Surtsey in 1963 (Thorarinsson 1967). Since then the surtseyan field has been used in a general way to group basaltic fall deposits resulting from different types of hydrovolcanic explosion. Kokelaar (1983) has pointed out there may be significant differences between true surtseyan activity, where water floods into the top of an open vent, and phreatomagmatic activity involving trapped groundwater.

In the Newer Volcanics Province groundwater induced phreatomagmatic activity is well represented by the maars and tuff rings of the southern half of the province (e.g. Purrumbete, Leura, Red Rock, Tower Hill, Gambier). However, true surtseyan activity may also be represented by at least the Cape Bridgewater centre, which is now connected to the mainland via a peninsular dominated by aeolian deposits of the late Pliocene-early Pleistocene Bridgewater Formation. However during the late Tertiary,the Cape Bridgewater centre may have been located, and may have grown in a shallow marine offshore setting, as originally proposed by Boutakoff (1963). The Eocene-Oligocene Angahook Member of the Demon's Bluff Formation of the Otway Basin (Stops 28-29) also represents an example of true surtseyan activity.

Phreatomagmatic activity is very common in basaltic volcanic fields producing maars, tuff rings and tuff cones. These constructional forms are largely built up from the deposits of base surges, and thin ash-fall beds occur downwind. (e.g. Red Rock, Purrumbete, Leura, Tower Hill, Noorat).

The downwind air-fall deposits are thin, fine-grained ashes and internally they may be well laminated because phreatomagmatic activity seems to occur as a number of short explosions. They often contain accretionary lapilli (e.g. Tower Hill, Red Rock, Cape Bridgewater), and SEM photographs of the ashes show very angular, broken surfaces due to the magma-water interaction (Walker & Croasdale 1972, Heiken 1972, Heiken & Wohletz 1986). Bimodality and poor sorting are important properties and are attributed to premature fall-out of aggregated wet or damp ash in the eruption column or downwind plume. Accreted ash could occur as accretionary lapilli or unstructured ash clumps.

Nearer the vent this type of air-fall deposit is found interbedded with base surge deposits. In addition, although there has been a tendency to attempt to classify near-vent phreatomagmatic pyroclastic deposits into end member fall and flow deposits, in near-vent situations both modes of deposition are likely to occur simultaneously, as ash from a previous explosion, or from a maintained column, falls around the vent into newly generated base surges. Cas (1989b) has proposed that near-vent hybrid surge modified fall deposits should occur.

In summary, hawaiian and strombolian eruption styles, both of which contribute to the growth of scoria cones and to a lesser extent maars, tuff rings and tuff cones. In addition, surtseyan/phreatomagmatic styles are major contributors to the pyroclastic deposits in maars, tuff rings and tuff cones. Vulcanian eruptions may also occur in both groups of centres.

PYROCLASTIC TRANSPORT PROCESSES

Pyroclastic debris can be transported from vent by several distinct processes (Cas and Wright 1987; Fisher & Schmincke 1984):
-ballistic ejection,
-eruption column rise and dispersal,
-pyroclastic flows,
-pyroclastic surges
-surge-modified falls.

The ejection of coarse debris on **ballistic** trajectories is commonly observed in all eruption types. Blocks, fluidally shaped bombs and associated impact sag structures are common features, and signify near-vent settings. Particularly good examples occur at Red Rock and Tower Hill. Impact sag structures develop where substrate layers are cohesive, wet ashes. Where the substrate consists of a thick accumulation of cohesionless scoria, little or no impact structure may form. Examples of both types of impact effect are well developed in the quarries in the rim of the Tower Hill maar. In addition to the occurrence of isolated ballistic blocks or isolated clusters of ballistic blocks, there are rare occurrences of regular trains of ballistics (e.g. Red Rock Volcanic Complex). One particular horizon at Red Rock (Stop 3) consists of fines depleted lenses of accidental and accessory lithics together with very large scoria clasts at a regular spacing or wave length, suggesting an undulating, lateral, shortlived ballistic flow component.

Pyroclastic falls, as described in the previous section, are usually associated with the development of an eruption column, however short-lived. Such columns have a lower gas-thrust zone, which may rise up to several hundred metres above the vent, and above that a convective column in which particle support is entirely due to convection in the column and the turbulence it generates. At a density level in the atmosphere where the bulk density of the gas-steam-ash laden column equals that of the atmosphere, the column spreads in what is known as the umbrella region, and the column may be deflected downwind by upper atmosphere winds to produce a downwind plume. Air-fall deposits can form directly out of the column near-vent, or from the downwind plume, and usually (but not always) there is a regular decrease in thickness and grainsize downwind. Deposition occurs in a particulate form, and the column related sorting processes produce relatively well-sorted deposits. Fall deposits are well represented in all the pyroclastic volcanic centres of the Newer Volcanics Province.

In some instances, eruption columns become so overloaded with pyroclastic debris that the bulk density of the column exceeds that of the atmosphere. The column collapses gravitationally, and under the influence of the potential energy and of the lubricating effects of entrained volatiles and fluidising ingested air, the mass of pyroclastic debris, gas and steam, moves laterally as a very dynamic gas-supported, high particle concentration **pyroclastic flow**. Pyroclastic flows are common with intermediate to acidic plinian eruptions, and on a small scale with dense column vulcanian-strombolian eruptions. They are not recognised as significant transporting agents in basaltic terrains, but spatter flows have been documented (Ref..). None have been recognised from the Newer Volcanics Province.

Pyroclastic surge is also a type of pyroclastic flow, but of the low particle concentration type. It is commonly recognised as a discrete pyroclastic transport process. In surges the pyroclastic fragments are supported by turbulence in the interstitial gas and steam. Three types of surge are recognised: base surge, ground surge, and ash-cloud surge. The last two are spawned by pyroclastic flows and are therefore essentially not recognised in basaltic terrains.

Base surges are so named because they appear to develop from the bottom of phreatomagmatic eruption columns or explosion plumes. In some instances they may in fact originate from partial collapse of an eruption column, but more commonly they are initiated as lateral blasts from vent, and spread radially from vent as an expanding collar much like analogues from nuclear explosions. Some of the best descriptions of the processes and products are the early works such as those of Moore (1967), Fisher and Waters (1970), Crowe and Fisher (1973), Schmincke *et al.* (1973), Sheridan and Updike (1975) and Sheridan and Wohletz (1983). The best recent accounts include those of Sohn and Chough (1989) and Chough and Sohn (1990).

The transportation and depositional processes are complex and have been reviewed by Cas and Wright (1987) and Allen (1982). Although the system is essentially particulate, and produces tractional bedforms and structures, complications arise from the fact that base surges are three phase systems, consisting of solids, gas and liquid water. Fine ash and water commonly clump together to form cohesive ash-mud lumps which are constantly being reconstituted by the high shear stresses operating. There may also be significant adhesion between the flow, its components and perhaps a wet substrate. As such, wet ash may be intermittently at rest or in transit. Furthermore condensation of water during flow as the surge cools, may significantly change the character of the surge in transit.

Typical structures include low profile dune-forms and low angle fluidal cross-stratification, horizontal stratification and both massive ashes and lapilli-ashes/tuffs. Cross-stratification and horizontal stratification are common products of particulate tractional transport in epiclastic sedimentary systems and the same would appear to be the case here. However, the cross-stratification in surge deposits is almost always lower than angle of repose, suggesting that a significant lateral shear stress was operating at the bed, and that conditions were perhaps akin to high flow regime antidune stages in aqueous sedimentary settings. However, such analogies may be misleading because sedimentary flow regime concepts apply only to inertail, cohesionless granular flow systems and not to cohesive, viscous flow systems. The massive ash facies appear to be the product of deflation of the surge away from vent, whereas the lapilli-ash facies appears to be a near-vent, high concentration grain underflow developing out of the head of the surge, as suggested by Leys (1982), and verging on being a near-vent, small scale pyroclastic flow. Initial studies of lateral facies changes in single surge deposits by Wohletz and Sheridan (1979) have been found to be too simplistic (Edney 1987; Sohn and Chough 1989; Chough and Sohn 1990). Significant down flow changes do occur, but these will vary significantly according to the grainsize and moistness of individual surges. This has led to the concept of "wet" and "dry" surges.

Base surge deposits are commonly found in the rims of maars, tuff rings and tuff cones, and are well developed in such centres in the Newer Volcanics Province of southeastern Australia (eg. Purrumbete, Leura, Red Rock, Tower Hill).

Surge-modified fall deposits were recognised by Cas (1989b) in the Cape Bridgewater surtseyan volcanic succession (Stop 15). In the near-vent settings of maars, tuff rings and tuff cones, under the influence of a continual succession of phreatomagmatic blasts that produce rising explosion plumes and base surges, both airfall and surge processes must be simultaneously contributing to near-vent deposition of pyroclastic debris, producing aspectrum of deposits loosely called surge-modified fall deposits.

SUMMARY OF PROBLEMS AND AIMS OF FIELDTRIP

Although the principal focus of this fieldtrip is on hydrovolcanic, especially phreatomagmatic phenomena, other incidental volcanological phenomena will also be addressed. The principal problems to be addressed and aims of this fieldtrip are to consider:

1. The factors influencing phreatomagmatic explosive eruptions and the nature of the deposits.
2. Factors causing multiple vent volcanic centres.
3. The causes of fluctuations in explosive eruption styles of maars from phreatomagmatic to magmatic and vice versa.
4. Do maars erupt strombolian scoria deposits, and if so what are the prerequisites?
5. Are surge-modified fall deposits a reasonable concept, and if so, by what criteria could they be recognised?

6. The origins of highly vesiculated scoria clasts in less well vesiculated phreatomagmatic deposits.

7. Transportational and depositional processes in surges.

8. Distinguishing planar bedded fall deposits from planar bedded surge deposits.

9. The significance of grainsize in near vent phreatomagmatic deposits - does fine grainsize indicate intense explosive activity and course grainsize weak explosive activity?

10. The origin of lensoidal fines depleted ballistic deposit layers.

11. Is hawaiian-style fire fountaining necessarily a pyroclastic phenomenon?

12. Factors influencing the formation of intrusive pillows.

13. Erosional discordances (channels) in phreatomagmatic tuff/maar ring sequences - epiclastic or surge erosion?

14. Distinguishing epiclastically reworked, cross-stratified phreatomagmatic debris, from primary cross-stratified base surge deposits.

15. Massive, bouldery, matrix-supported deposits of phreatomagmatic deposits - debris flows or pyroclastic flow deposits?

PART III - FIELD GUIDE

STOPS 1-3: THE RED ROCK VOLCANIC COMPLEX

The Red Rock Volcanic Complex lies northwest of the township of Colac (Fig. 1.1) in an area that typifies the geomorphological character of the basaltic Newer Volcanic Province of Western Victoria. The area has the typical flat to slightly undulating surface relief of the lava plains, which are marked by two types of lakes: those that have been ponded on the landscape by the damming effects of lava flows blocking pre-existing drainage systems (e.g., Lakes Colac and Corangamite), and those that are the crater lakes of maar, tuff ring or tuff cone volcanic centres (e.g. Lakes Purdigulac, Coragulac and Gnalinegurk (maars), Werowrap). Rising above the level of the lava plains and lakes are the rims of maars and tuff rings, and the scoria cones of three closely placed volcanic centres: Red Rock (south), Mt. Alvie (central) and Mt. Warrion (north: Fig. 1.1). These closely spaced centres define a north-northeast trending lineament, presumed to reflect a major crustal fracture used by the magmas as a conduit.

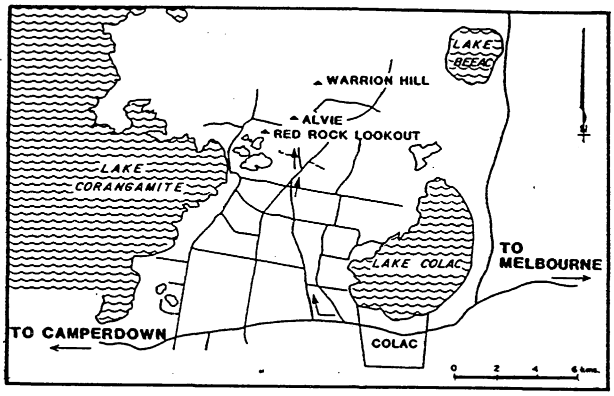


Figure 1.1 *Locality diagram for the Red Rock Vol canic Complex*

The Red Rock Volcanic Complex is a multi-vent volcanic complex, consisting of multiple maars, scoria cones and perhaps even tuff cones. It consists of in excess of 40 individual eruption points, these being represented by overlapping cones, and maars with multiple scalloped outlines (Figs. 1.2,1.3). Based on superposition of volcanic land forms, the cone complex is later than the maars. However, this raises the intriguing question of why strombolian scoria fall deposits are interbedded with phreatomagmatic fall/surge deposits in the maar rims. Either some strombolian cones were active simultaneously with phreatomagmatic maar volcanism, or the maars themselves regularly changed eruption style from phreatomagmatic to magmatic.

The basement to the Newer Volcanics in the area are Miocene limestones of the Port Campbell Limestone and Gellibrand Marl (Heytesbury Group), which are locally unconformably overlain by quartzose sediments of the Pliocene Moorabool Viaduct Formation. These in turn are overlain by the earliest Newer Volcanic lavas of Quaternary age, and then by components of the three volcanic centres mentioned, some of which are almost certainly Holocene. Gill (1978) has dated soil carbonate from a fossil soil in the volcanic succession by C^{14} means, giving an age of 7810 ± 115 years.

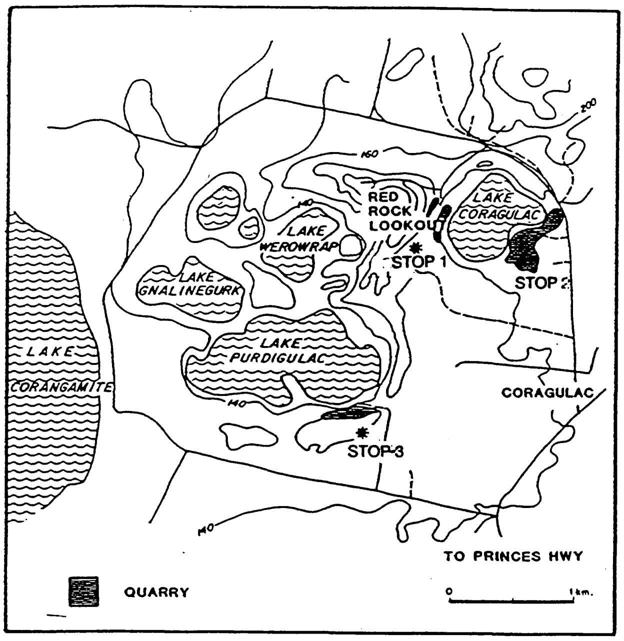


Figure 1.2 *Sketch map of the Red Rock Volcanic Complex showing the location of maars and cones. Eruption points are indicated by dots. Lobate outlines of maars suggest multiple eruption points. Over 40 eruption points are thus indicated.*

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

1. The earliest phase of Newer Volcanics lavas, which may have dammed the landscape initially to produce the first ancestral lake deposits of the Corangamite system.

2. Eruption of the stony rise lavas from the Red Rock region.

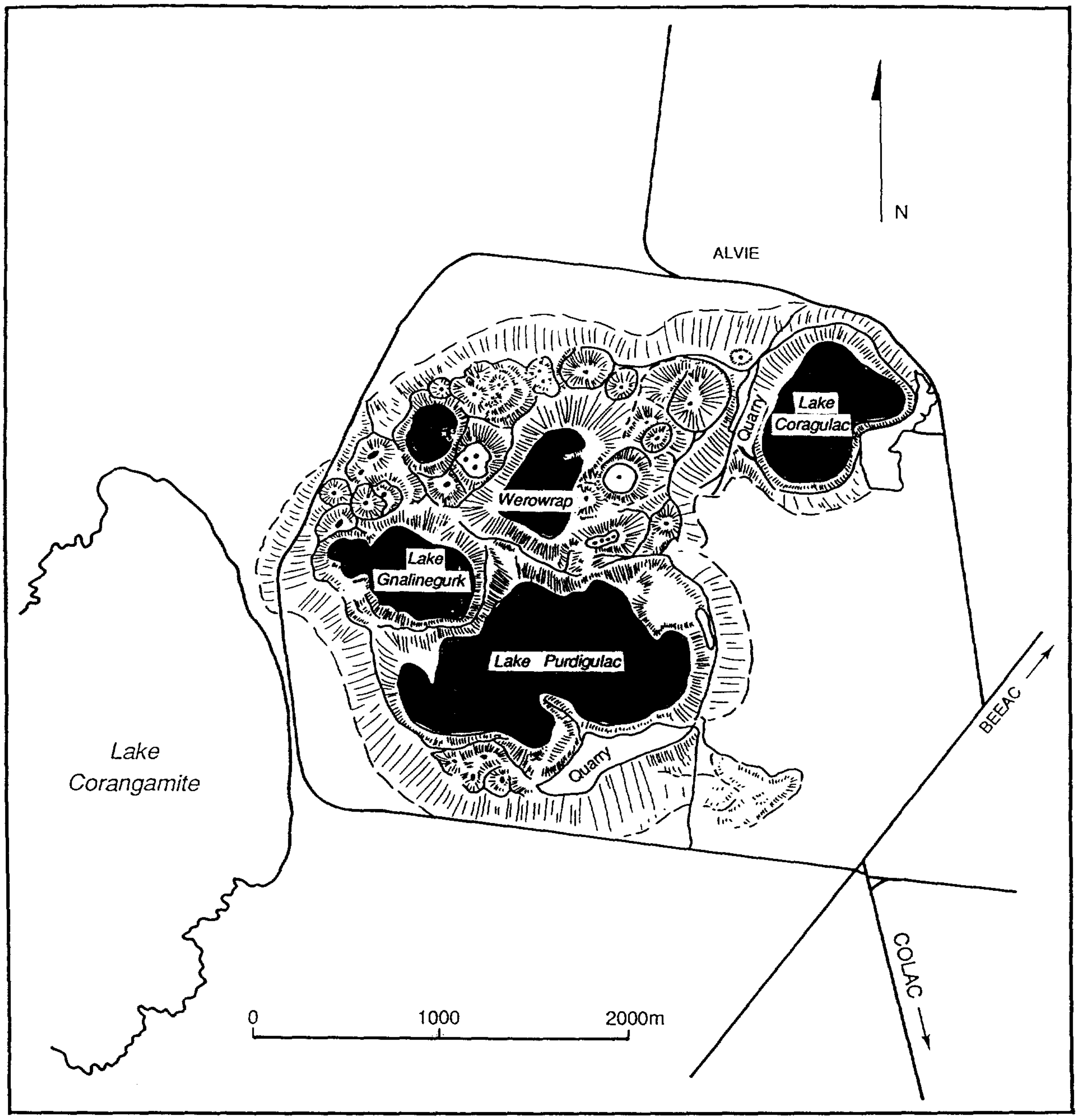


Figure 1.3 *Oblique aerial photo of the Red Rock Volcanic Complex.*

3. Eruption of the stony rise lavas from Mt. Warrion.
4. Mt. Warrion scoria eruptions.
5. Final lava eruption from Mt. Warrion.
6. Formation of Mt. Alvie tuff ring/maar.
7. Mt. Alvie scoria cones.
8. Formation of Red Rock maars.
9. Red Rock scoria cone complex.

The only detailed work done on the volcanic history of the region are the unpublished works of Leach (1977), who concentrated on regional stratigraphy and chronology of volcanism, Forster (1983) and Van Tatenhove (1983), who studied in detail the pyroclastic deposits and the modes of formation and deposition around parts of Lake Coragulac and Lake Purdigulac maars respectively, and Cas et al. (in prep), who are assessing the volcanology of the whole complex.

STOP 1 : Red Rock Lookout - 1 km south of Alvie. From Melbourne drive to Colac via the Geelong-Princes Freeway and Princes Highway. From Colac drive 3km west along the Princes Highway to the Alvie Red-Rock turnoff (Cororooke Rd) on the right. Drive to Coragulac, turn left into Corangamite Lake Road. At Alvie follow signposts to Alvie and Red Rock Lookout (Figs. 1.1, 1.2).

This outstanding vantage point is at the top of the scoria cone complex of the Red Rock Volcanic Complex. According to Leach (1977) the Red Rock Volcanic Complex was initiated with the outpouring of stony rise lavas which are partly preserved between Lake Corangamite and Lake Colac, well to the south of the Lookout. Lake Corangamite is the huge lake (the largest in the Western Districts, and the largest wet lake in Australia) to the west of the lookout. Lake Colac lies in the distance to the southeast. The next phase of eruption was the maar form-

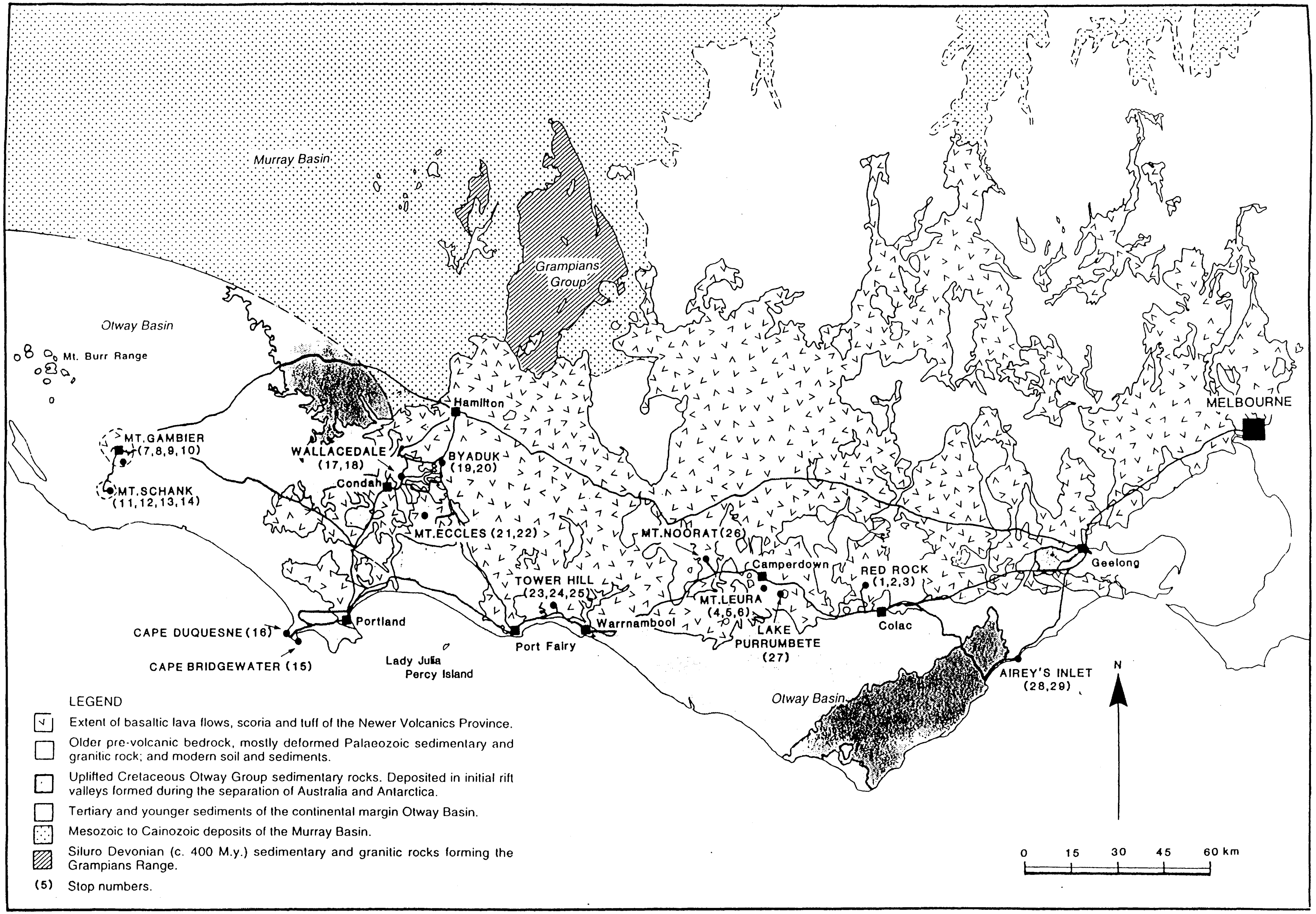


Figure 6: *Route map and location of stops.*

ing phase, of which Lake Coragulac (east), Lake Purdigulac (south), and Lake Gnalinegurk (southwest) are representatives (Fig. 1.2). The final phase was the scoria cone building phase, represented by the hills and several small craters and crater lakes surrounding the Red Rock Lookout. Leach has suggested that there are some 14 eruption points contained within the scalloped margins of the maars, and some 28 eruption points in the scoria cone complex.

The chronology proposed here suggests that the early pyroclastic phase of eruptive activity was predominantly phreatomagmatic, producing the maars, followed by a magmatic phase that produced the strombolian scoria cone complex. The controls on this change will be considered in discusion of Stops 2 and 3.

Other volcanic centres of the NVP can be seen on the skyline on a clear day, including the largest strombolian scoria cone of the NVP, Mt. Elephant to the northwest.

STOP 2: Alvie Municipal Garbage Tip, Lake Coragulac Maar. From the Lookout return to the Alvie Road, turn right, drive 1km and turn right into the lane signposted as "tip".

Outcrop 1

This old quarry, now being used as a community garbage tip, preserves the succession of the eastern part of the Lake Coragulac Maar (Fig. 2.1). Measured sections and lateral tracing indicate that stratigraphic units are laterally continuous, although variations in thickness and grainsize are clearly discernible, particularly in a direction perpendicular to the edge of the maar. The succession consists of layers of scoria ranging from cms to 70 cms thick, alternating with variably vesicular but denser clast lapilli-tuffs, and tuffs some as thin as millimetres. A course block and bomb bed represents the uppermost exposed horizon closest to the maar.

The scoria layers are massive to diffusely layered, and have s_f-Md_f plot characteristics consistent with airfall deposition (Fig. 2.2). The scoria is highly vesiculated (60%-85%), and was clearly produced by magmatic explosive eruption phases, i.e. driven by exsolution and explosive expansion of magmatic volatiles. A strombolian style eruption is clearly indicated, especially for the most vesicular horizon, H.

The lapilli-tuff horizons vary from massive, diffusely layered to lensoidal layering with low angle discontinuities. Some clearly contain large ballistics. The vesicularity of juvine clasts vary from low vesicularity (~ 20%) to high (60%$^{+}$). Ballistics include dense accessory basalt blocks (acessory lithics), sedimentary clasts including limestone and sandstone, and juvenile bombs. At the microscopic scale, abundant quartz silt grains are present, and in the finer ash deposits. This silt size quartz is xenocryst material, and like the larger sedimentary clasts, is derived from the Tertiary part of the Otway Basin. The finer ashes have cryptic accretionary lapilli. Many of these deposits are indurated, and juvenile fragments are palagonitized. These characteristics are consistent with phreatomagmatic explosive eruptive origins. Deposition appears to have been by near-vent base surge deposition, accompanied by fallout processes as evidenced at least by the ballistics. However, so near to vent, other debris in the lapilli-tuffs must also have originated as fall material. Many of the deposits are therefore surge modified fall deposits. On s_f-Md_f plots (Fig. 2.2), lapilli tuffs and tuffs plot in the overlap area of fall and surge deposits of Walker (1971, 1983).

An intriguing aspect of the succession is the alternation between scoriaceous and less vesicular phreatomagmatic layers, in places on a scale of millimetres and centimetres. It is clear that very rapid alternations have occurred in the mechanism driving explosive eruptions, from those driven by explosive expansion of magmatic volatiles to those driven by phreatomagmatic explosive interaction between groundwater and rising basaltic magma. Possible causes for such rapid alternations include slow recharge rates of the aquifer in the sub-surface zone of explosive interaction, or temporary development of, followed by collapse of a lining of impermeable basalt on the margins of the magma conduit. The absence of quartz silt and accessory lithics from the scoria deposits indicate that explosive disruption of the magma did not occur in the subsurface, as for the phreatomagmatic deposits, but in the open vent.

Although scoria fall deposits are usually associated with Strombolian scoria cone eruptions, in this case it would be difficult to imagine the scoria being derived from scoria cone sources, and the phreatomagmatic deposits being derived contemporaneously from the maar, producing such intricate layering. It seems more reasonable to consider the whole succession, including scoria deposits, to have been erupted from the maar, and the alternation of magmatic and phreatomagmatic deposits, to have been produced by variations in magma-water interaction. Scoria layers are therefore not just indicative of Strombolian scoria cone centres. Presumably scoria forming eruptions were too short to produce a cone, or if a small cone did begin to grow in the maar, it may have been destroyed by the next phreatomagmatic explosive burst.

Outcrop 2

Walk to the northern end of the quarry, and climb the northern wall walking towards the maar. Clamber down into the old quarry near the shoreline.

Massive to diffusely planar bedded Scoriaceous block and bomb facies are exposed, with bedding dipping into the maar crater, and wrapping over the rim of the crater to the east. This facies coincides with the uppermost facies in the tip quarry. This exposure contains numerous spindle shaped bombs, suggesting a near-vent setting. Such facies are more characteristic of scoria cone successions than more distal fall out deposits. However, the nearest scoria

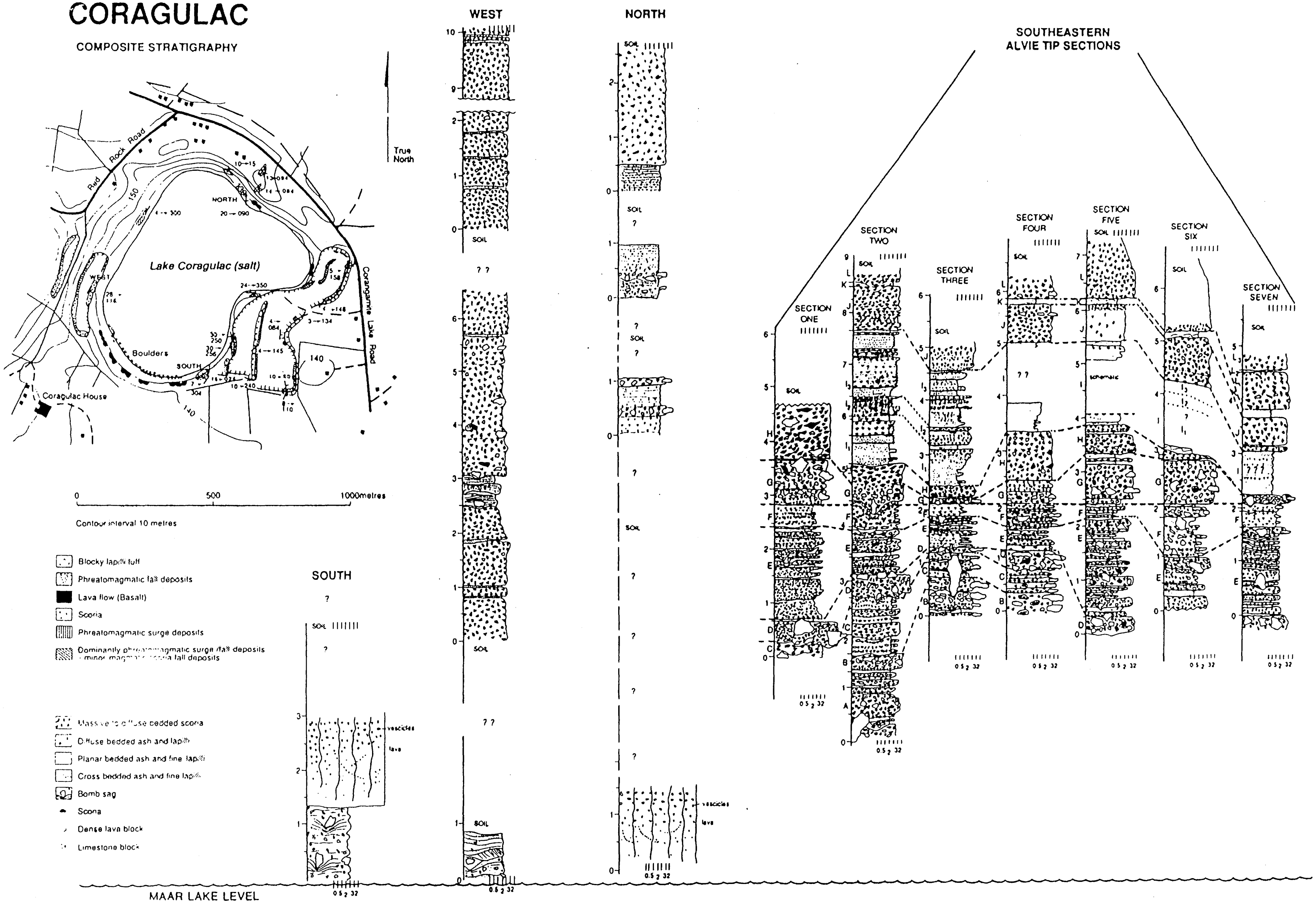


Figure 2.1 *Map of the Lake Coragulac Maar, Red Rock Volcanic Complex. Measured sections are from localities shown.*

cones are 500-700m away on the opposite side of the maar. Exposed slope deposits on these cones are finer scoria deposits, not block and bomb beds. As for Outcrop 1, there is a clear implication that strombolian style deposits, including bedded deposits of substantial thickness can be produced by maars, without forming substantial scoria cones.

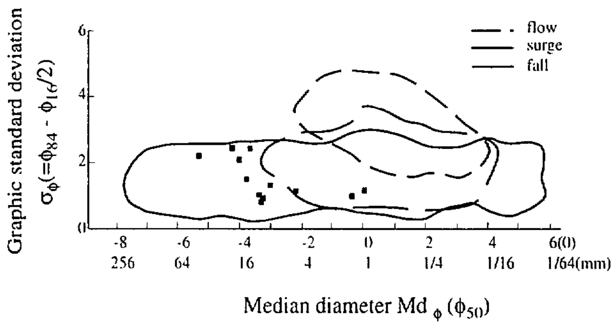


Figure 2.2 *sf-Mdf plots of scoria and phreatomagmatic lapilli-tuffs, Alvie garbage tip, Lake Coragulac maar.*

Outcrop 3

Return to the tip quarry and walk along northern boundary to gate. If permission has been sought, pass through gate into another old disused quarry.

This quarry exposes a similar succession to that exposed in the tip quarry. 50m-100m to the north west, there are east-west orientated faces. In one of these there is a discontinuous horizon of accessory lithics, dense juvenile lithics and coarse scoria occurring as a series of fines depleted lenses (Fig. 2.3). The overlying unit in a fine grained ash and lapilli-ash with undulating layering. Some of the elongate blocks have landed with long axis upright, and partially embedded in the underlying lapilli tuffs. These blocks appear to have been emplaced from ballistic trajectories. However, a ballistic trajectory origin does not explain the lensoidal nature and the regular 1-1.5m wavelength spacing of the lenses.

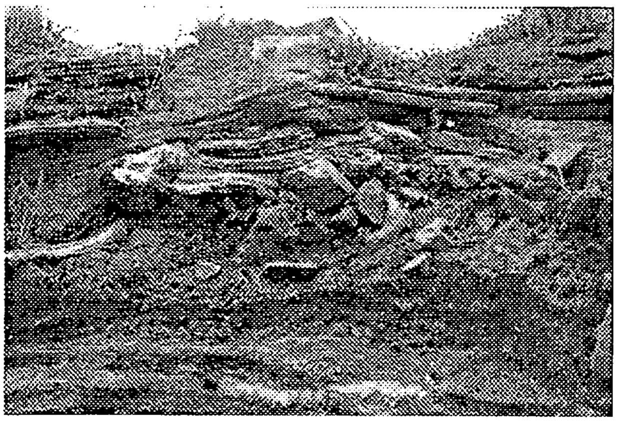


Figure 2.3 *Lensoidal fines depleted lithic-scoria deposit interpreted as a blast flow deposit.*

Two alternative explanations are possible. They may represent a trail of lithics and juvenile debris transported by the overlying surge deposits. Either the lithics segregated to the bottom of the base surge, or the lithics were incorporated into the base of surge from the existing depositional surface, and aggregated into regularly spaced lenses or dunes of debris as the surge passed through a flow regime stage where it began to oscillate.

The preferred interpretation is that the lenses represent a small fines depleted blast deposit. The blast flow would have produced disconnected debris lenses or dunes, much like starved ripple horizons produced by distal turbidites with a low granular sediment budget. The combination of identifiable ballistic blocks, with juvenile dense clasts and scoria, suggest a vulcanian type blast resulting from gas pressure build-up resulting from the development of a congealed lava crust in the vent.

STOP 3 : Russell's Pit, Lake Purdigulac Maar, Red Rock Volcanic Centre. From the Alvie Tip return to the Alvie Road, turn right and drive back towards Colac. Turn right into Lineen's Road and drive for 2km (Figs 1.1, 1.2). Stop at the farmhouse into Russell's pit/quarry on the right and ask permission. This is private property and permission must be sought. Drive into quarry.

This quarry lies on the southern part of the maar rim around Lake Purdigulac (Fig. 3.1). The lake has an irregular, scalloped shape suggesting that it hosts multiple eruption points. The quarry walls expose a diversity of pyroclastic products that produce a highly variable stratigraphy (Fig. 3.1).

The products include phreatomagmatic airfall and surge deposits as well as strombolian-style scoria fall deposits and distinctive ballistic block beds (Fig. 3.1and Table 3.1). The alternation of phreatomagmatic deposits with magmatic strombolian-style fall deposits suggest that significant fluctuations in the degree of magma to water interaction have occurred. This is even reflected in the phreatomagmatic deposits by virtue of the variations in grain size, slumping features, and degree of vesiculation of clasts.

Outcrop 1

A prominent channel structure cut into bedded phreatomagmatic lapilli ashes and filled with bedded ash, lapilli ash and towards the top, scoria beds (Figs. 3.2, 3.3) occurs at the eastern end of the quarry and has two possible origins: eroded by surges, or eroded by fluvial gullying. The channel base shows no evidence of pre-filling weathering. It is overlain directly by steeply dipping pockets of slumped wet surge deposits rather than fluvial channel deposits, suggesting that a surge origin is likely. The lensoidal pocket of volcanic breccia within the lower part of the channel is problematic. It may be a fluvial lag deposit or a pocket of coarse clasts that were entrained by and deposited by surges. It is conformable with interpreted surge deposits and its top is concave up, both suggesting a surge origin. Alternations of scoria deposits and

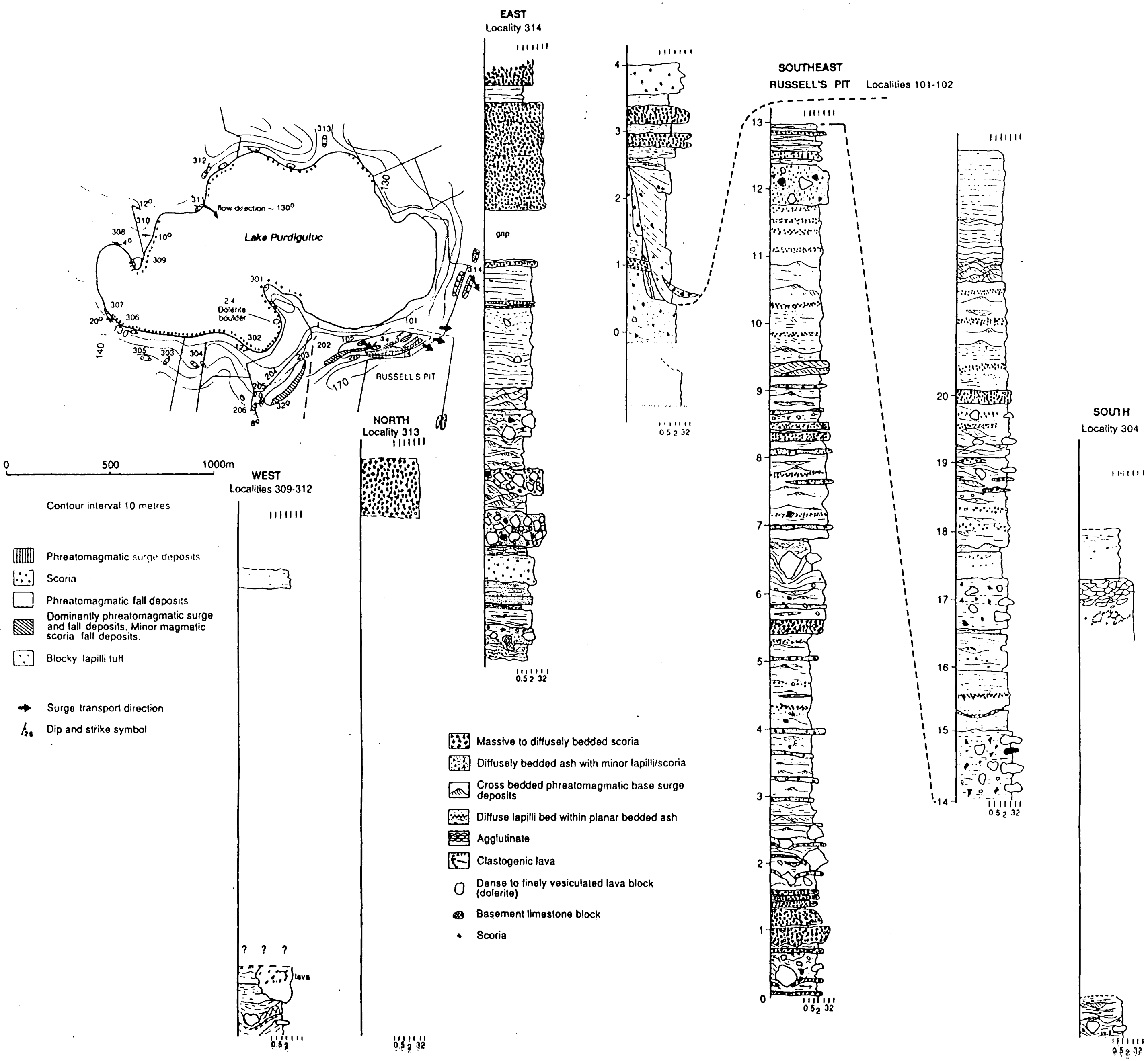


Figure 3.1 *Map of the Lake Purdigulac Maar, Red Rock Volcanic Complex. Measured sections are from the localities shown.*

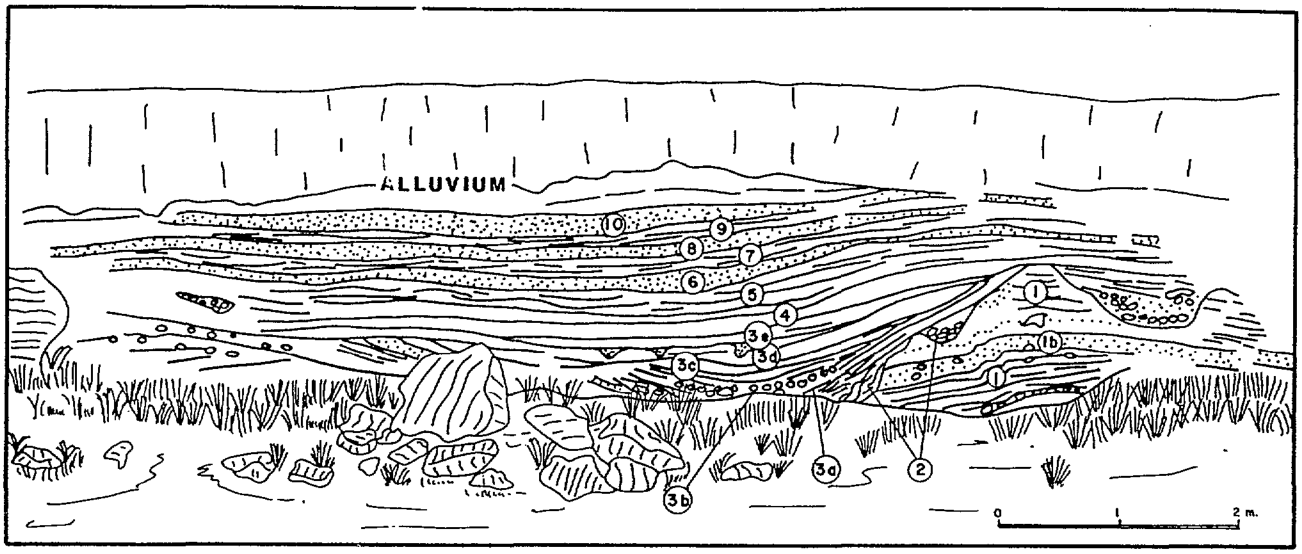


Figure 3.2 *Line drawing interpretation of channel and deposits shown in Fig. 5.*

phreatomagmatic deposits in the upper parts of the channel fill succession (Figs 3.2, 3.4) indicate magma-water ratio variations during a continuous explosive eruption phase.

Outcrop 2

At the western end of the quarry two distinctive block horizons occur (Figs. 3.1, 3.4) with the largest blocks being up to 1 m in diameter. Major impact sag structures (Fig. 3.5) testify to the ballistic, explosive origin of the blocks. Blocks consist of both basalt and limestone and their eruption corresponds to a change from fine surge ashes to coarser lapilli-ash surge deposits. The dual compositional character of the blocks suggests that they originated by vent-wall erosion and therefore correspond to significant vent widening. The limestones may be

Figure 3.3 *Channel margin draped by "wet" surge deposits at eastern end of Russell's Pit, Lake Purdigulac Maar.*

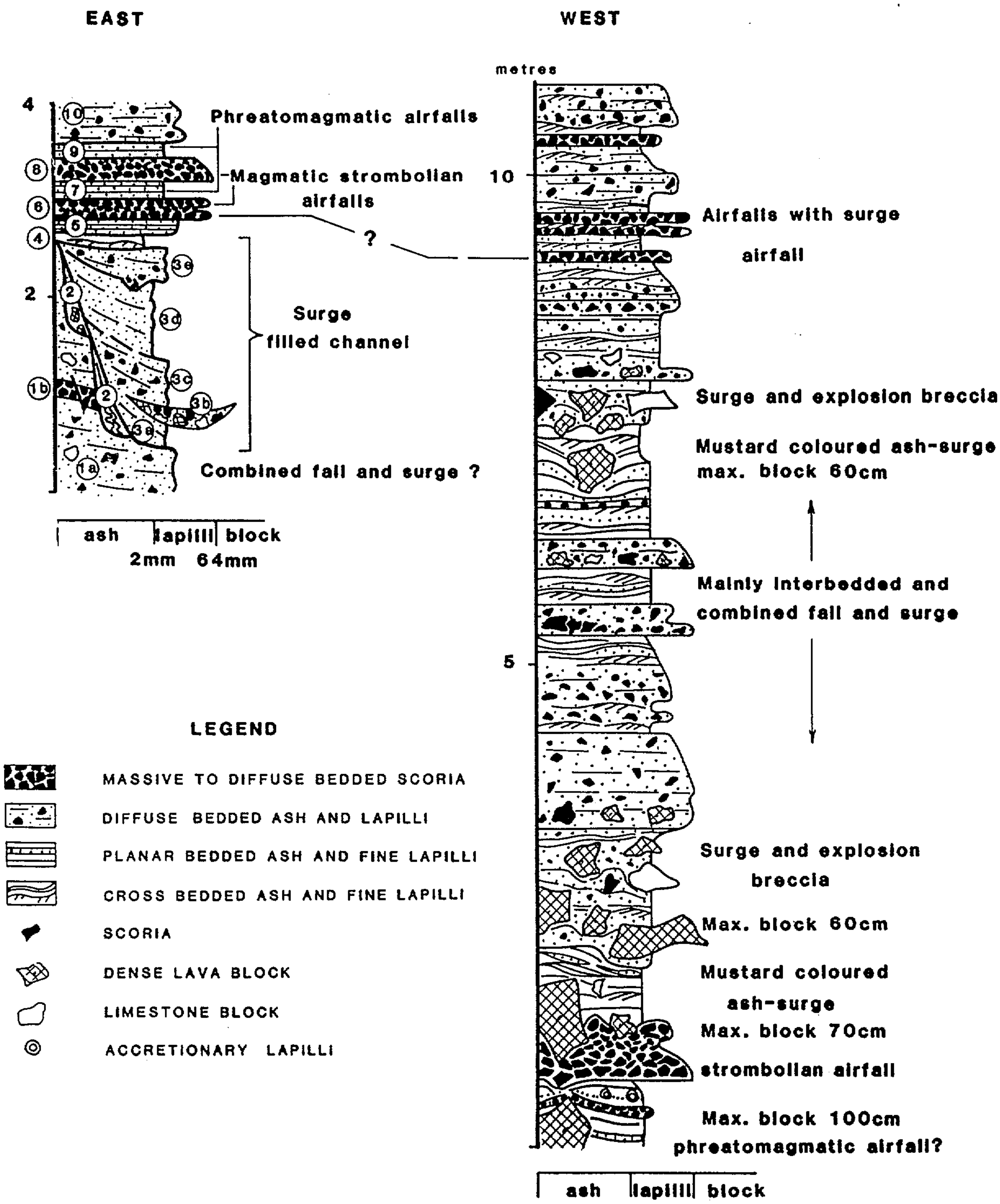


Figure 3.4 *Logged section of channel fill and subjacent succession and logged section of pyroclastic succession at southern end of Russell's Pit.*

representatives of the aquifer in which the phreatomagmatic explosions have occurred.

The distinction between fall and surge deposits is not easy but the principal criteria are: regular continuous layering in fall deposits, especially phreatomagmatic fall deposits; strombolian scoria fall deposits consist of highly vesicular scoria in massive or only faintly layered, laterally continuous deposits. Surge deposits are most rapidly identified by cross-stratification, low-angle truncations, pockets or lenses of sediment, all of which imply the influence of lateral transport processes. In near-vent settings, both fall and base surge transport and deposition may be occurring simultaneously, producing surge-modified fall deposits (Cas 1989b). The coarse lapilli-tuffs are considered to be examples of this. On s_f-Md_f plots lapilli-tuffs fall in the overlap area for fall and surge deposits (Fig. 3.6).

Outcrop 3

The low cutting at the crest of the tuff ring exposed in the road leading out of the quarry, contains dune form and low angle cross stratified lapilli tuffs. The cutting is perpendicular to the maar rim, and surge flow directions were clearly away from the maar.

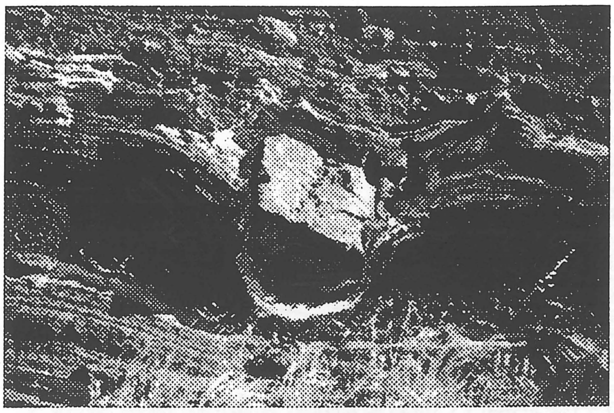


Figure 3.5 *Accessory ballistic impact structure, Russell's Pit.*

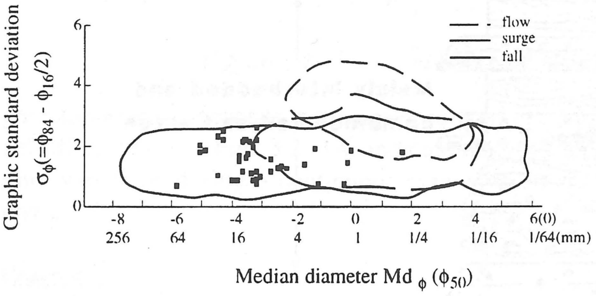


Figure 3.6 *sf-Mdf plots of lapilli-tuffs, Russell's Pit.*

Summary

1. The deposits of the Red Rock Volcanic Complex record a complex history of phreatomagmatic and magmatic explosive activity. Although magmatic eruptive activity appears to have become dominant towards the later stages of the eruptive history, producing the strombolian scoria cones, it is clear that such strombolian style eruptions were also occurring sporadically as short-lived episodes from the maars, when for whatever reasons, the vent "dried up". Scoria deposits do not necessarily therefore indicate scoria cone sources.

2. Periodic "drying" of the vent occurred either due to low recharge rates in the aquifer, or the walls of the magma conduit were temporarily lined with impermeable basalt.

3. A lensoidal horizon of fines depleted breccia represents a vulcanian blast flow deposit.

UNIT	FACIES	MAIN CHARACTERISTICS	MODE OF FRAGMENTATION	TRANSPORTATIONAL AND DEPOSITIONAL ORIGIN
1a	Diffusely bedded lapilli-ash tuff facies	Crudely stratified; local truncations; clasts non-vesicular to sparsely micro-vesicular	Phreatomagmatic explosions	Combined base surge and ? air-fall
1b	Massive scoria and lapilli facies	Relatively massive; significant scoria; clasts vesicular to non-vesicular	Magmatic explosions	Air-fall
2	Slumped lapilli-ash facies	Overlies channel base in irregular pockets; crudely stratified; slumped	Phreatomagmatic explosions	Wet base surges
3a	Diffusely bedded lapilli ash facies	Finer than 1a; drapes channel base; thins; erodes facies 2	Phreatomagmatic explosions	Moderately wet base surges
3b	Volcanic breccia	Hetrolithological including marls and volcanics; lensoidal geometry within channel; integral part of surge sequence	?	Entrained by base surges
3c (as for 3a, d &e)	As for 3a	Variable grain size; pinching thinning geometry in channel, cross-cutting relationships	Phreatomagmatic explosions	Moderately wet base surges
4	Laminated/cross-laminated ash facies	Fine grainsize; wavy laminations; low angle cross-stratification and truncations	High intensity phreatomagmatic explosions	Wet base surges
5	Bedded micro scoria facies	Variable vesicularity; regular, continuous stratification	Magmatic-incipient phreatomagmatic explosions	Air-fall resulting from pulsating explosive activity
6	Scoria facies	Doubly graded; vesicular scoria	Magmatic explosive activity	Strombolian falls, double grading from fluctuating ejection velocity or deflection of column by wind

Table 3.1 *Characteristics and origins of some deposits in Russell's Pit, Unit numbers refer to corresponding numbers in Figs. 3.2 and 3.4*

STOPS 4, 5: MOUNT LEURA VOLCANIC CENTRE

W.J. Edney, I.A. Nicholls & R.Cas

From Russell's Pit in the Red Rock Volcanic Complex, return to the Princes Highway and turn right (west), heading for Camperdown. Just past Pirron Yallock, the road crosses the margin of a hummocky lava flow erupted from Mt Porndon, 10 km to the west. These lavas have been called "stony rises" lavas. Mt Porndon lavas are mostly hawaiites, and cover an area of over 200 km^2. They are thought to be younger than 20,000 years old based on preservation of morphological surface features. The relief on the surface of the flow is up 10 m. The "stony rises" morphology has been explained by Skeats and James (1937) and Ollier and Joyce (1964) as resulting from rupturing of flow margins, leading to collapse of the surface crust as magma withdrawal feeds a newly developed narrow flow lobe from the rupture point. We will stop briefly at roadside parking bay on the left which exposes a section through a lobe of the youngest major lava flow. The outcrop consists of hawaiite with olivine phenocrysts and plagioclase laths. Vesicles are spherical to flattened parallel to the flow surface, and in places occur in subhorizontal trains. Vertical and horizontal joints occur.

Continue driving west past Mt Porndon on the south side of the road, towards Camperdown. 1 km before reaching Mt Leura and Camperdown, the Princes Highway passes over a gentle rise which is the tuff ring crest. Drive past the quarries on the right (north) side of the road to Adeney St on the left. Drive to the end of Adeney St, and turn left onto Mt Leura Road, to the lookout at the top. From the carpark walk to the viewpoint with the cairn identifying landmarks on the skyline.

The panorama is marked by the flat lava plains topography of the volcanic province, the large internal drainage lakes of Lakes Corangamite and Colungulac (east and north respectively), and about 20 volcanoes including both maars (e.g. Purrumbete) scoria cones (eg Mt Noorat and Elephant). To the south the Otway Ranges are visible, and to the north on a clear day the Central Highlands).

The road cuttings to the summit expose the typical scoria deposits of the central cone complex. Mantle nodules and xenoliths can sometimes be found in the cuttings or in roadside gravel.

Gill (1978) proposed that the Leura complex is about 22,000 years old based on the occurrence of tuff, thought to be derived from the Leura centre, interbedded with radio-carbon dated sediments at Lake Colongulac.

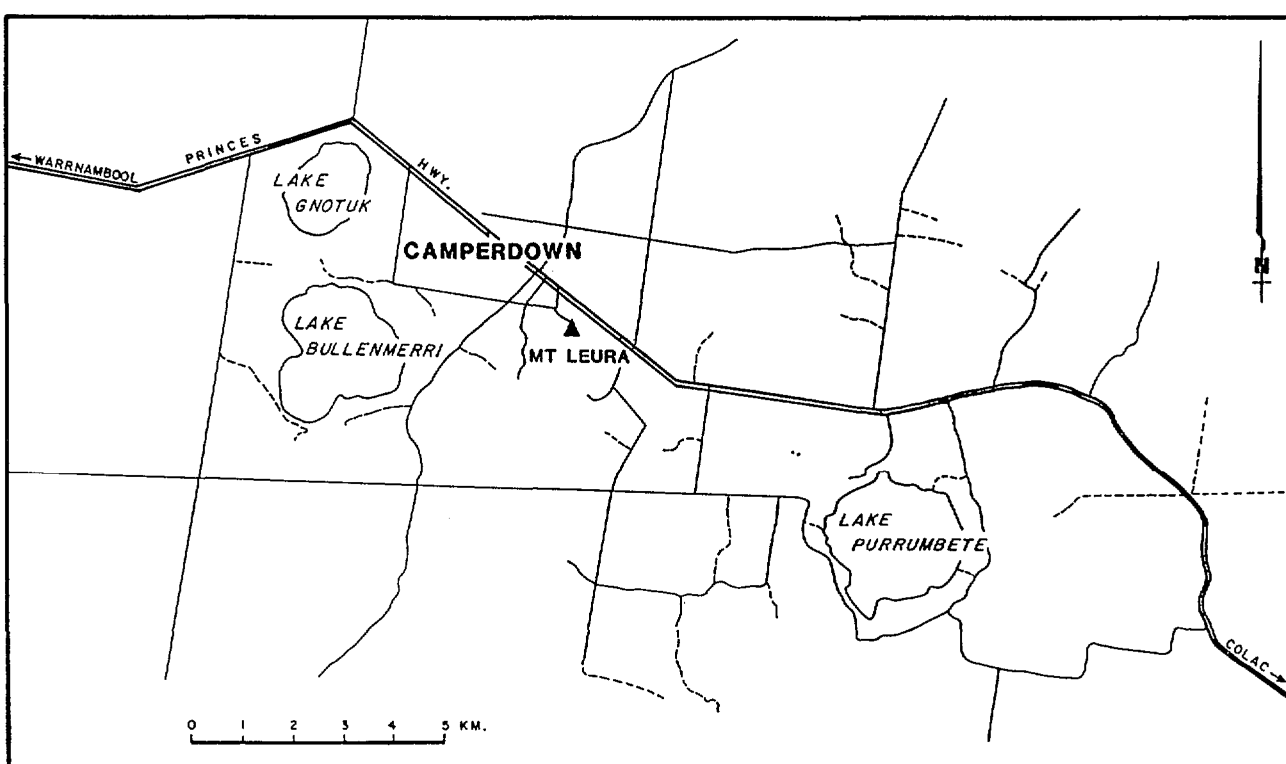


Figure 4.1 *Locality map for Mt. Leura*

STOP 4 : MT. LEURA LOOKOUT

Mt. Leura is a scoria cone complex contained within a tuff ring which is approximately 2.5 km in diameter, situated approximately 1 km west of Camperdown (Fig. 4.1). The Phreatomagmatic deposits of the tuff ring overlie, in part lava flows from nearby older eruptive centres and Tertiary marine sediments. This volcano has been previously described by Evans (1980) and Edney (1987). Eruptive activity of the centre occurred in essentially two main stages. The sequence opened with phreatomagmatic activity producing the well bedded and internally stratified and cross-stratified deposits found in the tuff ring wall (Fig. 4.2). One major angular unconformity occurs in these deposits (Fig. 5.1), but no soil or evidence of erosion is found associated with this. The final stage in the eruptive activity of the centre resulted in the deposits of the tuff ring being mantled by magmatically derived deposits of scoria fall, spatter and minor lava flows. The magmatic units were produced by strombolian to hawaiian type eruptions associated with cone building activity along a fissure located in the centre of the tuff ring crater.

The magmatic activity within the tuff ring produced one major scoria cone which is bi-peaked, Mt. Leura and Mt. Sugarloaf represent the highest points and less degraded rim sectors. The remaining landforms within the tuff ring are an intermediate number of scoria and spatter cones. In general the scoria cone slopes are between 35-40° depending on the degree of degradation. The single observed lava flow from the Mt. Leura scoria cone is approximately 65 m wide and 5-6 m thick, and travelled in a northerly direction down the flanks of the scoria cone.

STOP 5 : MT. LEURA TUFF RING QUARRY

Return to the Princes Highway, turn right (east) and drive to the quarry on the north side of the Princess highway, 1 km east of Camperdown. Exposed in the walls of the quarry are the phreatomagmatic deposits of the tuff ring and mantling scoria fall and lava flows from the Mt. Leura cone complex (Fig. 5.1).

The rim beds of the tuff ring have dips of generally less than 15° both inward and outward from the crater. 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 (Fig. 5.1). The degree of development of cross-stratification varies greatly from unit to unit, and from the quarry face parallel to flow direction compared with the face perpendicular to flow direction. On the face parallel to flow direction well defined dunes ocur with floww directions clearly away from crater. The cross stratification varies from forward climbing dune bedforms to highly truncated planar trough cross-sets. This variation is believed to be mainly proportional to the velocity of the base surges at the time of deposition, the proportion of ash sized material and the water content. The highly truncated bedforms developed during periods where base surges were produced in rapid pulses of variable explosivity or intensity with some being highly erosive. The thicker climbing dune units were produced in steadier longer lived eruptions, and deposited by base surges which were gradually slowing down and deflating and highly depositional; condensation of steam, trapped in the surge, to water would also aid greater degrees of cohesion with the substrata. On the face perpendicular to flow, stratification in what on the other face are clearly dune bedded, varies form undulating, to low angle cross-stratified to planar.

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 (Fig. 5.1). The massive air-fall ash deposits often occur as elutriation of fines out of moving base surge clouds. Accretionary lapilli are almost solely restricted to finer grained air-fall units. The diffusely bedded air-fall deposits, on the other hand, show no mantling relationship with cross-bedded units and seem to have been deposited during surtseyan-type explosive bursts with only minor associated surge development, and are discrete units in themselves. σ_ϕ-Mdϕ plots of surge samples fall in the surge field of Walker (1983), but alos lie in the fall field (Fig. 5.2).

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

The change from phreatomagmatic deposits to magmatic pyroclastic fall deposits clearly indicates that the subsurface water which fuelled the phreatomagmatic phase ceased to interact with the magma during the strombolian phase. This may have been due to the walls of the conduit becoming impermeable, most probably because a lining of basalt formed on the walls of the magma conduit. Less likely is the scenario of the aquifer drying up.

Edney (1987) schematically evaluated the likely fluctuations in water : magma mass ratios as a function of grainsize and vesicularity during the history of both tuff ring and cone forming phases (Fig. 5.1).

Summary

By comparison with the Red Rock Complex, the exposed eruptive hsitory of the Leura centre is simpler in that, like the Noorat Centre, the early history is dominated by the phreatomagmatic tuff ring forming phase, domi-

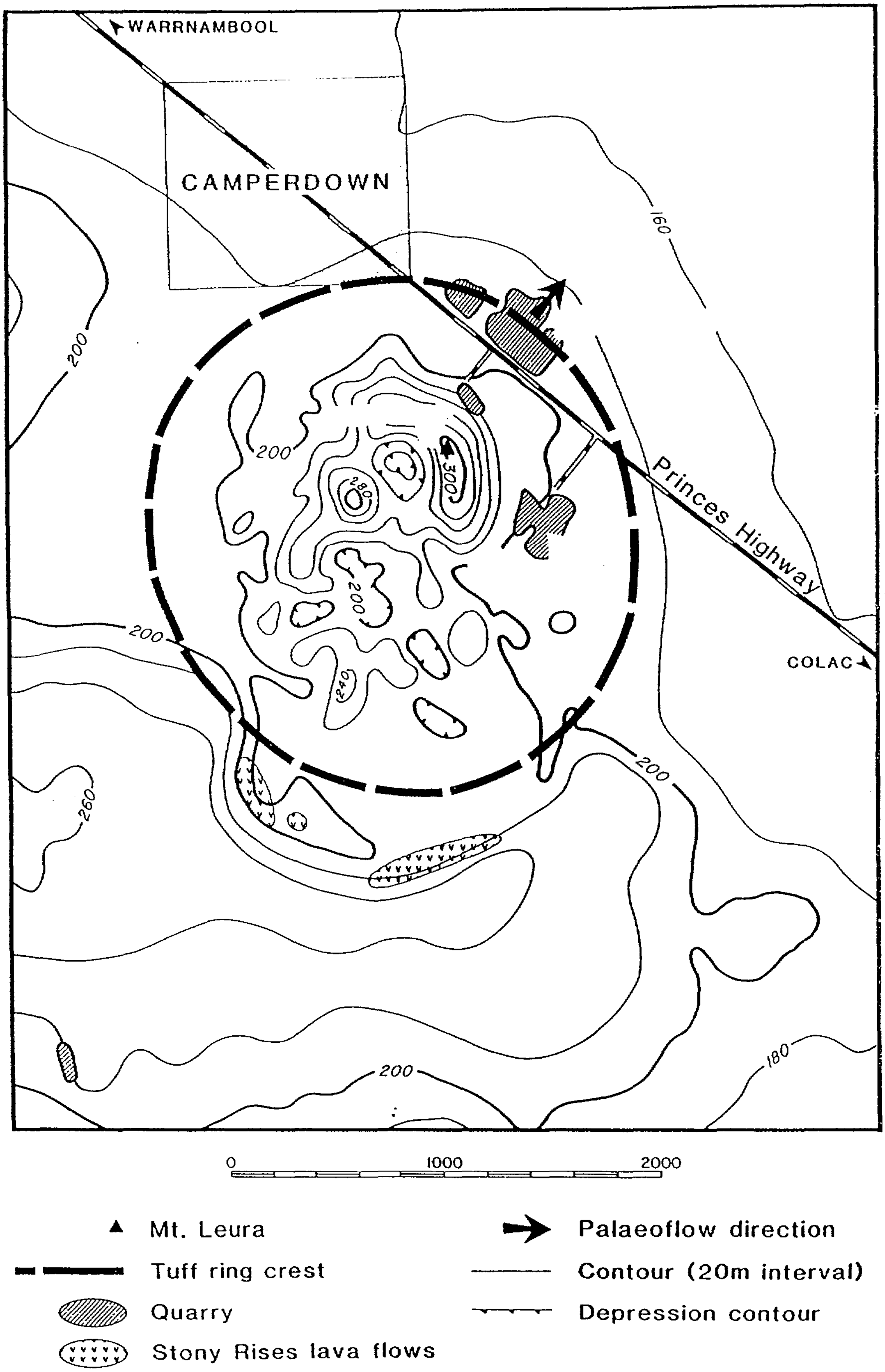


Figure 4.2 *Map of the Mount Leura volcanic centre.*

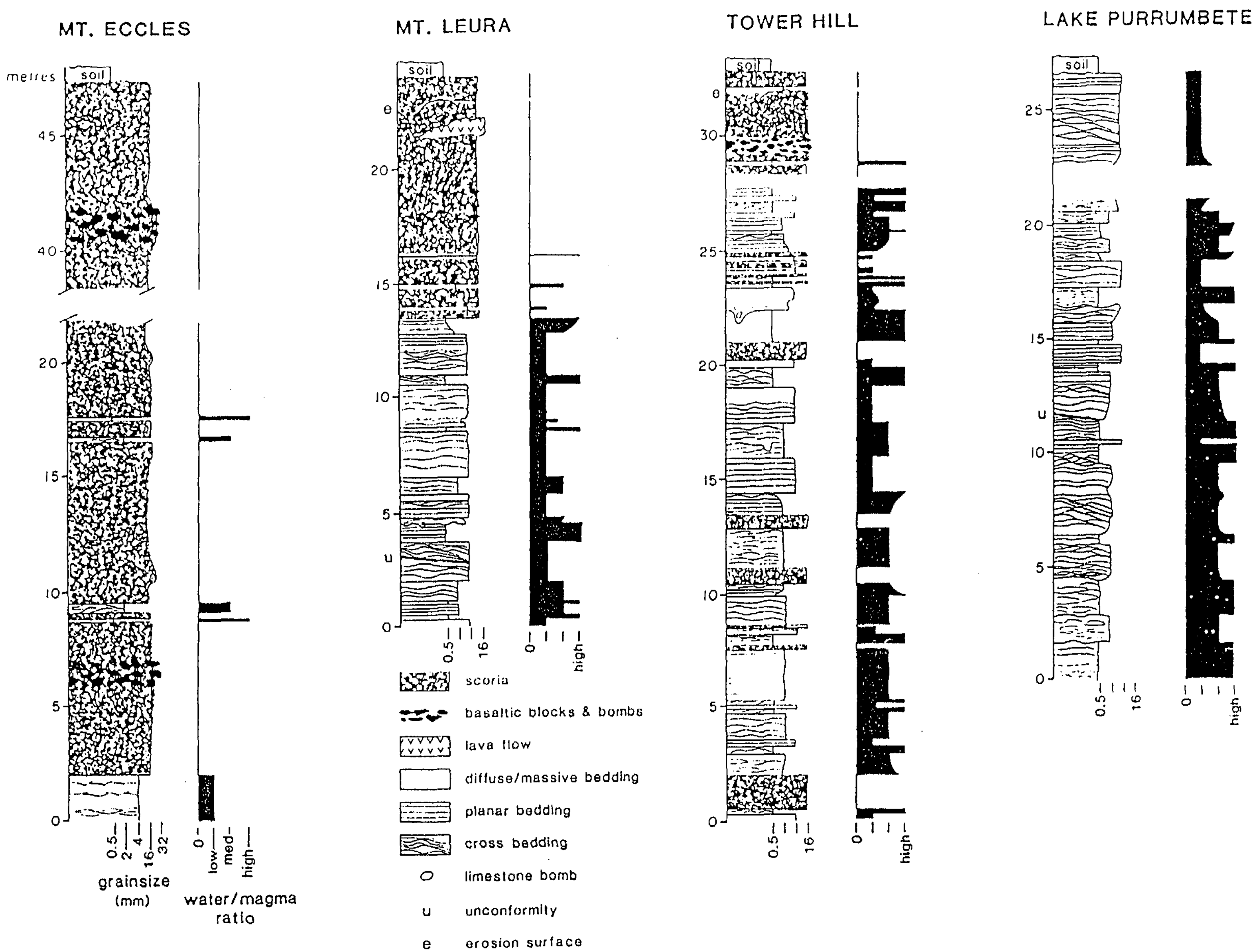


Figure 5.1 *Stratigraphic sections through tuff ring and mantling scoria deposits at Mt. Leura (STOP 5) compared with other centres. The bar graphs at the right of each column represent estimations water : magma mass ratios (from Edney 1987)*

nated by base surge processes. The second stage is represented by a strombolian scoria cone forming phase, presumably resulting from the blocking of the aquifer by the formation of a permanent lining of basalt along the walls of the magma conduit.

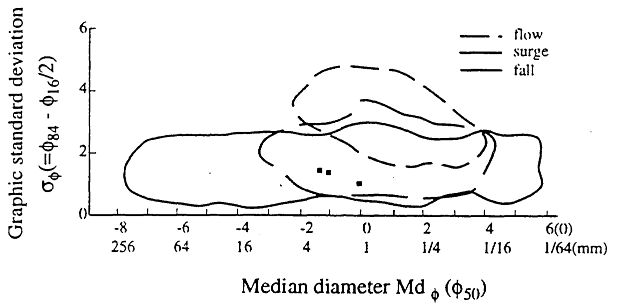


Figure 5.2 *sf-Mdf plots of surge deposit lapilli-ashes from the tuff ring quarry, Camperdown.*

STOP 6 : MT. LEURA SCORIA QUARRY.

Drive 0.5 km further east to a turn off to the right into a scoria quarry. Xenoliths and megacrysts are abundant in the scoria cone complex at Mt. Leura, and fragmented xenolith material, with olivine dominant, is an important constituent of surge and fall deposits within the tuff ring.

Xenoliths are particularly abundant in the two quarries in the north-eastern foot of the main scoria cone (Fig. 4.1). Cr-diopside spinel lherzolites are the dominant type, occurring mainly as sub-spherical nodules 5-15 cm in diameter with or without a basalt rind; Spinel wehrlites and hornblendites are rare, and plagioclase or garnet-bearing websterites are very rare. As in most western Districts centres, black glassy Al-Ti-augite is the most abundant megacryst mineral. Ti-pargasite and anorthoclase are common and ilmenite very rare (Wass and Irving, 1976; Ellis, 1976).

Most lherzolite xenoliths show the coarse equant textures typical of almost undeformed material. Olivine crystals are often unusually coarse (10-20 mm). Both pale and dark green lherzolites are present, the latter taking their colour partly from their pyroxenes, which have patchy exsolution of spinel. Some have rare phlogopite crystals, visible in hand specimen. Occasionally, deformed and partly recrystallized fine-grained lherzolites with weak planar fabric are found.

Lherzolite xenoliths from Mt. Leura have been included in a number of geochemical studies of Newer Basalt inclusions. Abundances of Th, U and K have been studied by Green et al (1968), Pb- and Sr-isotopic ratios by Cooper and Green (1969) and Dasch and Green (1975) and rare earth and incompatible element abundances by Frey and Green (1974).

Pyroxene rich xenoliths from Mt. Leura have been included in Newer Basaltic studies described by Irving (1974) and Ellis (1976). As noted by Ellis, the occurrence of amphibole megacrysts at a given volcanic centre usually indicates that coexisting pyroxenite xenoliths will carry minor amphibole. This is the case for Mt. Leura. In addition, coarse grained hornblend xenoliths consisting almost entirely of Ti-paragasite are present.

STOPS 7-14: A GUIDE TO QUATERNARY VOLCANOES IN THE LOWER SOUTH-EAST OF SOUTH AUSTRALIA

M.J. Sheard* & R. Cas

***Geological Survey of South Australia**

Drive to Mt. Gambier via the Princes Highway. At Tyrendarra, turn north to Heywood. Turn right onto the Henty Highway and then immmediately left again onto the Princes Highway to Mt Gambier.

The Quaternary volcanic province of southeastern South Australia constitutes a small western extension to the Quaternary Newer Volcanics of central and western Victoria. This province contains 17 eruptive centres (Sheard 1990; Fig. 7.1), many of which have experienced multiple eruptions. These volcanic structures are underlain and surrounded by a karst terrain of low profile with poorly developed surface drainage and abundant ground water.

Two distinct volcanic groups are evident; the northern Mount Burr range forms one group, while the more isolated Mount Schank and Mount Gambier form the second (Fig. 7.1). In a temporal sense, the volcanicity of the two groups occurred in separate and distinct pulses (Fig. 7.2). Several of the volcanoes are maars, having developed by multiple, shallow, explosive eruptions. These have naturally flat, open crater floors, and contain lakes where the water table is intersected; examples are Blue and Valley Lakes at Mount Gambier.

The Northern Volcanic Group

East of Millicent, the Mount Burr range includes 15 major volcanic centres. Most are associated with basement faults related to the Otway Basin Graben. Fissure controlled eruptions therefore predominated in this area and paralleled the Burr/Gambier Lineament and the Burr Peninsula (Fig. 7.1) described by Sprigg (1952) and Marker (1975). Seismic profiling has indicated a basement high underlying the Burr Peninsula. Three main fault lines were defined by this profiling and are reflected in the three trend lines of the volcanic centres (Fig. 7.1).

The volcanic features are varied, ranging from lava flows, scoria domes, composite domes and agglomerate cones to maars or tuff rings. Ejecta rest on the erosional surface of the Oligocene-Miocene Gambier Limestone and are overlain by the Pleistocene Bridgewater Formation aeolian beach ridge sands, up to 50 m thick. Partial covering by these Pleistocene sands has hidden the full extent of the volcanics, although drilling has revealed an areal coverage of 100 km^2 (Fig. 7.1).

Drilling and quarrying at both The Bluff and Mount McIntyre have revealed alternating sequences of ash, scoria and lava with occasional interbedded palaeosoils, implying major time breaks in their eruptive histories. Magma sources are likely to have been upper mantle as evidence by lherzolite xenoliths within tephra piles at Mount Edward, Lake Leake, Mount Lyon and Mount Watch (Walker, 1967; Sheard, 1980, 1983a).

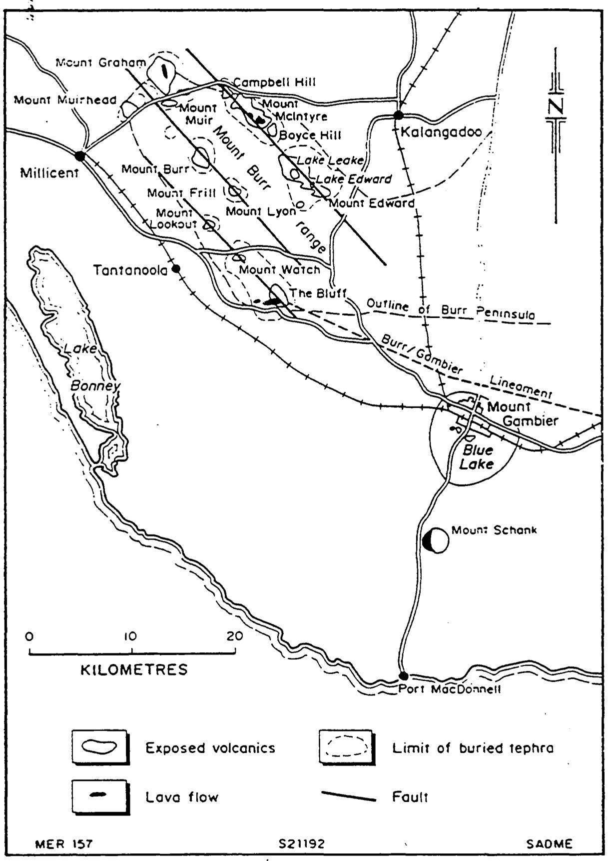


Figure 7.1. *Distribution of volcanic centres of the Newer Volcanics Province, Mt. Gambier region (From Sheard 1990).*

Only three centres have been analysed geochemically. Irving and Green (1976) identified the lavas at Mounts Watch and McIntyre as olivine analacimites and those of Mount Burr as K-rich nepheline hawaiite. They suggested that chemical and fractionation trends probably exist between adjacent centres but further analysis is required.

Pleistocene marine activity has had a marked effect on volcanic landform shapes and tephra distribution patterns. Mount Muirhead and The Bluff are very asymmetrical in cross-section due to the action of on-shore winds during eruption and coastal erosion by high-seas. The seaward truncation of tephra layers, infilled deep fluvial channels, slump structures and cross-bedding with high-angle sets are all prominent at Mount Muirhead (Sheard, 1983a, b). Subsequent upwarping of the region has caused a southerly retreat of the sea from the Burr Peninsula.

Dating of volcanic centres has been limited; K-Ar dating of the lavas was unsuccessful due to the presence of ubiquitous calcite derived from the overlying Bridgewater Formation. Pollen studies by Dodson (1974) on lake sediment cores taken from Lake Leake maar suggest that sedimentation began 20,000 years before present (B.P.). Stratigraphic evidence indicates an eruptive period commencing in the Early Pleistocene and ending during the Late Pleistocene (Fig. 7.2; Sprigg, 1952; Marker, 1975; Sheard, 1980).

Southern Volcanic Group

The southern volcanic group consists of Mounts Gambier and Schank (Fig. 7.1). Both complexes rest on Bridgewater Formation sand and are thus stratigraphically younger than the northern volcanic group (Fig. 7.2). Neither complex has been subjected to marine erosion, but Solomon (1951) described quench textures at Mount Schank, indicating either localised water ponding as swamps or, as suggested by Sheard (1986), eruption over rain soaked ground.

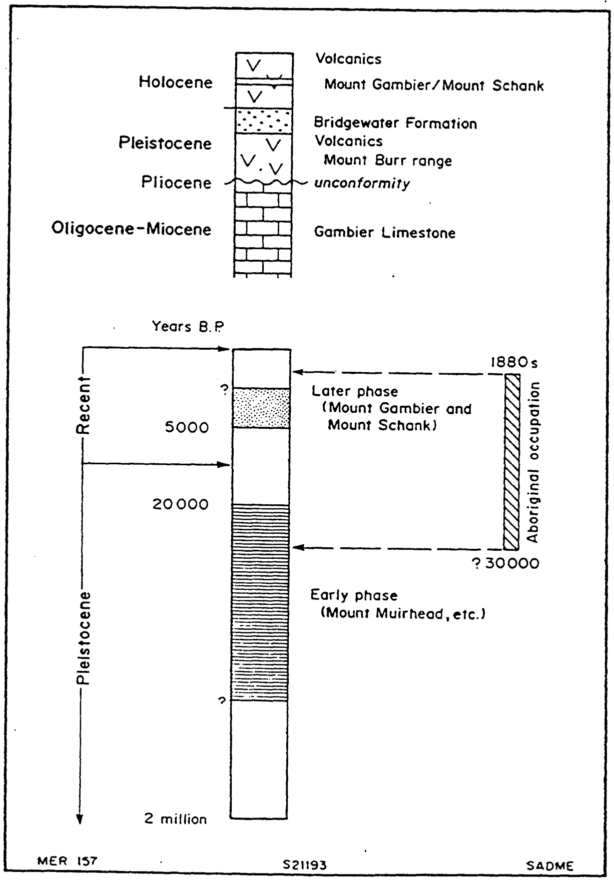


Figure 7.2. *Stratigraphy and chronology of the early and later volcanic groups, Mt. Gambier region (From Sheard 1990).*

Both volcanoes are complex maar and cone structures. They are dominantly constructional features built over eruptive fissures and strongly influenced by the presence of abundant ground water (Ollier, 1967; Joyce, 1971, 1985; Sheard, 1978, 1983a, 1986).

Mount Gambier (Figs. 7.3, 7.4, 7.5)

A detailed geological history of Mount Gambier is set out in Sheard (1978). Briefly the volcano has undergone two closely spaced periods of eruption, each with a distinctive style. Carbon-14 dating of charcoal fragments found within the basal tuff indicates that the eruption occurred 4,000 to 4,300 radiocarbon years B.P. or approximately 4,700 to 5,000 calendar years ago (Blackburn et al, 1982). This evidence agrees with the palaeomagnetic results of Barbetti and Sheard (1981); they also demonstrated no magnetic orientation difference from bottom to top of the volcanic pile, which implies a short time interval between the two main eruptive episodes.

Initial eruptive outbursts occurred at the western end (college oval area) of the present complex and where Leg of Mutton Lake now appears (Fig. 7.3). Small, low, open tuff rings or maars were produced, covering the surrounding countryside with ash and lapilli. Next, lava flowed from two sites; one was a fissure on the western side of the present Brownes Lake crater and the other was a vent in the present day Leg of Mutton Lake crater. These flows reach a thickness of 20 m where exposed in the western Blue Lake crater. Irving and Green (1976) classified these lavas as nepheline hawaiite. A scoria cone, now partly exposed in the crater walls west of Brownes Lake, completed this first period of eruption. Activity ceased for some time, long enough to allow lava cooling and jointing but not long enough to permit soil development on either lava or ash.

The second period of eruptive activity was on a much larger scale than the earlier one. Ground water, being abundant in both the Gambier Limestone and Cretaceous sand aquifers, caused explosive volcanism. The result is a linear group of nested maars, the major craters of which are now Brownes Lake, Valley Lake, Leg of Mutton Lake and Blue Lake. Agglomerate, vitric and accretionary lapilli, and ash were the main tephra products; these contain upto 25% by volume of country rock fragments. The non-volcanic fragments include basement granodiorite (Sheard, 1978) from approximately 6 km below ground level (Joyce, 1975; Sheard, 1985a, b) and representatives of all the Otway Basin sediments. Some tephra layers contain 5-10% by volume of lherzolite xenoliths, indicating an upper

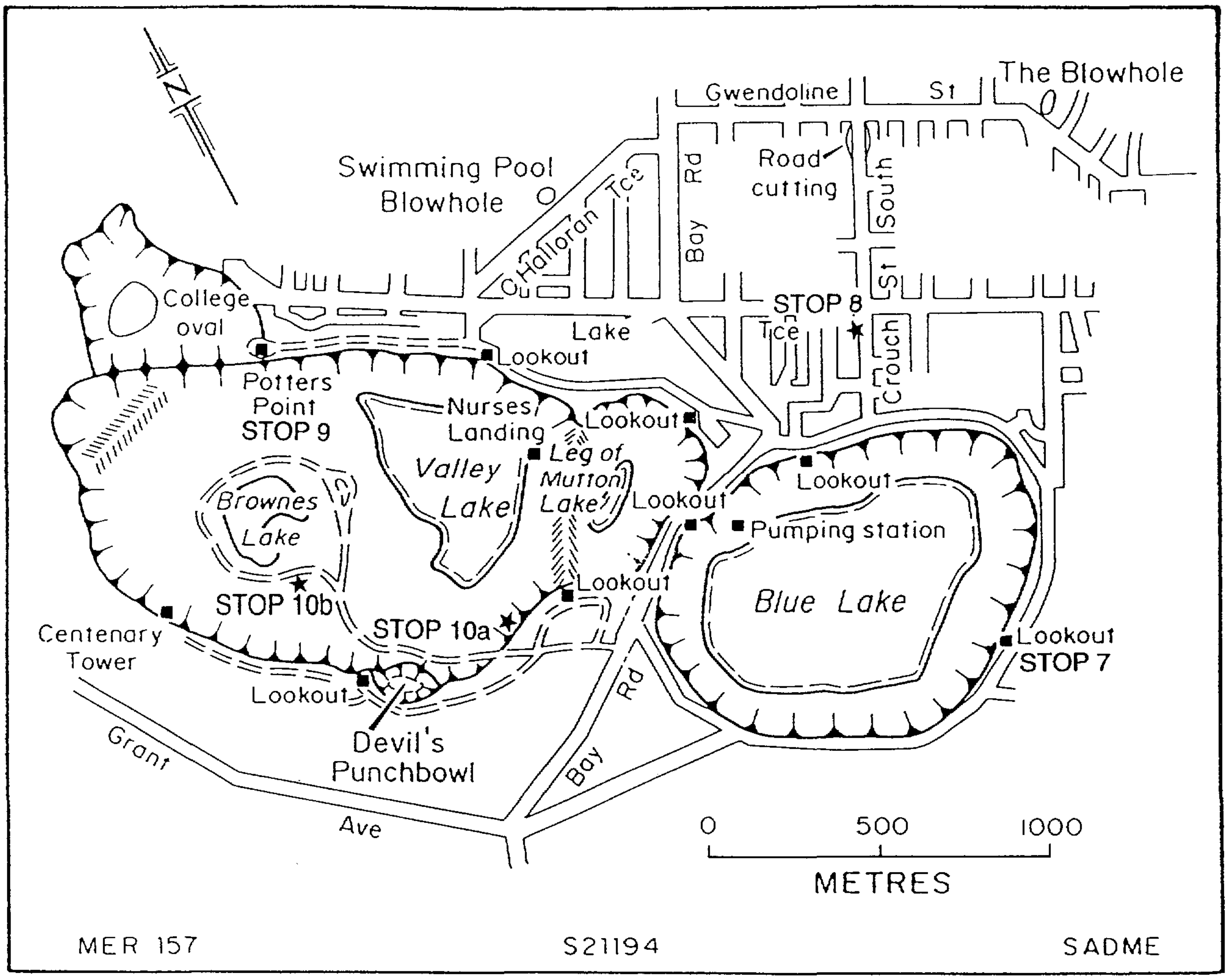


Figure 7.3. *Mount Gambier Volcanic Complex plan and locations of main features (From Sheard 1990).*

mantle source. These xenoliths are both coarse and fine-grained, with the fine-grained type often displaying a foliation fabric.

Base surge deposits, resulting from volcanic blasts directed radially outward from the vent, are ubiquitous within the tephra pile; excellent examples can be seen in the Crouch Street South cutting (Fig. 7.3; STOP ...). Surge cross-bedding can also be found in exposed road cuttings up to 5 km southeast and east of the Blue Lake crater. The present day Leg of Mutton Lake crater is a late-stage feature and represents a dwindling magma supply combined with the quenching effect of copious ground water. Accretionary lapilli are especially dominant in it's tephra sequence. Lava fountaining from small vents within the Brownes Lake crater represent the last major magmatic event, which created small spatter piles of vitric basalt (tachylyte).

Final volcanic activity was displayed by steam-emission blowholes, the largest of which is the Devil's Punchbowl (Fig. 7.3). Two black scoriaceous dykes, containing 50% by volume lherzolite blocks, were unearthed during roadworks in the late 1960's near the Devil's Punchbowl, but have subsequently been covered over. They are late-stage intrusions and may relate to the Blowhole nearby or reflect a final non-explosive magma pulse.

Mount Gambier is a unique volcanic landform, a fissure controlled maar complex, and may represent one of several end members of a maar landform series. The Blue Lake crater is an excellent example of the combination of a 'dry' magma in reaction with two highly transmissive near-surface aquifers. The flat-floored crater is now occupied by a 70 m deep lake.

Mount Schank (Fig. 7.6)

Mount Schank has followed a similar eruptive sequence to that of Mount Gambier, but it is an order of magnitude smaller by volume of materials erupted and in landform size (Fig. 7.1). A detailed geological history is provided by Sheard (1986). No satisfactory dating of Mount Schank has been achieved as charcoal has not been found within the soil profiles within the tephra pile, hence C^{14} dating has only been able to date soil processes within the underlying Bridgewater Formation (18,100±350 years B.P.; Polach et al., 1978). Palaeomagmatic measurements by Barbetti and Sheard (1981) indicated a different eruptive time to that of Mount Gambier but suggested that it was either between 5,000 and 1,000 years B.P. or older than 7,000 years B.P. More recently, Smith and Prescott (1987) used thermoluminescence to derive an age of 4,930 ±540 years B.P., which is a problematic date due to the unusual radiation doses and geometry. Hence, there still remains the question as to whether Mount Gambier or

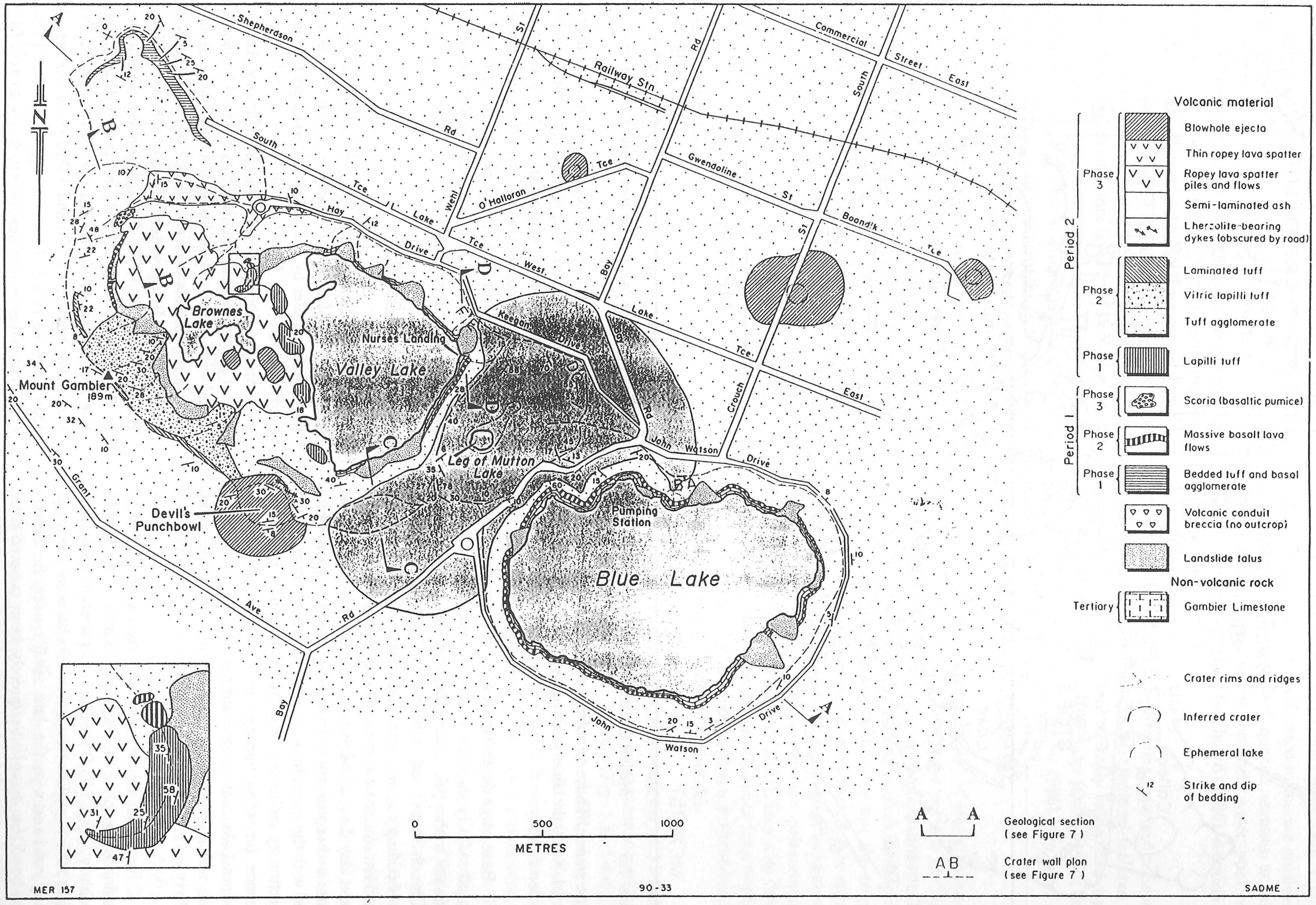


Figure 7.4. *Geology of the Mount Gambier Volcanic Complex (From Sheard 1990).*

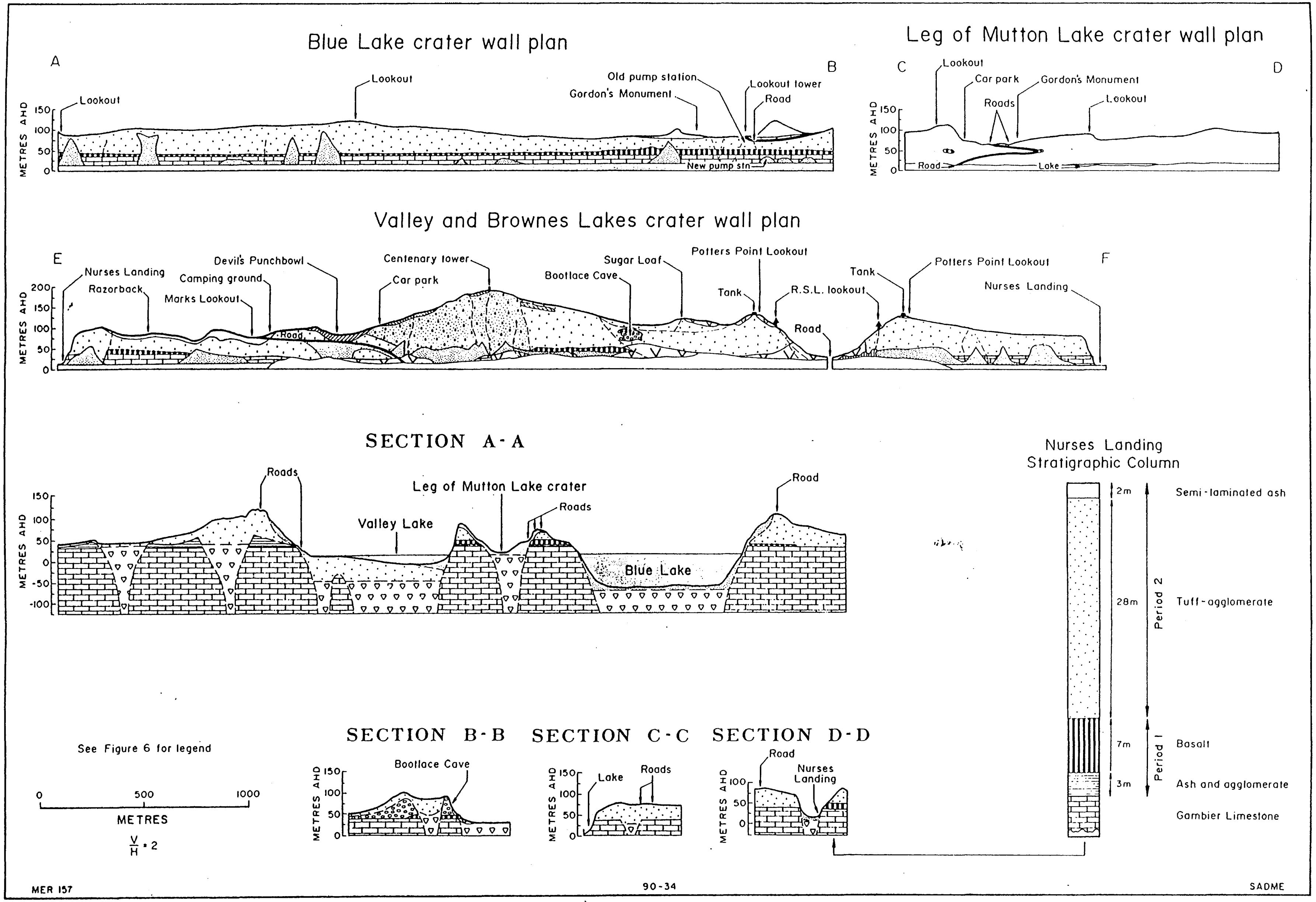


Figure 7.5 *Crater wall geological profiles and cross-sections of the Mount Gambier Volcanic Complex (From Sheard*

Mount Schank is the senior volcano.

The eruptive sequence began with the opening of a northwesterly trending fissure, 1,200 m long, in the Gambier Limestone. Basaltic ash was vented for a short time prior to the extrusion of lava, which flowed westwards and southwards over a flat terrain (Fig. 7.4); Irving and Green (1976) classified the lava as K-rich nepheline hawaiite. Activity concentrated towards the fissure's centre, where a large scoria cone developed, and to the southern end where a maar formed. The fissure's northern extremities are marked by a line of small scoria piles and cones. Phase two activity commenced with a new vent located halfway between the earlier cone and maar. This vent gave rise to a larger maar-cone hybrid, as described by Joyce (1971, 1985). It consists of bedded tuff, lapilli and agglomerate with up to 15% country rock fragments by volume. This cone developed to a height of 100 m and exceeded the first-phase eruptive products in volume by a factor of 2. Small, late-stage explosion craters formed on the western flank of the main vent and 300 m southeast of the complex (Fig. 7.4).

Mounts Gambier and Schank represent the youngest volcanoes on the Australian mainland. Sprigg (1959) postulated that three possible submarine lava flows 17 km west-southwest of Beachport are linked to two large earthquakes centres on this region in 1897 and 1948. This has yet to be proven but if the link does exist then this volcanic province is still active.

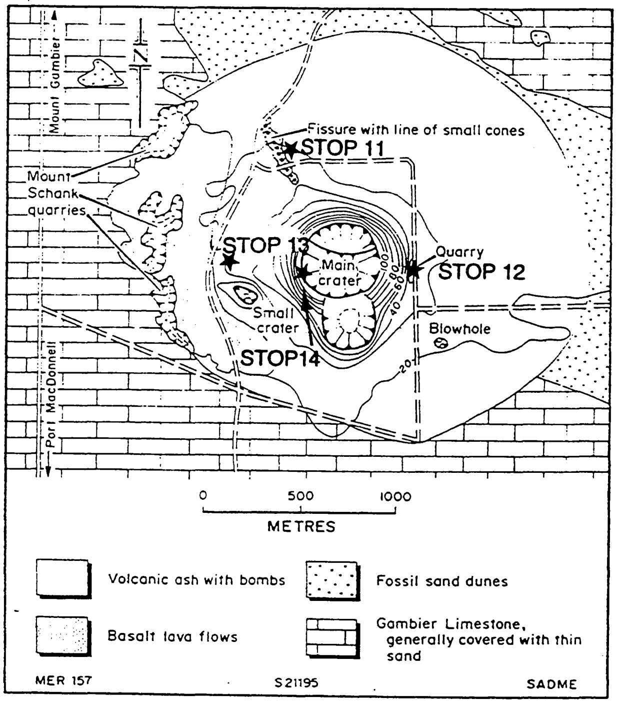


Figure 7.6. *Geology of Mount Schank (From Sheard 1990).*

STOP 7: ROTARY LOOKOUT, MOUNT GAMBIER VOLCANIC COMPLEX

Follow route map (Fig. 7.5) to STOP 7. Drive along Crouch St. to John Watson Drive, turn left, and drive to Rotary Lookout. At this lookout the main volcanic land forms of the Gambier Complex are visible. In the foreground is the Blue Lake maar, and beyond its margin the combined depression of the Leg of Mutton, Valley Lake and Browne's Lake maars. The tallest ridge to the southwest is the Tower Ridge, with the tower perched on the highest point, which is Mt. Gambier. To the south the impressive edifice of Mt. Schank is visible.

Here it is possible to see the water table expressed in the lake surface of Blue Lake; it is 14.2 m above sea level. Forming the white limey cliffs at the water's edge is the Gambier Limestone of Oligocene to Miocene age. Overlying this is thin veneer of loose, buff-coloured dune sand of the Bridgewater Formation. Resting on top of the sand is a khaki-coloured ash unit from the first period eruptions. The upper surface of this material has been baked hard and altered to a brick-red colour by heat from the once molten lava resting on top. The lower zone of this tuff comprises a country rock-ash agglomerate representing the initial break through phase. Activity ceased for some time following the lava outpouring, allowing the flows to cool and form joints, a process which may have taken several months.

Second period eruptions were on a much larger scale than those of the first, primarily due to the explosive reaction that occurred when abundant ground water came into contact with the molten rock. Explosions eventually produced the large open craters seen today. There is no evidence for large-scale collapse of higher volcanoes into hollow magma chambers as has been proposed by geologists in the past. Many small vents close together eventually joined to produce the large craters now containing the Blue, Valley and Brownes Lakes. The Leg of Mutton Lake crater is a late-stage feature, formed as activity was drawing to a close (Figs. 7.6 and 7.7). The basal ash unit varies from 0.2 to 3 m thick in the Blue Lake exposures. It is thinnest to the east and thickest to the west. The thick, dark basalt flow is easily recognised; the flow reaches its thickest point almost directly below the Queen Elizabeth Caravan Park, to the west of Stop 7.

Overlying the lava is a thick sequence of unsorted, compacted volcanics known as tuff-agglomerate. Particle size ranges from dust to large boulders of many tonnes weight. Non-volcanic material such as the Gambier Limestone and underlying strata, which once occupied the vent and conduit, now make up part of the bulk tephra. The proportion of country rock in the volcanics varies from 5 to 25%.

It is possible to examine the sequence at the Blue Lake Pumping Station by prior arrangement with either the Engineering and Water Supply Department regional office at Mount Gambier or the Regional Tourist Authority.

STOP 8: CROUCH ST. SOUTH

Return to Crouch St, Drive past cutting with surge dune bedforms just before Lake Terrace, and park around the corner in Lake Terrace. This spectacular outcrop preserves base surge deposits from the Blue Lake maar, as well as outstanding ballistic impact structures. Notable about the ballistics is the intraclast nature of many, soft sediment deformed bedded phreatomagmatic tuff clasts being common. In addition, limestone clasts of Gambier Limestone also occur as ballistics. Both ballistics and surge cross-stratification indicate transportation from south to north.

STOP 9a: POTTERS POINT LOOKOUT, MOUNT GAMBIER VOLCANIC COMPLEX

Follow route map (Fig. 7.5) to STOP 8a. Looking east, a dark layer of lava can be seen at the eastern end of the Valley Lake in what is called the Razorback. This lava is part of the same flow exposed in the Blue Lake crater walls. Continuing around the crater wall to the southeast, the Devil's Punchbowl (a blowhole) can be seen. South of the Lookout, the buttressed walls of the Tower ridge exhibit large-scale layering. Large blocks of Gambier Limestone are common in these layers. The Tower Ridge has the appearance of a strombolian scoria cone succession from a distance, but close up (STOP 10b), a phreatomagmatic influence is still clear.

STOP 9b: LOOKOUT SOUTH OF AND BELOW POTTERS POINT LOOKOUT, MOUNT GAMBIER VOLCANIC COMPLEX

To the west, an exposure of the buried scoria cone at Bootlace Cave can be seen as a bulging, cavernous outcrop below a cuspate break in the crater rim, between the Tower ridge and the Sugar Loaf. West of the water storage tank at the Potters Point Lookout, the now partially buried early craters form a distinct gully. The floor of one crater, a maar, forms the Tension college oval. This type of volcano has a naturally flat, open crater floor; in the southeast, many maars intersect the water table and thus contain lakes (e.g. Blue and Valley Lakes).

STOP 10a,b: BROWNES LAKE SOUTH, MOUNT GAMBIER VOLCANIC COMPLEX

Drive to Bay Road, turn into the Browne's Lake Road. Follow route map (Fig. 7.5) to STOP 10a at the Devil's Punchbowl. The Devil's Punchbowl is a late stage phreatic explosion crater. Few deposits are preserved of the phreatic event. The deposits outcroping are from the Valley Lake centre.

Drive on towards Browne's Lake and stop at the scoria and block exposure in the road cutting (STOP 10b). Lava spatter from late-stage lava fountain activity can be collected and viewed at this stop. This type of lava chilled rapidly on being thrown into the air, thus preserving forms resembling twisted rope and fresh cow dung. Composed almost entirely of glass, this lava has a metallic ring when struck. Many small spatter piles in this part of the crater give its floor a very irregular, hummocky appearance. Prominaent large blocks of Gambier Miocene up to 1m in diameter are prominent.

Walk around the corner to the next parking bay (30m), find path through bracken on left side of road and clamber up the slope to the bedded pyroclastics of the Browne's Lake maar succession. Lapilli-tuffs with bomb sags are prominent. Bedding is diffuse to undulating, and lensing on a subtle scale is evident. Basaltic clasts are micro vesiular to moderately vesicular. Phreatomagmatic influences are indicated by the relativley low vesicularity, poorly sorted nature and fine grain size of the matrix. Both ballistic and surge-modified fall processes are inferred.

STOP 11: SMALL LINE OF SCORIA CONES, MOUNT SCHANK VOLCANIC COMPLEX

Return to Bay Road, turn right (south) and continue south about 12km. Turn left immediately before the Bellum Bellum pub. Follow route map (Fig. 7.5) to STOP 11. The road cutting through the small cones has exposed red and black scoria and agglutinate and vesiculated bomb beds. Rare unoxidised samples are jet-black and have glassy bubble linings which often have iridescent colours. The cones were developed by hawaian and limited strombolian activity from a northwest trending fissure system. Numbering eight in all, the line of small cones is best seen from the top of Mount Schank. They continue under the main volcanic cone where they are buried and form weak topographic ghosts. This fissure sytem is the source of the extensive lava that is being quarried to the west of Mt Schank. The draping phreatomagmatic deposits are from the younger main Mt. Schank cone. Surge transportation is inferred based on undulating stratification and the inclusion of scoria clasts in the tuffs.

STOP 12: EASTERN ASH QUARRY, MOUNT SCHANK VOLCANIC COMPLEX

Follow route map (Fig. 7.5) to STOP 12. Layering in the volcanic pile can be viewed in this now abandoned quarry. A large size range in ejected fragments is apparent. Country rock fragments such as Mount Gambier Limestone, flint, dolomite, dune sand, and baked claystone are common. Lapilli tuffs are common, and are characterised by moderately vesicular juvenile lapilli in a finer tuff matrix. A phreatomagmatic influence is again apparent.

STOP 13: SMALL SUBSIDIARY CRATER, WESTERN SIDE OF MOUNT SCHANK VOLCANIC COMPLEX

Follow route map (Fig. 7.5) to STOP 13. To the southeast of the carpark, a small explosion crater has exposed the various layers making up the Mount Schank cone. The white, basal layer is Mount Gambier Limestone; a thin buff coloured layer of dune sand rests on this. Overlying the sand is a dark lava flow from the initial eruptive phase, and on top of this rests tephra from the last active phase. This point is close to the southern boundary of the lava field, hence its relatively thin nature. Much of the lava has been quarried as road aggregate and fill for the Port MacDonnell breakwater. Entry to the lava quarry is by prior arrangement with the quarry manager, Mount Schank Quarries Pty. Ltd.

STOP 14: TOP OF MOUNT SCHANK

Follow the walking track from the car park at STOP 13 to the summit of Mt. Schank. From the top of Mount Schank the extensive lava flow can be seen to the west, and the line of scoria cones which are associated with the flow are to the northwest. Across the northern rim of the larger crater, a lower, less prominent inner rim appears. This marks the buried remains of an earlier cinder cone.

The deposits on the rim are crudely stratified, indurated lapilli tuffs. If time permits, follow the rim in a clockwise direction to the point where the path into the crater begins. Descend into the crater and explore the stratified deposits on the lower slopes of the crater. Return to the crater rim and walking anticlockwise around the rim, the partially buried (or straddled) explosion crater on the southern side will come into view. This smaller maar indicates that ground water had more influence on eruptive style at this end of the main fissure than elsewhere along its length. Traverse around to the eastern side of this maar rim and descend along its margin. Work down to the lower levels of the maar succession, and then work upwards back through the succession. The succession is divisible into two intervals, a lower phreatomagmatic one with upwards of 25% country rock debris, mostly Gambier Limestone blocks which are up to 1m or more in diameter. Spectacular impact sags are visible. The upper succession which is only 2-3m thick is darker and contains a predominance of juvenile material. However, it is poorly sorted, the juvenile debris is micro- to only moderately vesiculated, stratification is diffuse, in places wavy, and coarser layers show lensing of coarser fragments. Despite the high juvenile content, this succession also shows signs of a phreatomagmatic origin, by surge and/or surge modified fall processes.

Mt Schank thus appears to have varied in its eruption style from magmatic hawaiian, to classical maar forming phreatomagmatic, to "drier" phreatomagmatic eruptive activity that produced a hybrid cone - similar in form to a strombolian cone and a tuff cone.

To the southeast, a small blowhole exists, marked by ETSA 'stobie pole" on its northern rim. This vent developed by steam emission away from the main vents. Mount Schank does not contain a crater lake as does Mount Gambier because its crater floor is only just below ground level of the surrounding plain and above the water table.

Summary: At both the Gambier and Schank centres, eruptive activity intially was largely magmatic, then became moore classically "wet" phreatomagmatic, and then finally "drier" phreatomagmatic.

STOPS 15, 16: THE BRIDGEWATER VOLCANIC COMPLEX

Volcanic centres of the Portland-Heywood District - Age and Geochemical Characteristics. Ian Nicholls and Jerry Sukhyar, Department of Earth Sciences, Monash University.

Introduction:

The thin veneer (normally <60 m) of basaltic lavas on the western plains of Victoria (see introductory notes) consist mainly of tholeiitic types, although alkaline basalts are also present (Irving, 1971). The earliest exposed lavas of the plains sequence have been K/Ar dated at around 4.5 m.y., or late Pliocene (McDougall et al., 1966). By contrast, most of the better known volcanic features (scoria cones and maars) of the Newer Basalt province belong to much earlier phases of activity (<25,000 yr), involving mainly strongly alkaline types. These rest on the plains basalt surface, or occasionally on Tertiary sedimentary rocks.

In the Portland-Heywood district, there is a group of volcanic complexes which on morphological evidence are older than the centres further east. and which are partly overlain by Pleistocene sedimentary deposits - either the calcareous aeolianites of the Bridgewater Formation, or the quartz-rich Malanganee sands (Boutakoff, 1963). Basalts of one such complex, at Cape Sir William Grant, south of Portland (Fig.15. 1) have been K/Ar dated at 2.8-3.0 m.y. (Aziz-ur-Rahman and McDougall, 1972). The available evidence therefore indicates that the complexes around Portland formed during the period of plains-building flood basalt activity. Deposits of several centres, at Capes Grant, Nelson and Bridgewater-Duquesne have excellent exposure in coastal cliff sections. They are of major interest in the interpretation of magmatic and phreatomagmatic eruptive mechanisms, and they also provide information on the geochemistry and magmatic evolution of the plains basalt sequence.

Morphology of Portland-Heywood complexes, and types of deposit present.

The inland volcanic complexes of the Portland-Heywood group: Mt. Kincaid, Mt. Vandyke, Mt. Deception, Mt. Richmond, Mt. Eckersley, Mt. Clay and Bald Hill (Fig. 1) are typically broad low shield volcanoes with a maximum height of <200 m. Mt. Richmond is completely buried by deposits of the Malanganee Sands, and Bald Hill has a partial veneer of similar deposits. The larger Mts. Eckersley and Clay have very little outcrop, mostly lava flows. Their very gentle slopes suggest that they consist mainly of lava flows.

Coastal exposures at Capes Grant and Bridgewater show a variety of internal structures of these complexes. At Cape Grant, the main rock types exposed in the Port of Portland Authority (PPA) quarry are coarse ophitic basalts with pegmatoid patches, which appear to represent a single thick lava flow or sill. However, on the western side of Cape Grant, at "The Wells" (Boutakoff, 1963) a cone with pyroclastic fall and mass-flow deposits is found buried by basaltic lavas. There is greater complexity at Cape Bridgewater, where pyroclastic fall and surge, and spatter and lava deposits probably define several small, overlapping tuff rings and composite cones (see below). By contrast at Capes Nelson and Duquesne exposed sequences consist almost entirely of lava flows.

Geochemistry of lavas.

Major element geochemical data have previously been published for lavas of three of the Portland-Heywood group of complexes: Mt. Kincaid, Mt. Eckersley and Cape Grant (Irving and Green, 1976). The analysed Mt. Kincaid and Mt. Eckersley samples are respectively a mafic olivine basalt and a felsic quartz tholeiite(see Table 15.1). The sample from PPA quarry at Cape Grant is and olivine tholeiite, previously dated at 2.76 m.y. by Aziz-ur-Rahman and McDougall (1972). This is more felsic and less alkaline than material of the thick lava or sill currently exposed in the quarry.

J. Sukhyar has analysed a range of basaltic lava samples from Capes Grant, Nelson, Bridgewater and Duquesne. The overall range is from mafic alkali olivine basalt or olivine basalt with 8-10% MgO (Cape Grant) to much less mafic slightly olivine - to quartz normative tholeiites with 5-6% MgO (Cape Bridgewater). For most major elements, the analyses appear to define a single coherent trend, suggesting a genetic relationship between lavas of the various volcanic complexes. However, this is unlikely to be the case, since the trend is from moderately SiO_2 - oversaturated alkaline compositions to SiO_2 - oversaturated tholeiitic compositions. Similar trends are not observed amongst primitive lava compositions in other parts of the Newer Basalt province (Irving and Green, 1976). Nor is such a trend likely to be related to fractionation processes at either mantle or crustal depths (Frey et al., 1978). Direct evidence of the low pressure fractionation trend for the alkali olivine basalts of Cape Grant comes from analysis of the pegmatoid patches. Here the trend is toward iron-rich, felsic alkali olivine basalt.

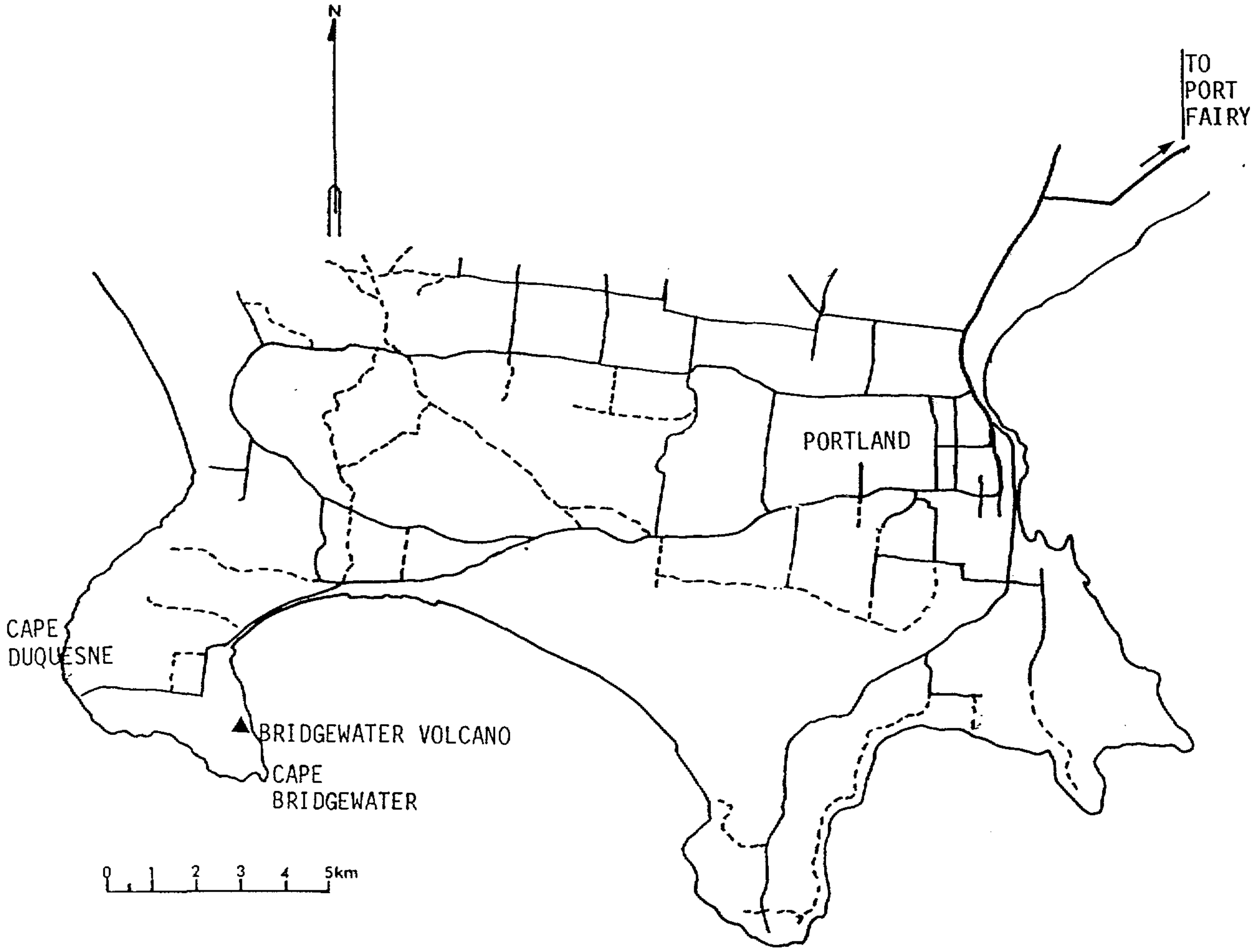


Figure 15.1 *Location of the Bridgewater Volcanic Complex.*

It seems more probable that the overall alkaline to tholeiitic trend for the Portland-Heywood centres represents increasing degrees of melting of mantle sources. Since only the rocks of Cape Grant are sufficiently magnesian (100 Mg/Mg + Fe^{2+} ≈ 65) to closely reflect the compositions of primary magmas, it appears that fractionation of primary magmas becomes more extensive for progressively less alkaline compositions.

The Bridgewater Volcanic Complex

From Mt. Gambier drive via the Princes Highway to Heywood in Victoria, and then along the Henty Highway to Portland. On entering Portland look for the sign to Cape Bridgewater (Bridgewater Road) on the right. Follow the coast road for 15km to the end of the long beach. Park and walk along the beach and rock platform to the south.

The Bridgewater Volcanic Complex is an old, dissected, multi-vent complex consisting of lavas, pyroclastics and probably some reworked volcaniclastics. The rock succession is best exposed in the coastal cliffs around Cape Bridgewater (Figs. 15.1 and 15.2). Inland exposure is poor being dominated by grassy rolling hills on the degraded volcanic pile. The eastern coastline of Cape Bridgewater exposes much of the pyroclastic sequence, as well as lavas. Two basalt necks interpreted by Coulson (1941) and Boutakoff (1963) as relic vents are also exposed (Fig. 15.2) The western side of the Cape consists almost wholly of coherent lavas, which will be examined at STOP 16 at Cape Duquesne.

There is little constraint on the age of the Bridgewater Complex. It predates the overlying calcareous dune deposits (aeolianites) of the Bridgewater Formation, which is generally considered to be mid to late Pleistocene in age, and it is thought to unconformably overlie the Miocene Port Campbell Limestone. A latest Pliocene to mid-Pleistocene age is therefore likely.

Accounts of the geology of the Bridgewater Volcano have been given by Coulson (1941) and Boutakoff (1963), while details of the volcanology have been addressed by Pope (1983). The model proposed by Boutakoff (1963) for the Bridgewater Complex is of overlapping pyroclastic cones, capped by basalt lavas. Boutakoff (1963) also suggested that the volcano may have originated as a shallow marine volcanic centre, erupting offshore before the dune complex which now links the Bridgewater headland with the mainland was formed. The analogy with Surtsey is clear although this was not proposed. If the Bridgewater centre did begin as a surtseyan cone complex, it then subsequently evolved into a lava shield.

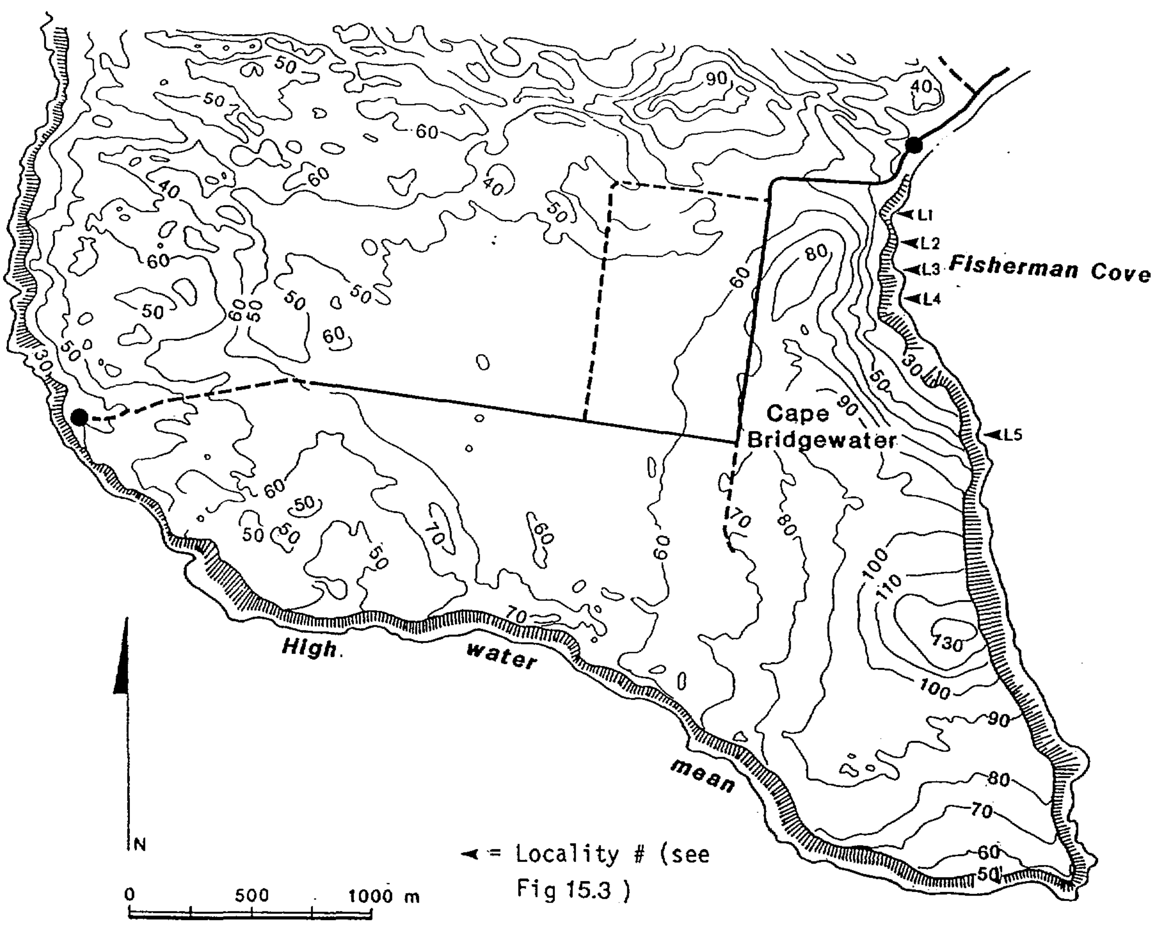


Figure 15.2 *Bridgewater Volcanic Complex showing the location of the measured sections shown in Figure 15.3.*

There is no evidence that any of the preserved succession was deposited under water. All facies are consistent with emplacement above sealevel: surge deposits, airfall deposits, agglutinate deposits, accretionary and cored lapilli. However, lapilli-tuff from Locality 5 contains what appear to be foraminifera, indicating incorporation from subjacent marine strata.

Geochemistry of lavas (I. Nicholls and J. Sukhyar)

Major element compositions are available for lavas at three Cape Bridgewater localities. Samples were taken from near the end of the large flow, originating from Stony Hill, where it intrudes well bedded ash deposits at Fisherman's Cove (Locality 4), from several flows of the agglutinated lava sequence (Locality 5), and from a lava sequence on the south coast of Cape Bridgewater.

Analysed samples fall into two groups. The lava at locality 4 is felsic tholeiite with 6% MgO, <1% normative olivine (Ol) and Mg-number of only 56 (Table 12.1). The agglutinate samples are appreciably more mafic olivine tholeiites, with 8% MgO, 6-10% Ol and Mg-number 61. Those from the southwest locality include representatives of both the previous types, those with low MgO content and Mg-number becoming slightly quartz-normative. The latter have strong similarities with the analysed quartz tholeiites of Mt. Eckersley, near Heywood (Table 15.1).

None of the analysed Cape Bridgewater lavas have primitive geochemical characteristics, and all are thought to be the products of fractionation of the more mafic olivine tholeiite magmas.

STOP 15: Bridgewater Volcanic Complex - coastal traverse from the southern end of the beach in Fisherman's Cove, Bridgewater Bay, to end of platform access at Locality 5 (Fig. 15.2). Traverse recommended at low tide only.

In this traverse a spectrum of pyroclastics and lava types, as well as the aeolianites of the Bridgewater Formation, are well exposed. In the volcanic succession, dips are mainly gentle and the dip directions reverse several times, suggesting that overall, approximately the same stratigraphic level is exposed between localities 1 and 5 (Figs. 15.2 and 15.3). Given this there are significant lateral facies variations.

The pyroclastic rocks appear to be dominated by tuffs and lapilli tuffs of phreatomagmatic explosive origin. Although vesicular scoria fragments occur within the pile, non-vesicular to microvesicular fragments predomi-

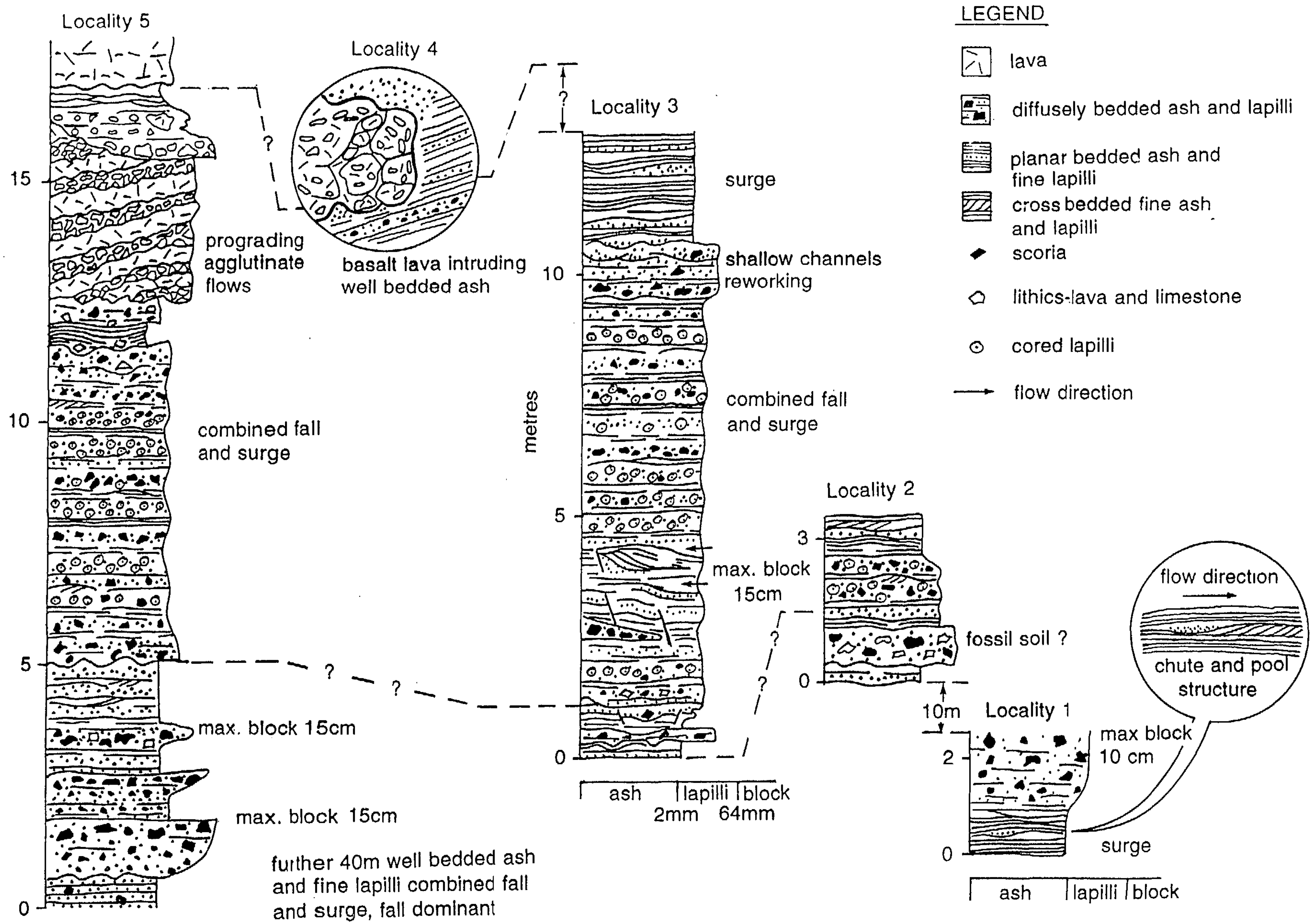


Figure 15.3 *Cape Bridgewater Stratigraphic Sections (see Figure 15.2 for locations).*

nate. The occurrence of isolated scoria fragments in lapilli-tuffs dominated by a largely non-vesicular phreatomagmatic tephra is anomalous. This is perhaps explained by combined phreatomagmatic and magmatic fragmentation as a body of lava rising in a cylindrical conduit, is subjected to explosive interaction around its margins, where it is contact with groundwater, whereas in its centre it is protected, and vesiculates to produce scoria. In addition abundant cored lapilli (subspherical accretionary fragments with a nucleus and a wet, finer rind accreted during transit through the eruption column) at localities 2, 3 and 5 (Fig. 15.3), testify to this. Magmatic explosions do not appear to have been significant, given the absence of strombolian scoria beds such as those at Mt. Leura, Tower Hill, Mt. Eccles and Red Rock. However, clastogenic lavas at Locality 5 clearly indicate the influence of magmatic, hawaiian style volcanism, as do the younger shield lavas.

The clasts are predominantly basaltic, but limestone basement blocks also occur. Lapilli-size clasts are frequent, and form an integral part of the common lapilli-tuffs of the succession. Some blocks lie in well defined sag structures, usually in fine tuffs, suggesting firstly an explosive, ballistic near-vent origin for the blocks, and secondly that the fine tuffs were probably wet phreatomagmatic ashes.

The tuffs and lapilli-tuffs appear to have been transported and deposited by both pyroclastic fall and base-surge processes. Surge influences are recognised by chute and pool structures (Locality 1), low angle truncations (all sections), pockets of coarse sediment (all sections), and ? festoon trough cross-beds (Locality 3, near top of section). The last of these could debatably however, represent sheetwash gully erosion and reworking, based on the irregularity of the scour surfaces. Fall influences are suggested by intervals of the section with regular, continuous layering, almost devoid of truncations (e.g. Locality 5). In reality, in near-vent settings, both processes may be operating simultaneously, leading to hybrid deposits that could be called 'surge-modified fall deposits'.

The lavas are also diverse in character, and include a lava with an intrusive margin, which contains incipient

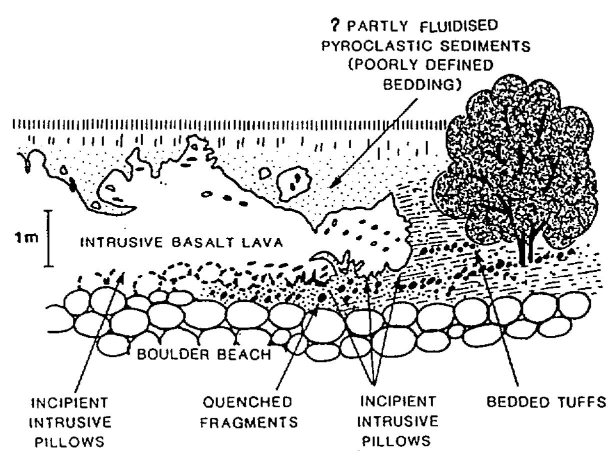


Figure 15.4 *Intrusive contact betweenbasalt and bedded pyroclastics, Locality 4.*

intrusive pillow lava pods, as well as quenched fragments that have spalled of the lava surface, into the wet(?), bedded pyroclastic deposits (Locality 4, Figs. 15.3 and 15.4). At Locality 5, a succession of at least 11 thin agglutinated clastogenic lavas is exposed. The lavas overlap, suggesting a progradational lava delta, and each lava is separated from the other by a spatter horizon. The succession appears to be the product of near-vent hawaiian-type lava fountaining. The stratigraphically highest lavas (Localities 4 and 5) appear to be relatively continuous, coherent sheet-like lava(s) that were probably pahoehoe in character. They contain an internal sheet-like jointing parallel to the tops and bottoms of the flow(s) in places, as well as large cavities with highly irregular spinose linings.

Sections have been measured at five localities (Figs. 15.2, 15.3).

Locality 1:

The lower part of the cliff succession is dominated by planar bedded tuff that is thinly bedded. Although a fall origin is possible for some horizons, small scale chute and pool structure suggest at least some base surge transportation. The overlying lapilli-tuff is crudely stratified. Is this a surge or fall deposit?

Locality 2:

The 3m outcrop contains interbedded tuffs with planar, wavy and cross-stratified bedding suggesting largely surge deposition, and lapilli tuffs with limestone lithics as well scoria clasts and cored lapilli with scoria cores. The lapilli-tuffs are massive to crudely stratified, and one unit passes into cross-stratified tuff, suggesting surge transportation.

Locality 3:

At this 12m section, interbedded Lapilli-tuffs with cored lapilli, scoria and some limestone lithics are common. In addition, syn-depositional faults, and onlapping chute and pool type structures occur, indicating at least some surge transportation, although some of the lapilli-tuffs beds are probably fall deposits, or surge modified fall deposits.

Locality 4:

In this small bay, the low cliffs expose a basalt with unusual lobate margins abruptly truncating bedded tuffs and lapilli tuffs. The lobate margiond appear to represent incipient pillows. Quench fragmented basalt fragments appears to underlie, and be mixed into the underlying tuffs, and the overlying tuffs have poorly defined bedding suggesting that they have been fluidised. The succession is interpreted as an intrusive basalt into unconsolidated water saturated ash and lapili-ash.

Locality 5:

After a long walk along cliffs with limited outcrop of largely basalt, there is spectacular outcrop of at least 11 clastogenic lava layers with irregular margins and intervening spatter layers (Figs 15.5, 15.6). The succession has a southward progradational structure, and clearly represents the products of a nearby hawaiian fire fountain event.

Figure 15.5 *Overview of prograding clastogenic lava and spatter succession, Locality 5.*

The interbedded lapilli-tuffs and tuffs to the south have well-defined ballistics and impact structures, and it is from this succession that the foraminiferal remains have been found. Juvenile fragments from this locality are poorly vesicular, and palagonitised, both indicating a phreatomagmatic origin.

However, spectacular cored accretionary lapilli occur in planar bedded lapili-tuff succession with numerous contemporaneous faults (Fig. 15.7). The core fragments are mostly highly vesicular, and are coated and associated with less vesicular ash. Nearby a thinly bedded tuff and fine lapilli-tuff succession with fine scoria lapilli ripple lenses enclosed in phreatomagmatic tuff occur. This dual vesicularity can only be explained by either explosive recycling of pre-existing strombolian fall deposits during a change from magmatic to phreatomagmatic activity, or by the model proposed above involving a cylindrical conduit with phreatomagmatic disruption of the rising magma occurring around the margins of the conduit, whilst vesiculating magma rises up through the centre of the conduit unaffected by water-magma interaction. At the furthest possible outcrop, thinly bedded tuffs occur with accretionary lapilli, some fragmented. One small U-shaped channel is also visible. Much of the succession from the clastogenic lavas to here, although generally planar bedded, also shows lensing and low angle truncations, and together with the evidence of the accretionary/cored lapilli and the ballistics, are interpreted as near-vent surge modified fall deposits. The ubiquitous faults are considered to have formed contemporaneously, probably as a result of explosive shocks.

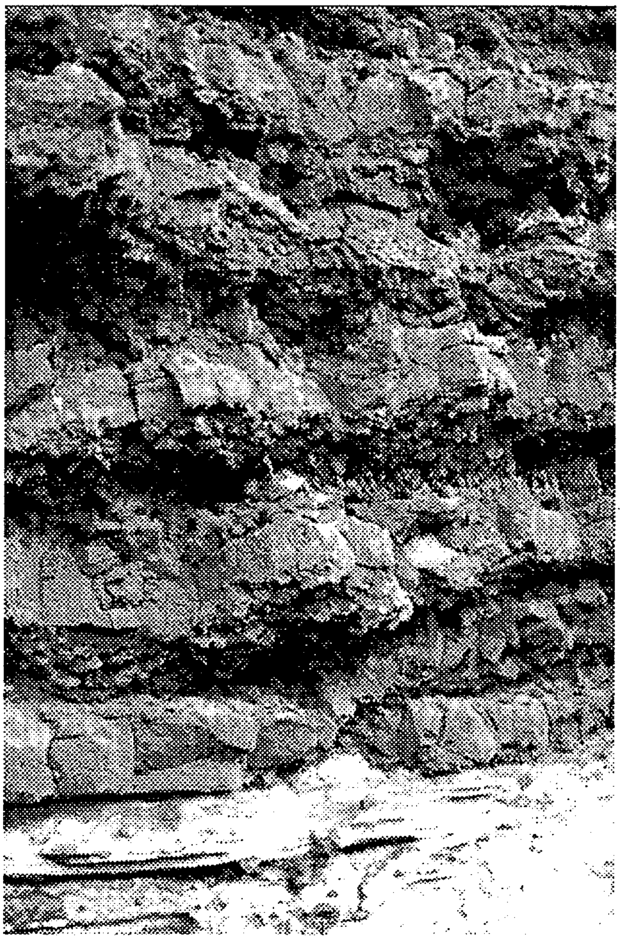


Figure 15.6 *Closeup of clastogenic lavas and interbedded spatter deposits, Locality 5.*

Figure 15.7 *Cored lapilli in bedded, contemporaneously faulted lapilli-tuff.*

Summary:

1. This apparent surtseyan succession is dominated by bedded phreatomagmatic deposits that are largely planar bedded, with low angle lensing and truncations. Classical dune bedded base surge bed sets are rare. Surge modified fall deposits are the preferred interpretation, implying a near vent setting.

2. The occurrence of highly vesiculated scoria and less vesicular fine phreatomagmatic ash fragments in the same deposit appear to require a special eruptive mechanism that produces both, involving phreatomagmatic fragmentation around the margins of the magma conduit, but magmatic vesiculation and fragmentation in the interior of the conduit.

3. Local hawaiian style fire fountaining appears to be responsible for the succession of thin clastogenic lavas and spatter deposits.

STOP 16: Cliffs at Cape Duquesne. Lava sequence, calcareous aeolianite deposits and "Petrified Forest".

At Cape Duquesne, westward facing vertical cliffs 20-30 m high, expose a flat lying sequence of at least 10 lava flows, which presumably continues below sea-level. The thickness of individual flows is typically 2-5 m. Most flows show massive interiors and highly vesicular oxidized bases and tops, and in some cases the upper surface has a pronounced ropey structure. The more massive flows show well developed regular columnar jointing on a range of scales. Column cross sections are well exposed on horizontal benches.

Boutakoff indicated that the lava sequence at Cape Duquesne was derived from vents at Cape Bridgewater (Stony Hill). However, the much greater total thickness of lavas at Cape Duquesne, the greater thickness of individual flows and the complete lack of evidence for appreciable hiatuses within the Duquesne sequence argue against this. Lava compositions (Table 1) show that while Cape Bridgewater and Cape Duquesne lavas are geochemically related, they overlap in composition.

As at Cape Bridgewater, the basaltic sequence is overlain by the calcareous aeolianites of the Pleistocene Bridgewater Formation. South from the car park is an area of closely spaced roughly cylindrical features within the calcareous sands, oriented vertically. This was interpreted by Boutakoff as a "Petrified Forest", the cylindrical features representing the casts of tree-trunks.

The remarkably close spacing of the supposed tree-trunks, and the common observation that cross-bedding in the dune sands continues through the supposed casts, argue against an organic origin. It seems more likely that the cylindrical features have been formed by aqueous solutions percolating down through the dune deposits, causing transport and redeposition of carbonate about the solution pipes.

Geochemistry of lavas.

Major element analyses are available for four lava flows of the Cape Duquesne sequence. The extremes of composition in terms of MgO content are given in Table 12.1. All analysed samples are olivine tholeiites (5-8% Ol), with non-primitive Mg-numbers (61). In most respects they fall almost exactly midway between the two groups of analysed lavas from Cape Bridgewater. It seems clear that while the two groups are closely related, eruption points at Cape Bridgewater were not the source of the Cape Duquesne sequence.

	Cape Bridgewater		Mt. Eckersley	Cape Duquesne Lavas	
	Lava, Locality 4	Agglutinate, Locality 5	Lava (Irving and Green, 1976)		
SiO_2	53.43	51.56	53.53	52.63	53.12
TiO_2	2.01	1.67	1.80	1.93	1.77
Al_2O_3	15.30	15.16	15.32	14.53	15.12
Fe_2O_3	1.24	1.35	1.59	1.29	1.23
FeO	8.24	8.99	7.94	8.17	8.17
MnO	0.11	0.15	0.11	0.11	0.11
MgO	5.89	8.16	6.52	8.03	7.11
CaO	8.25	8.45	8.38	7.97	8.05
Na_2O	3.76	3.61	3.65	3.68	3.82
K_2O	1.34	0.70	0.85	0.98	1.23
P_2O_5	0.36	0.27	0.31	0.29	0.29
Mg-number	56.4	61.8	59.4	62.5	60.8
Qz	-	-	1.04	-	-
Or	7.92	4.14	5.01	5.79	7.27
Ab	31.81	30.54	30.88	31.14	32.32
An	20.92	23.10	22.90	20.24	20.48
Di	14.47	13.91	13.61	14.16	14.16
Hy	17.53	12.46	20.11	16.32	14.26
Ol	0.92	10.09	-	6.14	5.64
Mt	1.80	1.96	2.30	1.87	1.78
Ilm	3.82	3.17	3.42	3.36	3.36
Ap	0.85	0.64	0.73	0.69	0.76

Table 15.1 *Representative analysis of lavas of Cape Bridgewater (STOP 15) and Cape Duquesne (STOP 16) localities.*

STOPS 17-20: HARMAN VALLEY LAVA FLOWS

Portland to Wallacedale and Byaduk.

From Cape Bridgewater drive back to Portland and north along the Henty Highway through Heywood to Condah. Past Condah turn right into North Wallacedale Road and drive through Wallacedale. The road joins the valley of the Harman Valley Lava flow which was erupted from Mt. Napier to the east, along the Wallacedale-Byaduk Road. It passes spectacular tumuli (STOP 17), and marginal levees (STOP 18) before joining Old Crusher Road to Byaduk.

STOP 17: Lava tumuli, Wallacedale. (E.B. Joyce, Melbourne University)

These unusual steep-sided tumuli, rising as hemispherical mounds from the generally flat surface of the Harman Valley flow from Mt. Napier, have a height of 5 to 10 m. The main group of tumuli lies at the junction of the main valley with a side valley which also contains lava (Figs. 17.1, 17.2).

Skeats and James (1937) first described these "steam blisters" as they termed them, and suggested that they were due to gas pressure below the flow surface, perhaps caused by the lava flow passing over a marshy flat. They noted the radial fracturing, depressions in the crests, and "gaping joints which . . . give one the impression that the cones are hollow" (p.275). This concept fitted in with their general theory of the origin of the Byaduk Caves and those at Mt. Porndon, which they explained as huge steam blisters, with lava tunnels developing later and connecting the blister chambers.

Ollier (1964) explained the features as unusually steep-sided tumuli, noting the lack of a hollow interior, and their similarity to the other tumuli and stony rise features in Victoria. He described how the "crust lava has layering parallel to the surface, formed by partings and flattened vesicles; the inner lava is usually much more frothy . . " (see Fig. 17.3).

STOP 18: Marginal lava levees, Wallacedale

The road follows the course of the Harman Valley lava flow, sometimes passing over it, other times following its margin. At several localities the margin is a sharply defined ridge-like feature or levee. The levees formed during flow and acted to confine the main body of the lava within an interior channel. After lava supply ceased some deflation of the level of the lava in the interior channel occurred.

Levees can have several origins (Hulme 1974, Sparks et al. 1976, Cas and Wright 1987). Initial levees

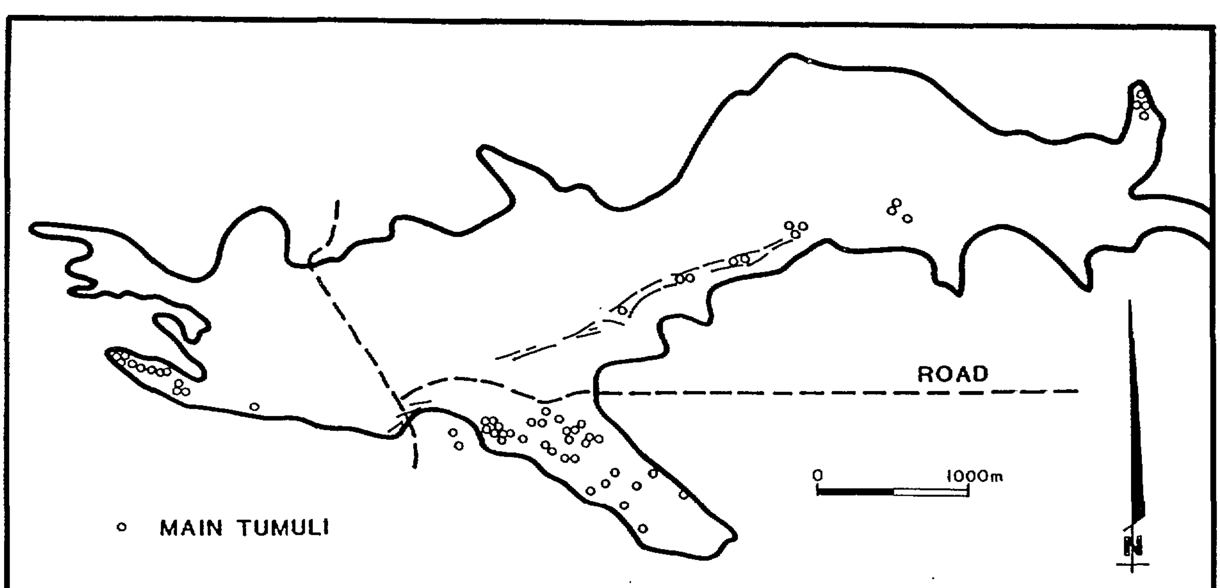


Figure 17.1 *Distribution of tumuli on the Harman Valley flow. The dots represent all the main tumuli, barriers (pressure ridges); (from Ollier, 1964).*

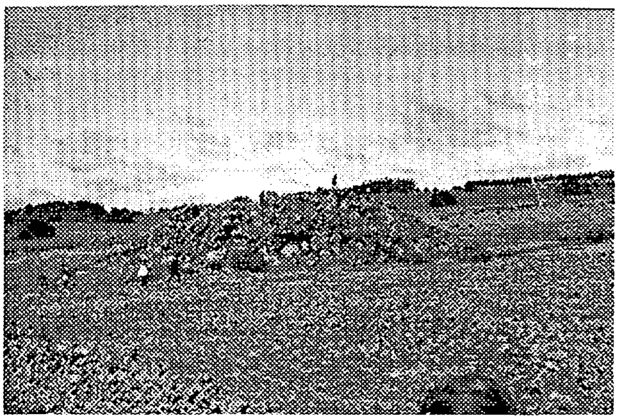


Figure 17.2 *Features of one tumulus, Harman Valley lava.*

form as the margins of the lava flow cool and their yield strength increases, so leading to freezing of the margins, whereas the interior continues to flow. Accretionary levees consist of piles of clinker accreted to smooth pahoehoe lava channels. The clinker blocks weld together to form a steep solid levee. Rubble levees are associated only with aa lavas and result from the avalanching of aa debris down the margins of the flow, forming piles of rubble that are approximately at the angle of repose. Overflow levees form when lava repeatedly floods over existing levees. Levees can infact be hybrids of several of these types.

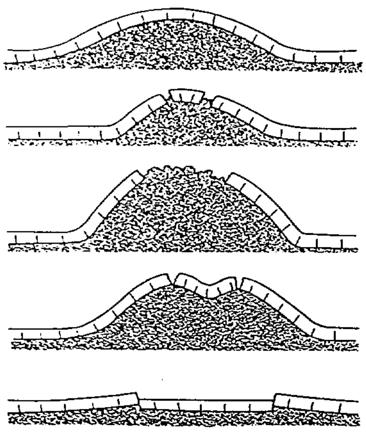


Figure 17.3 *Range of variation among tumuli. From top to bottom: a simple tumulus; a cracked tumulus, with a slight extension of lava; a tumulus breached wide open, with a dome of vesicular lava in the centre; a tumulus with an inverted top and cracked rim; a down faulted disk of crust lava, the remains of a collapsed tumulus. (from Ollier, 1964).*

STOP 19: Lava surface morphology, east of Byaduk. (E.B. Joyce, Melbourne University)

At the end of Crusher Road-Harper's Road turn north along the Port Fairy-Hamilton Road, cross the Harman Valley flow and stop on the right hand side of the road overlooking the Valley. To the east is the Mt. Napier volcano, consisting of a low-angle lava shield capped by several scoria cones with minor craters. An extensive sea of lava has spread radially from Mt. Napier for 10 km (Joyce, 1976a), and a flow has then extended down the Harman Valley for a total distance from the vent of some 20 km (Fig. 19.1). At this viewpoint the flow is near its narrowest, at 300 m, but elsewhere it is up to 3 km across.

The valley is incised into weathered earlier Newer Volcanic flows and Tertiary sediments, and an exposure may be seen in the road cutting opposite. Lateral streams have not yet formed, and a radiocarbon date at the base of Buckley's Swamp, formed on the northeast side of Mt. Napier by lava damming of a stream, gave an age of 7,000 (Gill and Elmore, 1973).

Features of the flow related to constriction at this point and the resultant sub-surface pressure may be seen below the lookout point (Fig. 19.2).

The Byaduk Caves occur in this flow about 3 km upstream (STOP 20). Further lava caves, lava channels and a natural bridge have been described from the lava field to the west of Mt. Napier (Gill and Elmore, 1974; Webb, Joyce and Stevens, 1982). Similar lava channels and caves including the remarkable Gothic Cave can be seen at Mt. Eccles (Joyce, 1976).

STOP 20: Byaduk lava caves.(E.B. Joyce, Melbourne University).

Follow the main road northwards through Byaduk north, and turn east at signpost "Byaduk Caves" to drive east and south to car park and reserve at edge of flow. This group of caves (Fig. 20.1) is the largest and best known in Australia, and has been classified as of national significance (Joyce and King, 1980). The caves form a pattern indicating a major sub-surface flow, which would have allowed the lava to retain its heat and travel down the valley for many kilometres. Other tube systems may have been active, but apparently only this section was left empty by the final withdrawal of lava. Collapse entrances have developed at some later stage (Fig. 20.2), providing access down rubble piles, and showing excellent cross sections of the layered lava which makes up the flow; the collapses also give shelter to locally-rare trees, ferns and mosses.

The caves were first described by Skeats and James (1937) and later by Ollier and Brown (1964). Some nineteen caves are known in the area, averaging 4 to 7 m high and 10 to 20 m wide, with Church Cave being the longest at 400 m. Features of the caves include lava linings, lava stalactites and stalagmites, lateral benches, lava "tide-marks" and ropy lava floors (Webb, Joyce and Stevens, 1982).

Three main theories have been proposed for the formation of lava caves - withdrawal of the interior of a chilled lobe; crusting of an open lava channel; and liquid segregation in the layered lava of a partly cooled flow, with subsequent drainage (Joyce, 1980). The possibility of this third type of origin for lava caves was first proposed by Ollier and Brown (1965) using evidence from this area, and the concept and its relationship to the formation of layered-lava has caused much controversy.

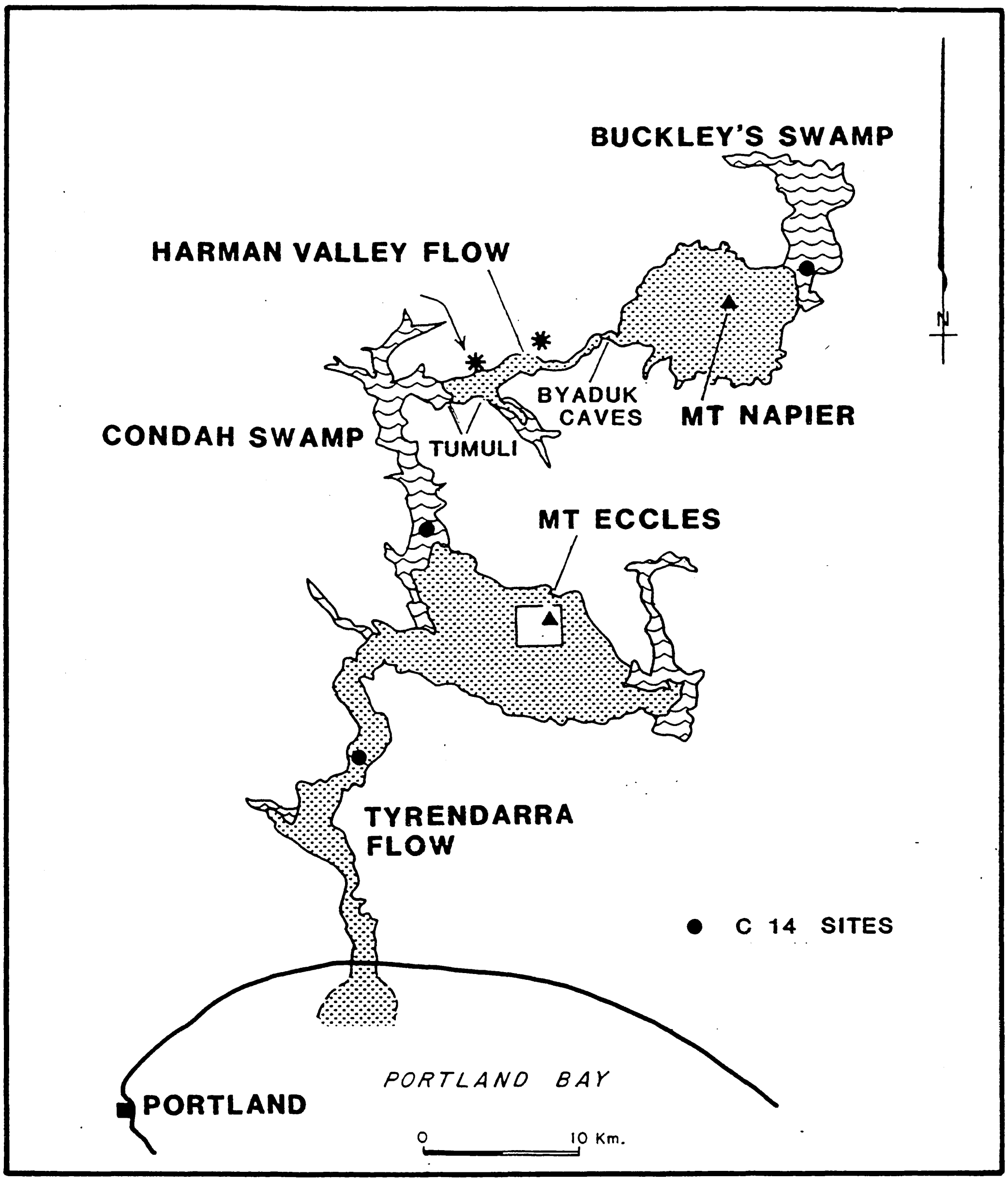


Figure 19.1. *Mt. Napier and Mt. Eccles, Western Victoria (from Webb, Joyce and Stevens, 1982).*

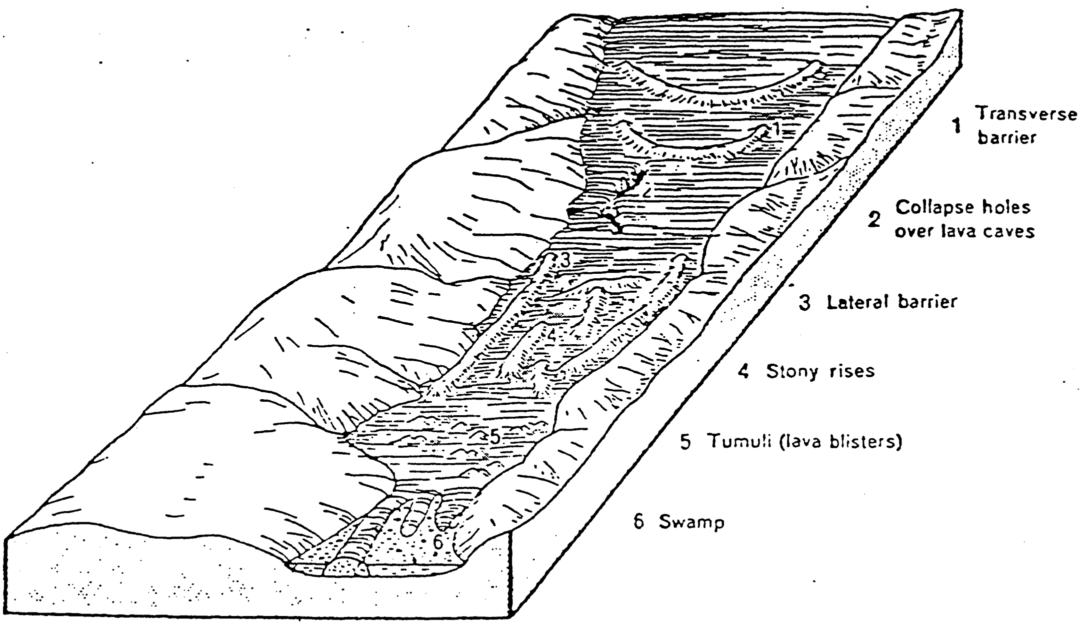


Figure 19.2. *Features of the Harman Valley lava flow, Byaduk (from Ollier, 1967b).*

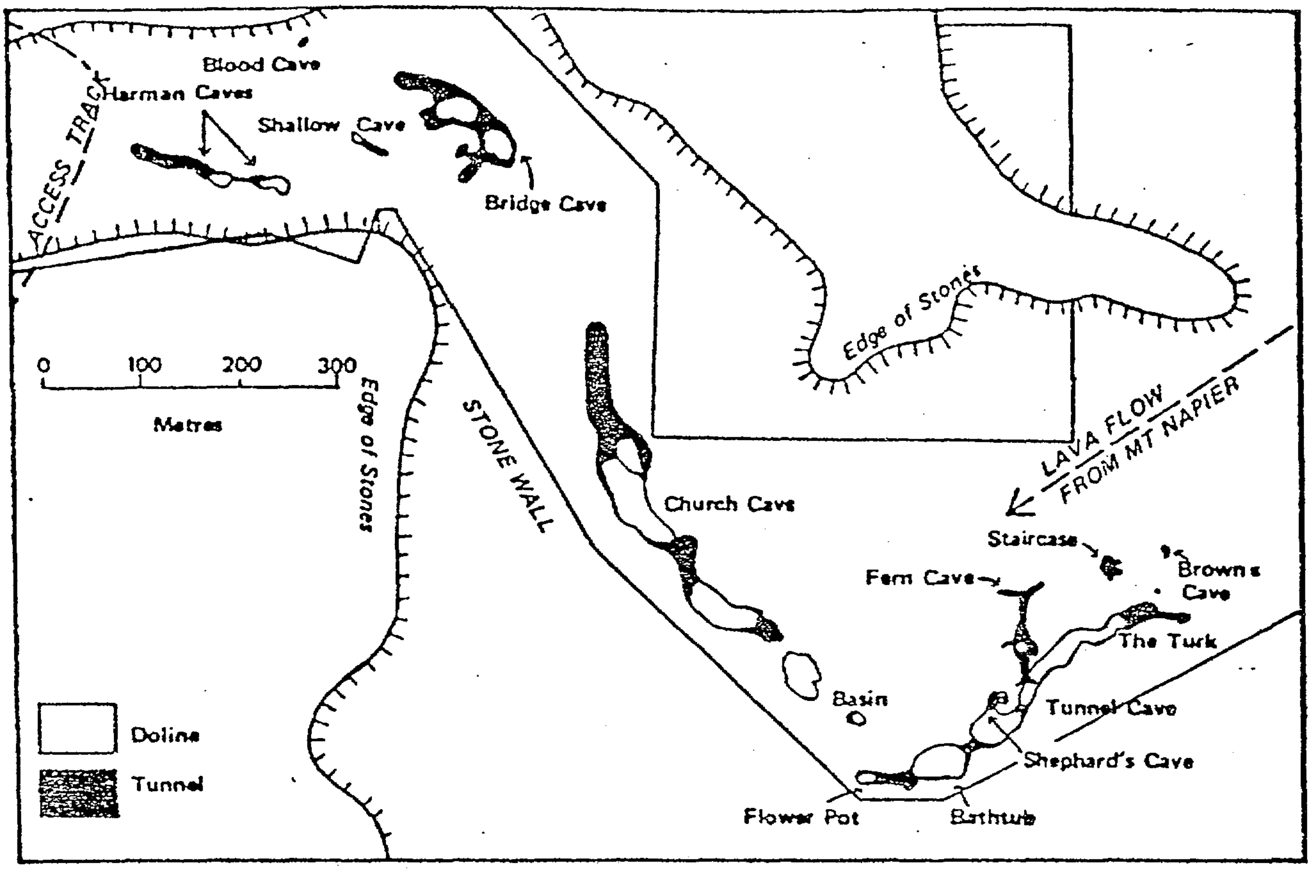


Figure 20.1 *Map of the Byaduk Caves area (based on Ollier and Brown, 1964).*

Figure 20.2 *Lava cave in the Harman Valley lava, Byaduk, resulting from the collapse of the roof of a drained lava tube.*

STOP 21: MOUNT ECCLES VOLCANIC COMPLEX

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STOP 21: Lavas, canals, crater lake, spatter cones.

From Byaduk, drive south to Macarthur, and turn right (west) to the Mt. Eccles National Park. Drive to the top car park at the rim of the fissure lake system. The Mt. Eccles volcanic complex is 8.5 km WSW of Macarthur, and approximately 60 km NNW of Port Fairy (Figs. 21.1 and 21.2). Mt. Eccles is the name given to the largest (180 m high) scoria cone within a volcanic complex which includes a crater lake (Lake Surprise), a number of lava channels and tunnels which fed extensive lava flows, various spatter cones, and a second, smaller scoria cone (Little Mount- now removed by quarrying). The complex is one of the youngest group of the Newer volcanic centres (including also Mounts. Napier and Rousse) which contain few or no ultramafic xenoliths and megacrysts. Radiocarbon dating of charcoal beneath lava flows in the area around Mt. Eccles indicated activity in the period 5,000-7,000 years B.P. (Gill, 1978). The magmas giving rise to the Mt. Eccles complex were of hawaiite to nepheline hawaiite composition (Irving and Green, 1976).

Lava flows

Lava flows extended at least 2 km in all directions from Mt. Eccles. Toward the north, they were diverted by Bald Hill, one of the oldest (pre-coastal dune) group of Newer Basalt centres. The largest of these flows (Tyrendarra Flow) moved westward into Condah Swamp, then southward down the valley of the ancestral Fitzroy River (Fig. 21.1).

Erupted at a time of low sea level, the Tyrendarra Flow now extends 15 km from the coast (Fig. 21.1). Its total length was nearly 50 km, while its width was at times only 100 m.

Locality 1: Crater Lake

The crater lake within the Mt. Eccles complex, Lake Surprise (Fig. 21.2), is approximately 700 m in length, with a maximum width of about 150 m. It is almost totally enclosed by 50-70 m high cliffs developed in the lava flow sequence, with 8-10 flows being exposed. At its north end, the lake is about 20 m below the beginning of the largest lava channel ("canal") of the complex.

The NNW to SSE trend of Lake Surprise is extended into a series of small eruption points, suggesting alignment along a fissure, or along a deep narrow section of a lava flow (Ollier and Joyce, 1973).

Locality 2: Lava Channels and Tunnels

The lava channels, or canals, represent lines of drainage within the extensive lava sheets centred on Lake Surprise. Lava flowed within and beneath the channels, occasionally overflowing the banks and raising the general level of the sheets. When a skin was formed over parts of the channel system, and fluidial lava drained out, lava tunnels (or lava caves) resulted. The most extensive of these is Tunnel Cave, above the northern end of Lake Surprise (Fig. 21.2). This appears to have formed in a side flow, almost perpendicular to the main lava channel (Fig. 21.2).

Within the smaller southern lava channel, Gothic Cave (with its roof, the Natural Bridge), is a short section of unusually deep lava tunnel (Fig. 18.2). The walls appear to have bulged inward due to pressure from surrounding plastic lava. Various levels of flowing lava are recorded by "tide-marks" on the tunnel walls.

Locality 3: Spatter Cones

A series of smaller spatter-related features begins at the southern end of Lake Surprise, where a deposit of agglutinated lava bombs may represent part of a spatter rampart. South of the Middle Mt. Eccles quarry are the spatter cones named "The Shaft", "The Pitt", and "The Alcove" (Fig. 21.2). The best developed, The Shaft, is a cone formed of breadcrust bombs and lava driplets, with an open vent extending about 30 m below the surrounding lava flow surface (Fig 21.3).

Ollier and Joyce (1973) suggest that these features may represent adventitious cones, fed with lava from an underlying thick flow.

STOP 22: Mt. Eccles Scoria Cone.

The cone sequence incorporates no constructural features recognisable as being of phreatomagmatic origin. Phreatomagmatic deposits are however exposed at the base of the quarry section through the main Mt. Eccles scoria cone (Figs. 21.2, 22.1, and 5.1). The eruption of this cone therefore seems to have opened with phreatomagmatic explosions, with a further two very short-lived

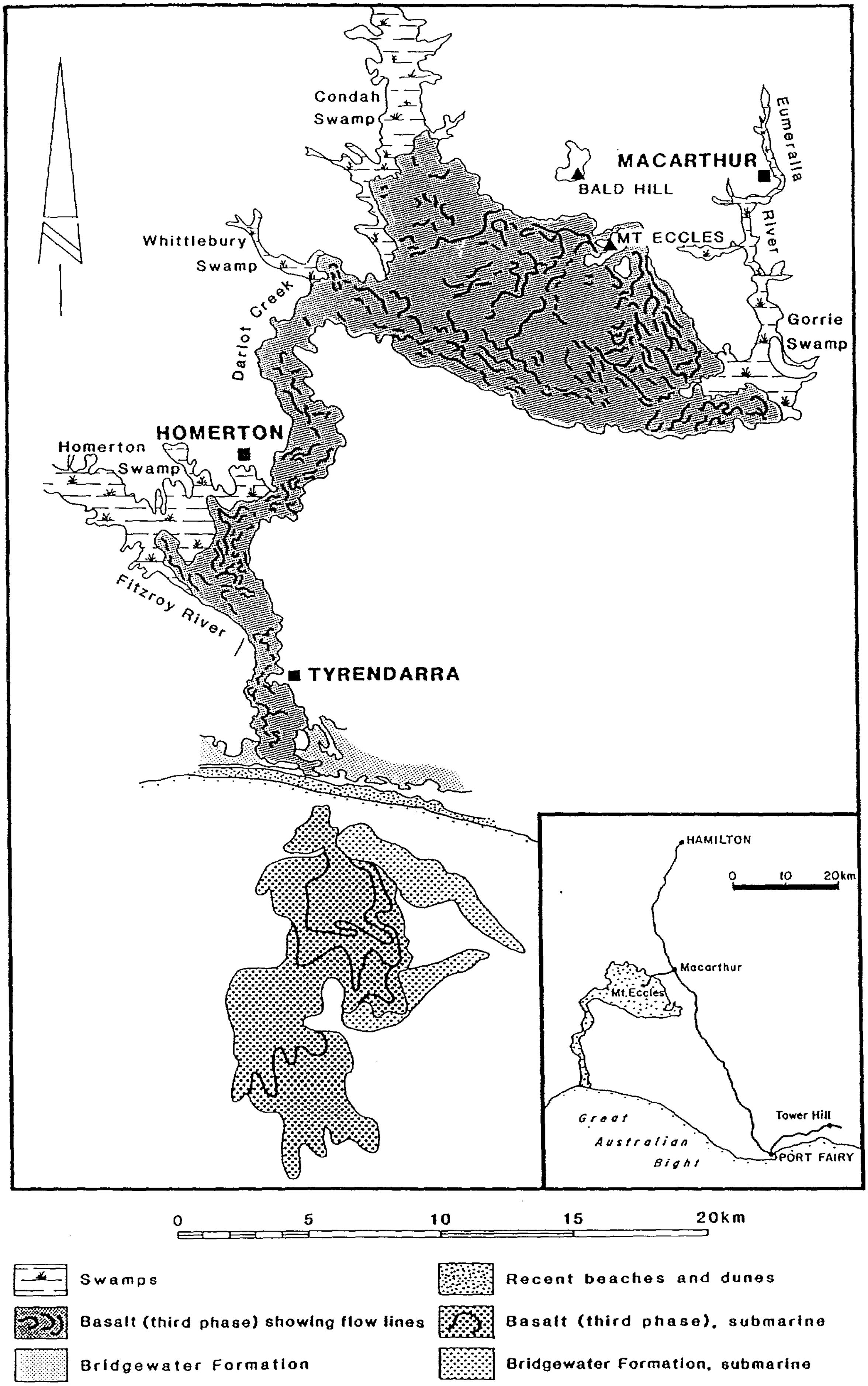

Figure 21.1 *Plan of Mt. Eccles and Tyrendarra Lava flow (after Boutakoff, 1963).*

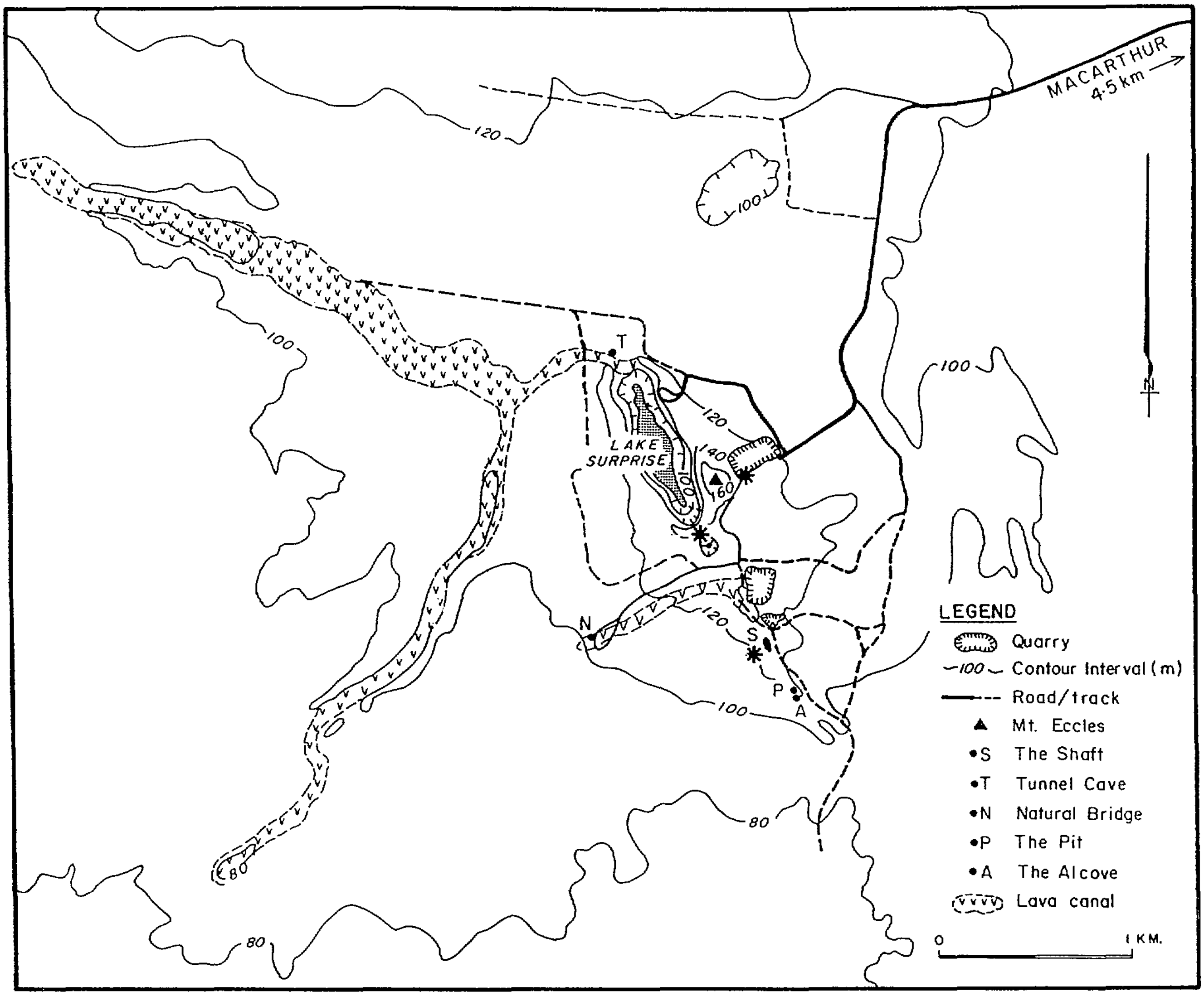

Figure 21.2 *Map of the Mt. Eccles volcanic complex (STOP 21).*

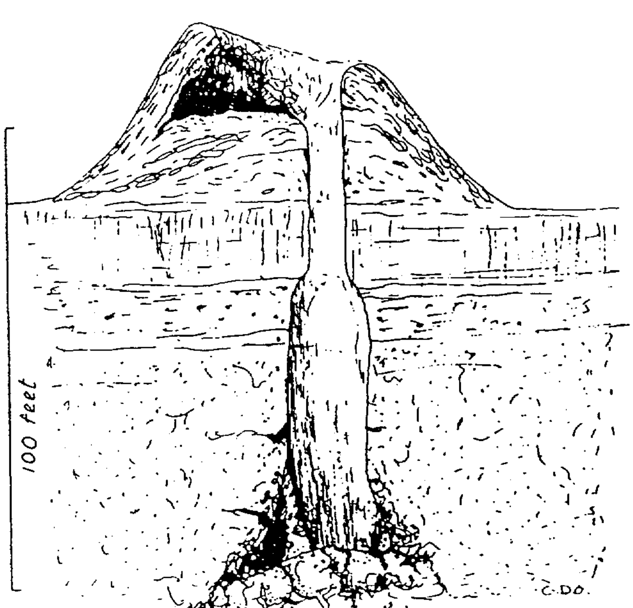

Figure 21.3 *The Shaft, vertical exaggeration 2.5 times (after Ollier and Joyce, 1967).*

phreatomagmatic periods of variable efficiency and intensity, occurring approximately a third of the way through the cone-building episode (Fig. 22.1, 5.1).

The initial phreatomagmatic activity produced cross- to diffusely- bedded deposits of semi- to highly vesicular lapilli and ash. This suggests that the dominant mode of fragmentation was by magmatic gases and the water/magma interaction was not efficient (the water/magma ratio would perhaps have been about 0.1; Fig. 5.1). The water source for the original phreatomagmatic activity was most likely one of the many aquifers in the area, allowing water to contact rising magma at the beginning of the eruption episode.

As time progressed the water/magma ratio decreased so that phreatomagmatic eruptions no longer took place. The cessation of phreatomagmatic explosions may have been due to either the sealing-off of the conduit/aquifer intersection by magma, the using up of all the available water, or the flooding of the system with magma due to an increased magma rise rate. Other periods of phreatomagmatic activity seem generally to have been much more intense in nature and produce massive ash beds and very low-angle highly truncated cross-bedded units. The water/magma mass ratio for these stages may have fluctuated from approximately 0.1 to 1.0 with perhaps an average of around 0.3. The renewal of phreatomagmatic activity may be the result of erosion of a conduit wall allowing the renewed access of water to the

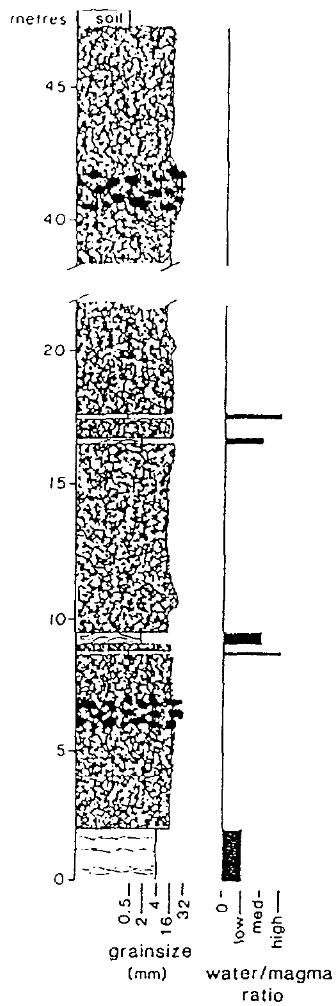

Figure 22.1 *Stratigraphic section through one of the scoria cones of the Mt. Eccles volcanic complex (STOP 22; see also Fig. 5.1).*

magma or replenishment of a dried-up aquifer. The phreatomagmatic deposits in the later stages display no evidence for unidirectional transport but show mantle bedding. It is therefore likely that these deposits are of air-fall origin, while others are cross-bedded and hence clearly of base-surge origin.

The eruptions subsequently reverted to strombolian activity producing scoria, bombs and spatter and forming the scoria cone which is now present (Figs. 21.2, 22.1and 5.1). The pyroclastics which make up the cones are massively bedded and show variable grain size, densities and vesicularities. The scoria deposits at several stratigraphic levels display varying degrees of welding produced during periods of rapid accumulation. Generally the ejecta display little in the way of gravity sorting and only at greater distances from vent do they begin to show graded bedding. At the top of the cone, the deposits include large (30 cm - 1 m) blocks of red oxidized dolerite, presumably derived from a thick lava flow or sill immediately beneath the exposed lava sequence.

Summary: Although the Eccles complex appears to have been a largely magmatic effusive and pyroclastic centre, involving a fissure centre, the Eccles scoria cone shows evidence of an early phreatomagmatic phase, changing to a dominant strombolian magmatic phase.

STOPS 23-25: TOWER HILL VOLCANIC CENTRE

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[2]Geological Survey of Victoria

The Tower Hill volcanic centre (Field Guide Frontispiece) is 320 km WSW of Melbourne and 12 km west of Warrnambool on the Princes Highway (Fig. 23.1). Drive to the parking area at the main entrance and observe the panorama. Tower Hill is made up of an arcuate shaped maar with average diameter of approximately 3 km, which contains within its crater lake a scoria cone complex (Fig. 9.2). This volcano has been previously described by Gill (1967) and a more detailed description is given by Edney (1984, 1987) and Orth (1988). Radiocarbon dating of plant material found intercalated with epiclastic material from the maar lake indicates a minimum age for the centre of 20,000 years B.P. (Edney et al., 1985).

The maar was formed by dominantly phreatomagmatic activity, a result of the interaction between rising basaltic magma and groundwater from a high flow rate aquifer approximately 600 m below the present

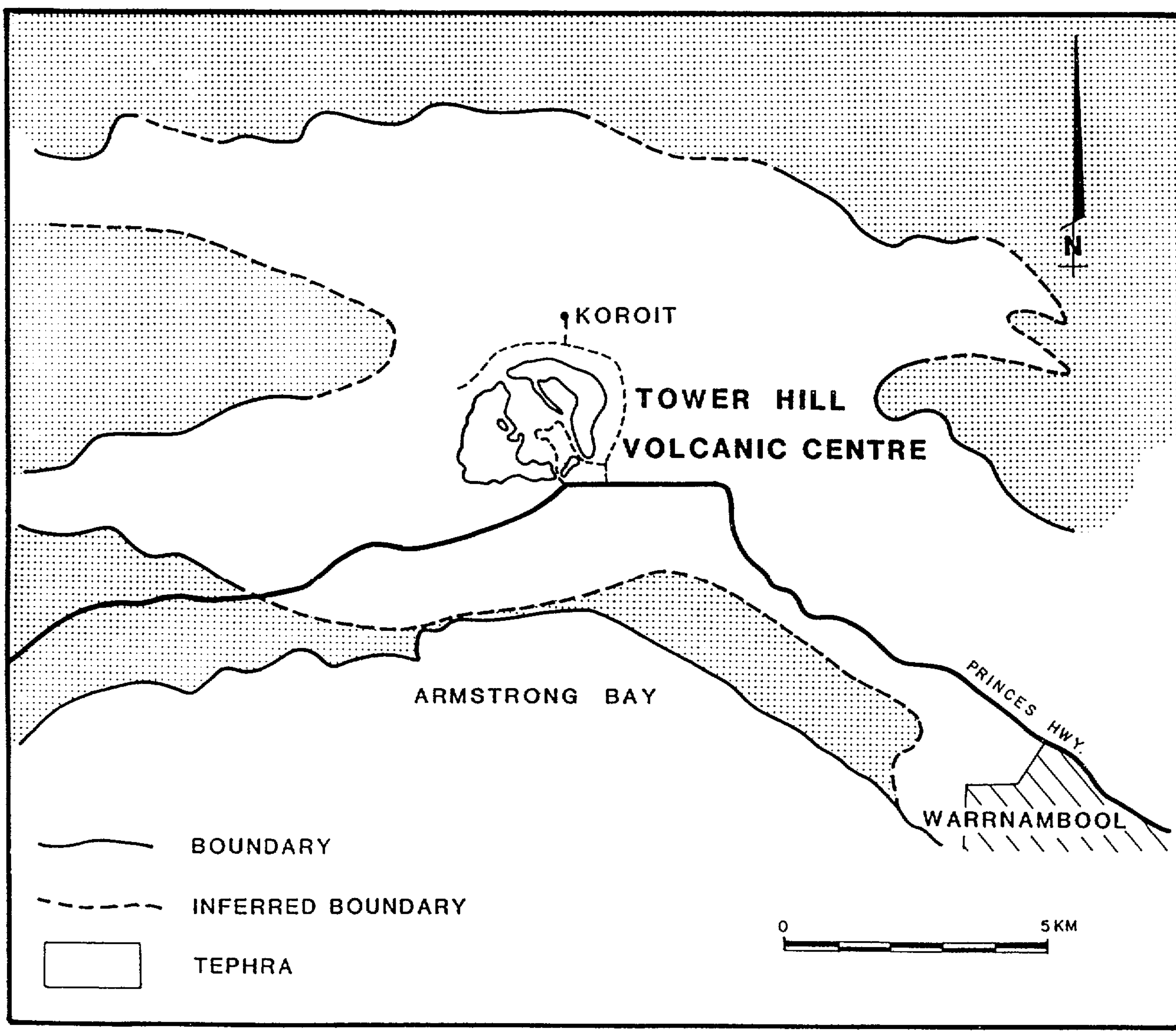

Figure 23.1 *Areal extent of tephra ejected from the Tower Hill volcanic centre (after Edney, 1984).*

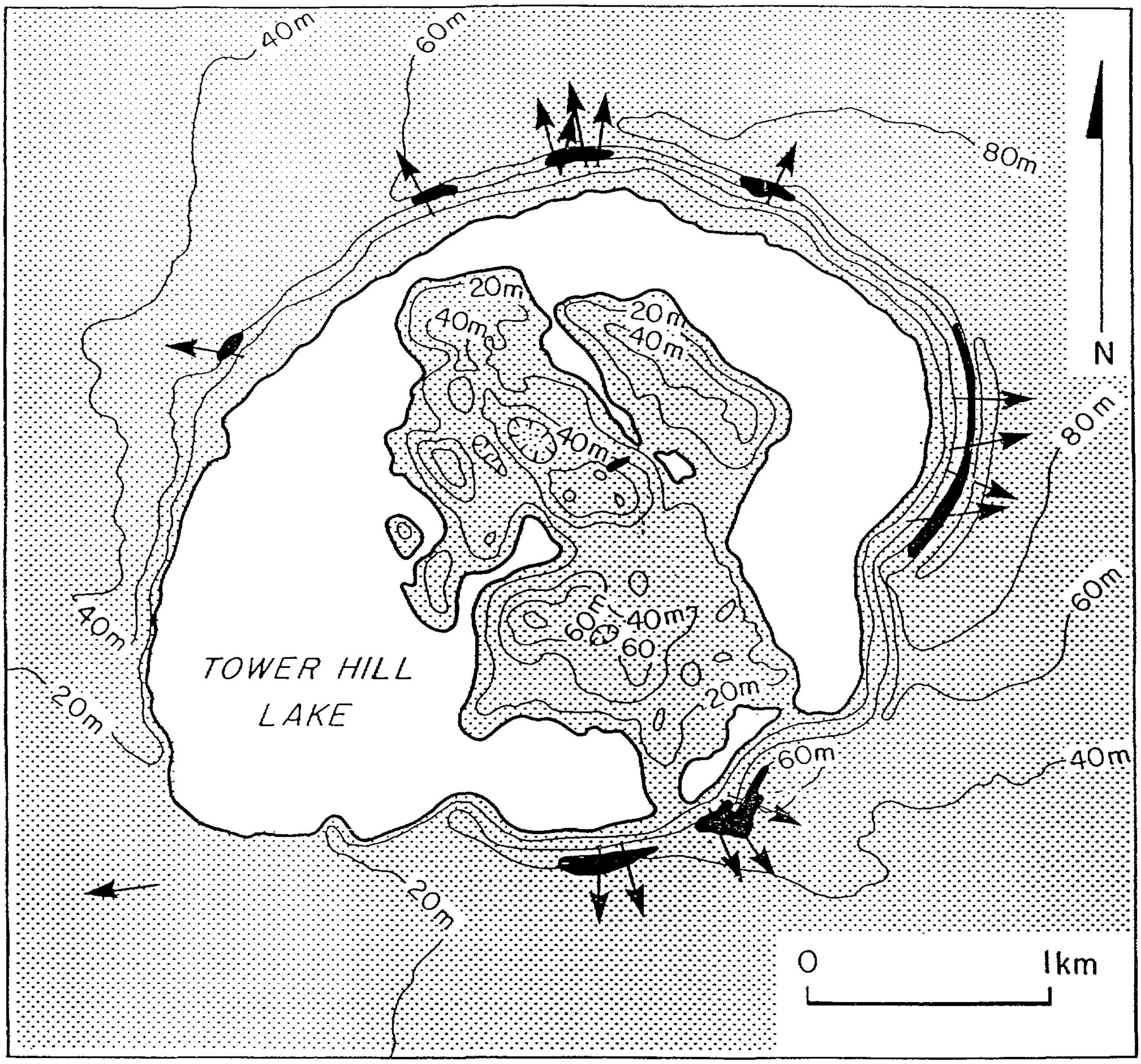

Figure 23.2 *Map of the Tower Hill volcanic centre (after Edney, 1984, 1987).*

lake level. The maar apron has an approximate areal extent of 150 km^2, with a volume in the order of 10 km^3 (Fig. 23.1). The maar rim and apron deposits in general dip gently away from the crater, exposures of steeply inward dipping beds ($\approx$ 40 °) are rare but do occur.

The water:magma mass ratio fluctuated considerably during the period of maar forming eruptions and resulted in the production of ejecta which show a wide range of characteristics, indicative of eruption by phreatomagmatic processes, all the way through to those resulting from purely magmatic activity. The phreatomagmatic eruptions gave rise to base surge, surge modified fall deposits and minor air-fall deposits of microvesicular lapilli, ash and variable country rock component.

The scoria cones within the maar lake today were almost entirely produced in the last stages of the eruptive activity of the centre, along two NNW-SSE aligned fissures (Fig. 23.2). The longest period and probably the most recent activity, occurred along the southwestern most fissure, which has approximately nine scoria cones sited along it, only two of which are well preserved. The deposits making up the scoria cones are the result of dominantly magmatic eruptions. Ranging from strombolian and hawaiian activity producing scoria, vesicular bombs, dense blocks, spatter and agglutinate to effusive activity producing four lava flows of limited areal extent. Interbedded with the strombolian and hawaiian deposits are phreatomagmatically derived explosive breccias and proximal base surge deposits.

The Tower Hill volcanic centre emphasises the complexity of controls on explosive basaltic volcanism. A complex interplay of factors such as: rate of magma rise, rise rate and formation depth of gas bubbles within the magma, depth of interaction between magma and water, water:magma mass ratio, recharge rate of aquifer, and rate accumulation of ejecta, all combined to determine the nature of the deposits (Edney, 1984, 1987).

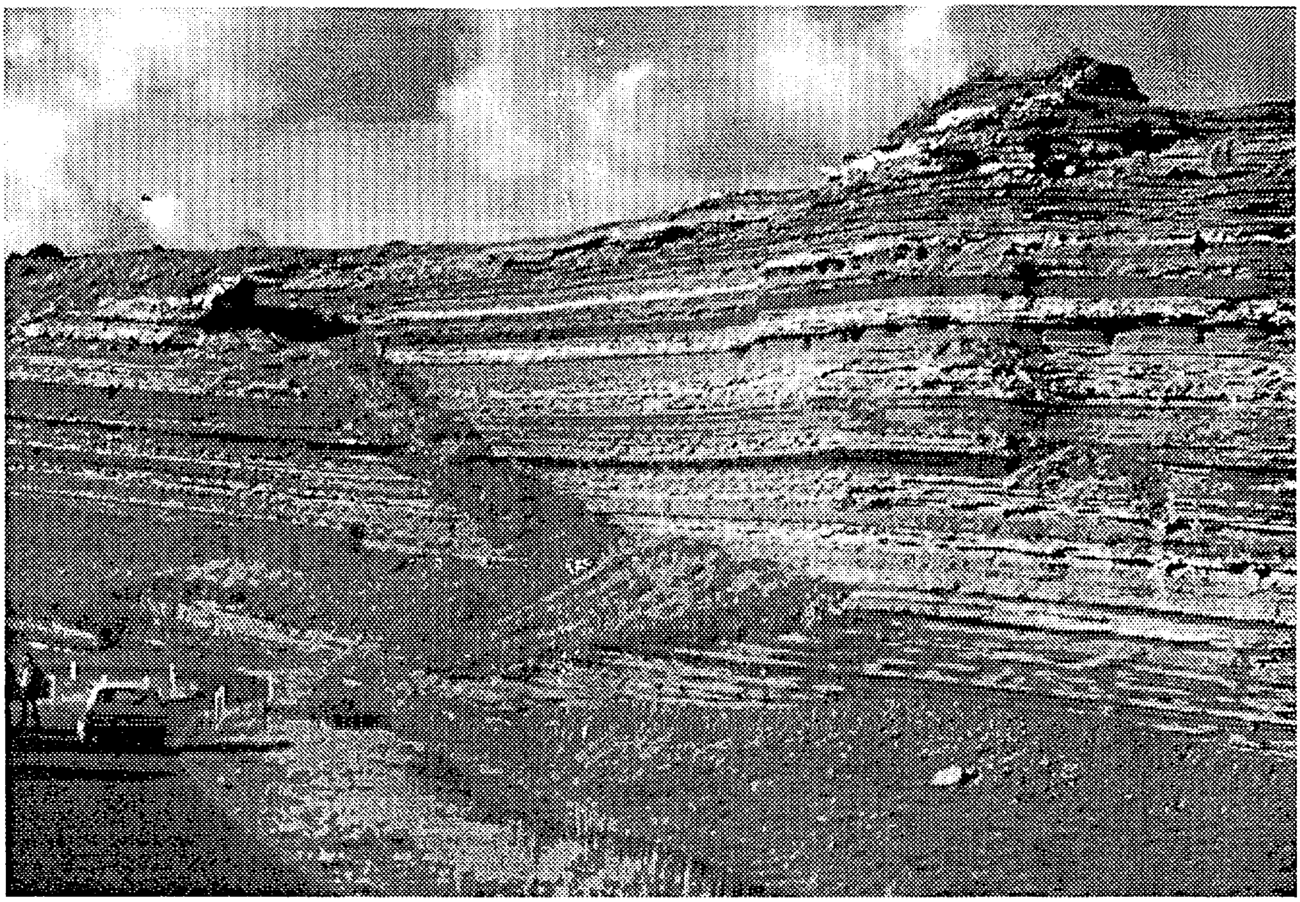

Figure 23.3 Bedded pyroclastic succession, CRB quarry, Tower Hill maar.

STOP 23 : C.R.B. - Quarry on the Tower Hill maar rim.

Drive into the Tower Hill Reserve to the foot of the quarry cutting on the right. Excellent exposures of the pyroclastic successions occur in quarries in the steep crater walls which are up to 90 m high (Figs. 23.2). The C.R.B. Quarry is one of many and is located on theentrance road to the Tower Hill Wildlife Reserve, 12.5 km west of Warrnambool (Figs. 23.1 and 23.2). Park near the foot of the cutting, and walk up the sloping walking track up the face.

The eruption sequence exposed in the C.R.B. Quarry is complex. Deposits of phreatomagmatic activity are interbedded with magmatically derived ejecta, and in excess of thirteen reversions to solely magmatic activity have taken place in producing the observed stratigraphy (Figs. 23.3, 23.4, 5.1). The magmatic deposits are characteristically strombolian in nature and consist of scoria fall deposits (up to 3 m thick) and thinner units of blocks and bombs (Fig. 23.3). The phreatomagmatic deposits are varied and display a variety of bedforms and grain sizes (Fig. 23.3). The major bedform types are massive to diffusely bedded, planar-bedded or -laminated and cross-bedded or -laminated. The depositional mechanism for the massive to diffusely bedded units is variable, some units are mantle bedded and are probably of air-fall origin while others display erosive basal contacts and are of base surge origin or surge modified fall origin. All other phreatomagmatic deposits are of base surge origin and display a variety of unidirectional sedimentary structures which indicate paleoflow directions radially away from

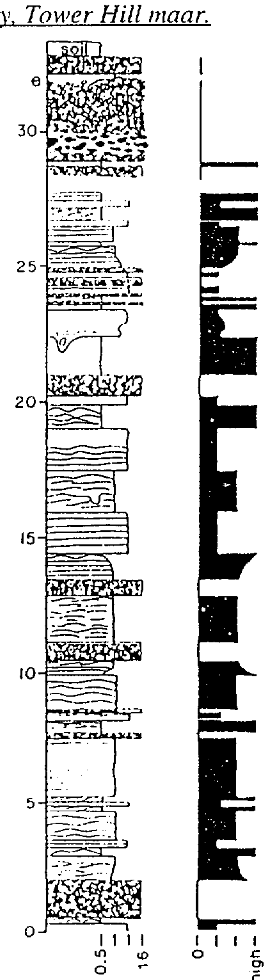

Figure 23.4 *Stratigraphic section of the Tower Hill maar rim deposits (C.R.B. Quarry, after Edney, 1987).*

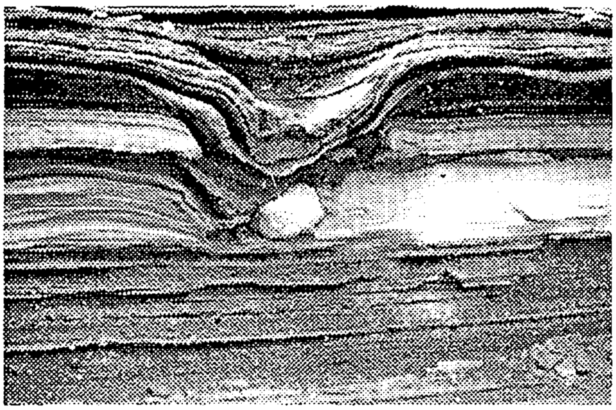

Figure 23.5 *Ballistic impact structure, CRB quarry, Tower Hill maar rim.*

the crater (Fig. 23.2). Spectacular ballistic impact sags are also visible (Fig. 23.5), and near the top of the succession, there are excellent exposures of accretionary lapilli rich beds. sf-Mdf plots of scoria and phreatomagmatic deposits are shown in Figure 23.6.

STOP 24: Tower Hill Tourist Centre.

Continue driving through the reserve to the tourist centre. The tourist centre has a comprehensive display of the natural history of the Tower Hill volcanic centre that is well worth spending time examining.

STOP 25: Borough Quarry in the Tower Hill scoria cone complex.

Exposures of the deposits making up the scoria cone complex are limited and can best be seen in the Borough Quarry which is situated on the outward flank of one scoria cone about 500 m north of the tourist information centre (Figs. 23.2 and 25.1).

The scoria cones are composed of variably sized basaltic ejecta (spatter, bombs, blocks, scoria and ash) and a minor component of limestone country rock. The stratigraphy of the cones is dominated by units of coarse scoria, blocks and bombs which have in places been faulted or show evidence for slumping after deposition. The country rock component in the eruption stratigraphy decreases downwards through the stratigraphy (Fig. 25.1) as a result of conduit wall rock erosion during the initial

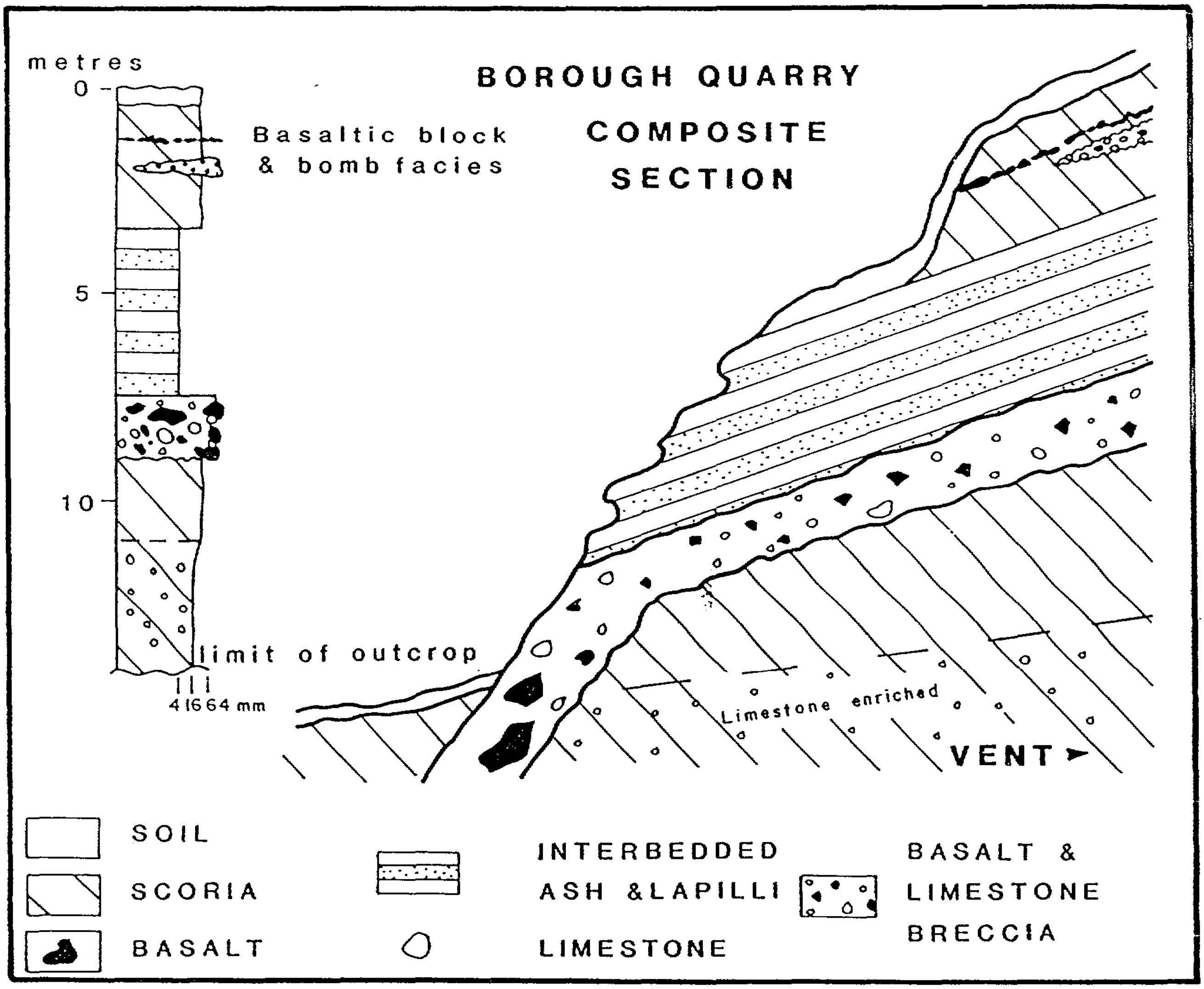

Figure 25.1 *Borough Quarry composite section and field sketch (after Edney, 1984)*

stages of activity. Phreatomagmatically derived deposits can also be found in the scoria cone complex and consist of a basalt limestone breccia unit which displays an erosional contact with underlying scoria deposits and has been interpreted as an explosion breccia/debris flow, and the other is an interbedded ash and lapilli unit which is dominantly planar-bedded and occasionally shows microscopic truncations of laminae (Fig. 25.1). The lapilli and ash of this unit display the same range of morphological characteristics as those of the maar rim base surge deposits and this unit has been interpreted as being a proximal base surge deposit. sf-Mdf plots of scoria and phreatomagmatic deposits are shown in Figure 25.2.

The presence of these phreatomagmatic deposits within the scoria cone complex indicates that while the maar was forming successive scoria cones were also being formed and producing the scoria units of the maar rim which were degraded by successive periods of more violent erosive phreatomagmatic activity.

Return to the cars and drive to the northern exit. An optional stop is the cutting on the right side on th approach to the exit gate. This cutting contains a broad channel like discordance. Is this due to surface processes, or to surge erosion?

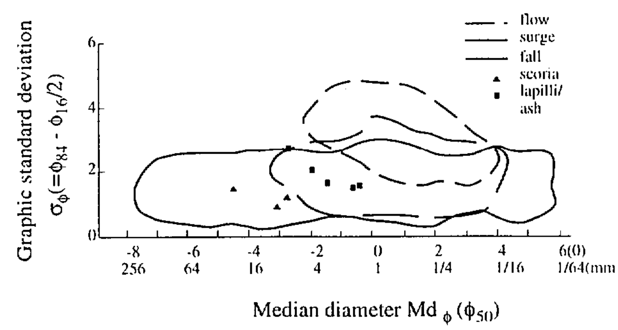

Figure 25.2 *sf-Mdf plots of scoria and phreatomagmatic lapilli-tuffs, Borough Quarry.*

<u>Summary</u>: Like the Red Rock maars, the Tower Hill maar experienced a complex alternation of magmatic and phreatomagmatic explosive activity in its early history. Fluctuations in magma rise rate, aquifer recharge rates, ephemeral development of an impermeable basaltic lining on the wals of the conduit, are the most likely causes. Later history was dominated by magmatic explosive activity, producing the central scoria cone complex, although phreatomagmatic phases still also occurred.

STOP 26: THE MOUNT NOORAT VOLCANIC COMPLEX

Introduction

Mt Noorat is located 6km north of the township of Terang. From Warrnambool follow the Princes Highway to Terang and on the eastern edge of the business centre turn left at the signpost to Noorat and Mortlake. At the township of Noorat, veer left following the road to Mortlake. About 0.5km north of Noorat, there are two large quarries on the right side of the road. Stop at the entrance to the two quarries (Fig. 26.1).

The Mt Noorat Volcanic Complex is a combined phreatomagmatic tuff ring (early) and scoria cone (late) volcanic complex of nepheline basanite composition. An early phreatomagmatic tuff ring building phase was succeeded by a later scoria cone forming phase, the products of which have almost buried the tuff ring succession. The only recent work on Mt Noorat, a preliminary study by Rawling (1990) suggested that the early tuff ring phase may have produced two partially overlapping tuff rings. The original tuff ring(s) appear to have had a north-south

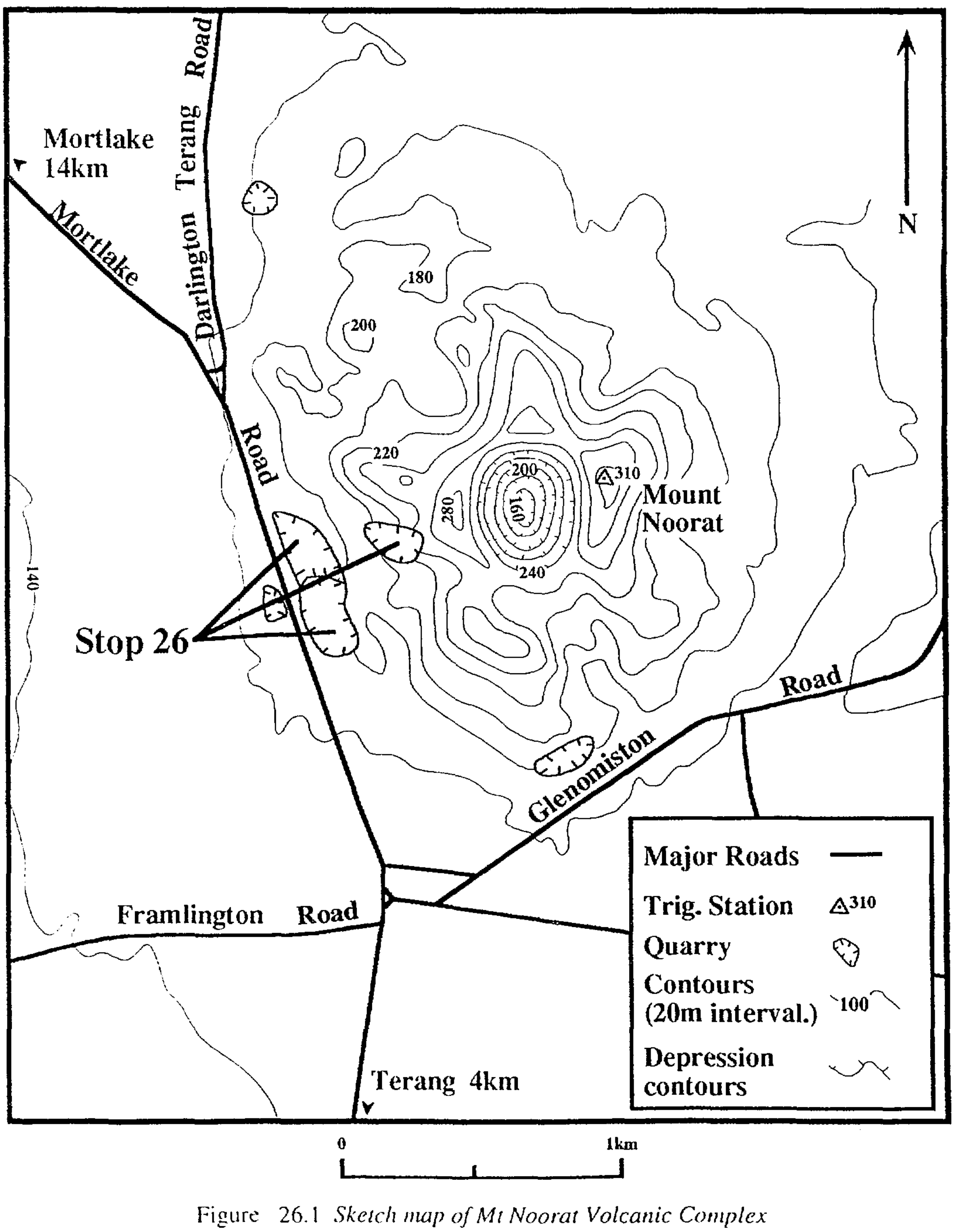

Figure 26.1 *Sketch map of Mt Noorat Volcanic Complex*

diameter of about 3km, and an east-west diameter of 2km. At least four scoria cone forming eruption points are known, and the highest, youngest scoria cone rises 170m above the surrounding plains. The Mt Noorat complex sits on top of old plains lavas of basaltic icelandite, but has also produced its own lavas, which are hummocky, like the stony rises lavas of Mt Porndon. The old plains lavas overlie Tertiary limestones, marls and sandstones of the Otway Basin.

Quarrying has produced excellent exposures of both the phreatomagmatic phase, and strombolian magmatic phase successions. Although the early phase was dominated by phreatomagmatic activity, as evidenced by cross-bedded base surge deposits and palagonitised and accretionary lapilli bearing tuffs and lapilli-tuffs, there were also magmatic explosive stages intermittently represented in the phreatomagmatic succession by thin black scoria beds. Similarly, in the later scoria cone forming strombolian magmatic explosive phase, there are intermittent, thin phreatomagmatic layes represented. A spectacular outcrop through the inner tuff ring margin at Outcrop 2, preserves the transition from the phreatomagmatic tuff ring forming hase to the scoria cone forming phase, and again indicates an alternation in eruption styles during this transition.

The Mt Noorat complex is also notable as a mantle xenolith locality. Xenoliths are dominated by Cr-diopside, olivine rich lherzolite.

STOP 26

Outcrop 1

Walk into the old southern quarry. The walls of this old quarry expose part of the tuff ring forming phreatomagmatic succession mantled by thick deposits of strombolian scoria fall deposits. Rawling (1990) subdivided the succession into 8 pyroclastic facies (Fig. 26.2).

Phreatomagmatic Block and Bomb Facies is wedge-shaped, thinning away from vent from 80cm to 15cm. Clasts range from 1m to ash size, with blocks and bombs constituting up to 40% of the facies. Sorting is poor, and deposits are massive to diffusely, discontinuously laminated. At the base ballistic impact structures and scours are common. Clasts include juvenile basanite fusiform bombs, blocks of scoria, and accessory icelandite, fossiliferous tertiary limestone, quartzite and marl blocks. Vesicularity of juvenile clasts ranges up to 60% (bombs, scoria), but lapilli and ash particles have vesicularities as low as 20%.

The combination of ballistic impact structures, basal scours and discontinous lamination suggests a combination of fall and surge transportation. The facies is thus a coarse, near-vent surge-modified fall deposit. The variation in vesicularity of juvenile clasts from $60\%^{+}$ for scoria to 20% for matrix ash and lapilli suggests a complex continuum of explosive fragmentation processes. The scoria suggests fragmentation driven largely by explosive expansion of magmatic volatiles. The poorly vesiculated clasts and the accessory lithics indicate phreatomagmatic mechanisms. The two can be accommodated in a single eruption model. If the magma conduit were viewed as a cylinder, magma around the margins could be chilled before significant vesiculation, and interact explosively with groundwater whereas magma in the centre of the conduit, buffered from direct contact with the groundwater by the outer magma selevedge, was able to rise to near ground surface level and undergo normal vesiculation, and magmatic explosions.

Interbedded Scoria and Ash Facies occurs in interbedded 1-10cm thick alternating planar layers with relatively sharp contacts. Ash layers are very well sorted, and scoria layers slightly less so. Ash fragments are blocky and moderately to poorly sorted, whereas scoria fragments are highly vesiculated, although some have vesiculated interiors, and microvesicular, breadcrusted surfaces. Nepheline and olivine crystals occur as well as Cr diopside xenoliths. Scoria layers are structureless, but ash layers are massive to diffusely planar laminated, often changing from massive to laminated away from vent.

Intepretation: The scoria layers are interpreted as magmatic strombolian-style airfall deposits, and the ash layers as phreatomagmatic base surge (and fall) deposits. Massive to laminated transitions are consistent with downcurrent changes noted in base surge deposits by Wohletz and Sheridan (1979). The alternation of magmatic and phreatomagmatic deposits suggests a rapid alternation of magma-water interaction and water-free magma eruption. Either the walls of the magma conduit were repeatedly lined by chilled magma, so preventing explosive magma-water interaction, or the aquifer supplying water had a recharge rate that was too low to allow continuous explosive magma-water interaction or surging of the magma through the conduit at high velocities limited water:magma interaction, whereas during low velocity passage of magma, interaction occurred.

Planar Laminated Ash Facies is the most common facies in the tuff ring succession, and occurs in beds 10-60cm thick, with sharp margins. Beds may thin away from vent. Grainsize varies from coarse to fine ash, sometimes a size grading is developed with basal lapilli size layers, and blocks and bombs are usually absent. Ash particles are blocky in shape, poorly vesiculated, and palagonitised.

Intepretation: Since the lamination is planar and continous, either an airfall or base surge origin is possible, although the latter is favoured.

Cross-laminated Ash Facies is the next most common facies, and shares many characteristics with the laminated ash facies in terms of bed thickness, grainsize and grain characteristics. The facies either makes up individual beds, or grades up from basal massive to laminated ash. Ballistic impact structure may be associated. Cross-stratification and climbing dune forms are characteristic. Dune forms climb at an angle of 4-6^{0}, and have a

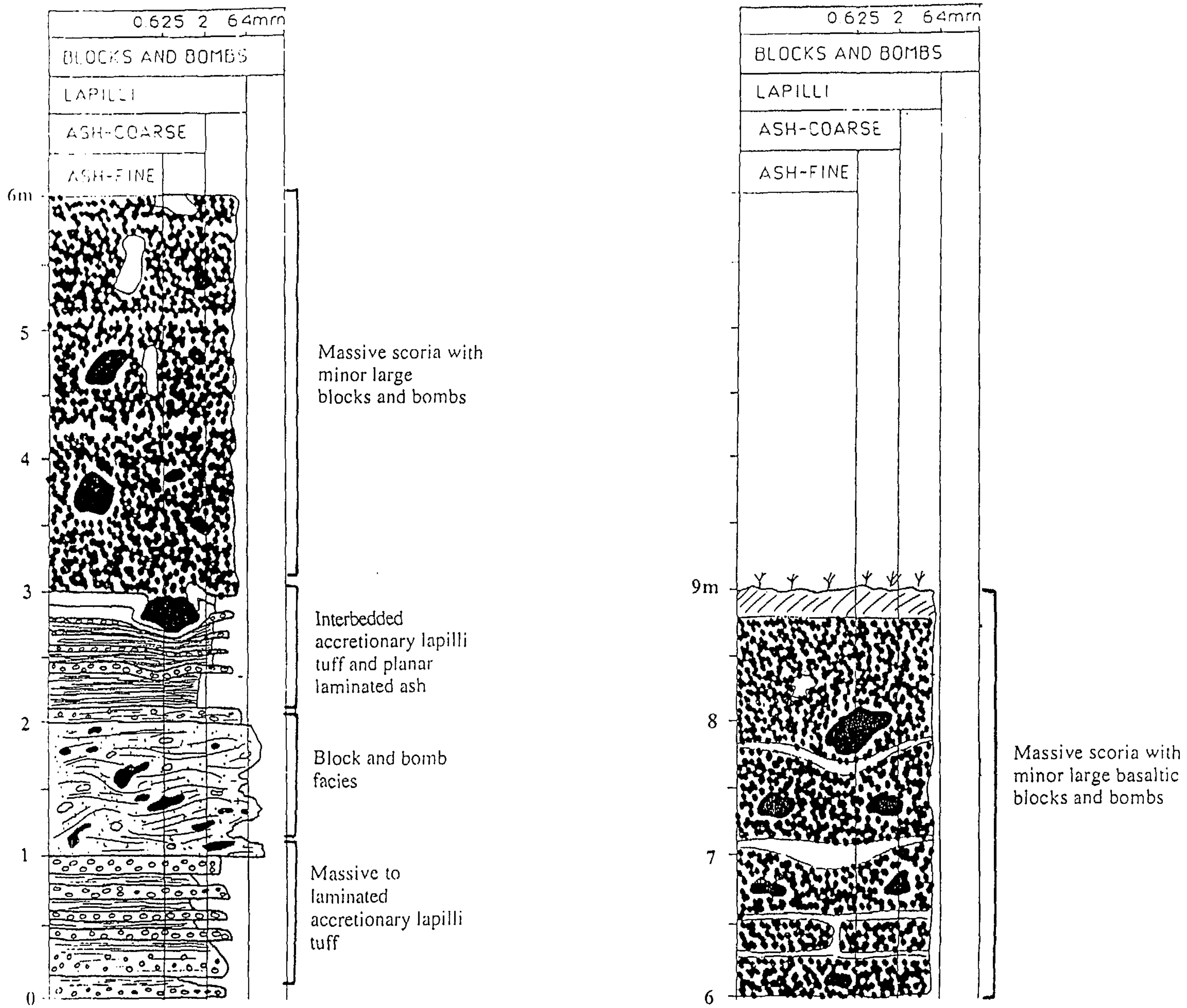

Figure 26.2 *Measured sections from "south quarry", Noorat-Mortlake Road, depicting the principal facies.*

wavelength of about 2.5m.

Intepretation: This facies is interpreted as the deposits of base surges. Dune forms and cross-bedding indicate flow away from vent.

Massive to Planar Laminated Accretionary Lapilli Bearing Lapilli-Tuff appears to dominate the upper part of the phreatomagmatic succession. Beds are 10-60cm thick, facies intervals are up to 4m thick, and internally vary from massive to diffusely laminated to well laminated. Bedding contacts are sharp. Accretionary lapilli are up to 1cm in diameter, and beds of the facies commonly have basaltic olivine/lherzolite, chert and limestone lapilli-size ballistic clasts included. Sorting is poor, and normal grading from lapilli at the base to ash at the tops of beds is common. In addition to massive to laminated structures, the facies also fills in basal scours and channels.

Interpretation: The facies is also interpreted as the result of phreatomagmatic explosions and base surge deposits. Ballistics and stacked graded beds, indicate repeated explosive bursts (cf. surtseyan eruptions/explosions. The accretionary lapilli indicate "wet" eruption plumes and/or wet base surges.

Massive Ash Facies is a rare facies, especially by itself. Beds are 5-30cm thick, have sharp boundaries and show relatively little thinning over the extent of the outcrop. Sorting is excellent, the ash is usually coarse, but sometimes normal and reverse size grading occur. Occasionally massive ash passes up into cross-laminated ash. Particles are blocky and poorly vesiculated.

Intepretation: The high degree of sorting is consistent with a fall origin, perhaps from the tail of base surges.

Massive Scoria Facies forms the scoria cones and covers the tuff ring. Dips therefore vary from 25^{o}-30^{o} angle of repose to nearly horizontal. The scoria is moderately well sorted, and plots within the airfall field on the sf-Mdf plot of Walker (1971; Figure 26.3). Poor sorting occurs in the intercalated Scoriacenous Proximal Block and Bomb Facies (see below). The vesicularity of the

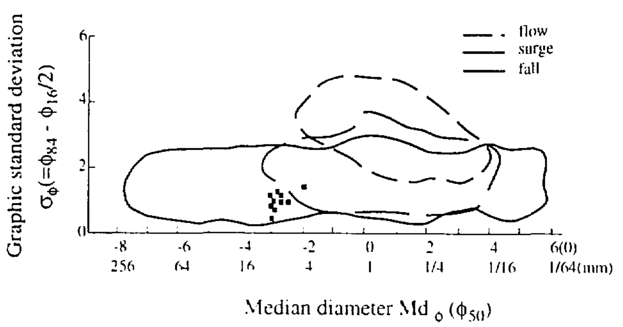

Figure 26.3 *sf-Mdf plots of strombolian scoria deposits, south quarry and north quarry, Noorat-Mortlake Road. Fall and flow fields from Walker (1971).*

scoria is typically high (60-85%) for strombolian fall deposits (cf. Houghton and Wilson, 1989). Olivine xenocrysts occur in scoria clasts, and bombs often have cores of mantle xenoliths. Beds vary from many metres thick to cms thick in the tuff ring sequence. Although the facies is generally massive, diffuse layering, defined by grainsize variations in the scoria, and sometimes thin phreatomagmatic horizons occur.

Interpretation: This facies is clearly the result of strombolian style magmatic pyroclastic eruption involving explosive expansion of exsolving magmatic volatiles and fallout from a maintained eruption column. Thin layers interbedded in the tuff ring succession indicate rapid alternations between magmatic and phreatomagmatic eruptions. The younger cone forming scoria succession indicates maintained magmatic eruptions, indicating that access by groundwater to the magma conduit was blocked for the latter part of the eruptive life of the Noorat volcanic centre. This is most likely to have occurred through the development of a thick impermeable basalt collar around the margins of the conduit. Grainsize variations in the scoria may indicate changing magma discharge rates or changing wind directions, causing the axis of dispersal to shift marginally. Minor intercollated phreatomagmatic layers indicate brief seepage of groundwater into the magma conduit.

Scoriaceous Proximal Block and Bomb Facies is a coarse grained variant of the Massive Scoria Facies. In addition to a matrix of scoria, it is marked by a wide array of juvenile, fluidally shaped bombs, including spindle-shape, "elephant trunk", and other irregular shapes. Ropey textures, breadcrusted surfaces and lherzolite xenoliths in the cores of bombs are common features. This facies represents a more energetic phase of Strombolian activity.

Agglutinated Spatter Facies, Clastogenic Lava facies and Lava Facies, although not represented in the quarries, outcrops around the rim of the highest scoria cone, in a small quarry to the southeast, and in the hummocky lava flow areas to the north and south. They appear to represent hawaiian-style phases of the eruption history of the complex, leading to the formation of lavas. The lavas to the north and south occupy 45 km^2. It is not clear if these were sourced from the cone vents or from flank fissures.

Outcrop 2

Walk into the northern quarry and along the track leading to the ramp on the eastern side of the quarry.

The southern wall of the quarry, exposes a significant section through the tuff ring succession (Fig. 26.4) which is mantled by thick deposits of cone building phase scoria, at its eastern end. This cutting contains many of the facies described for the southern quarry, and these can be examined again.

The significant feature of this cutting is the nature of the eastern margin of the tuff ring and the relationship

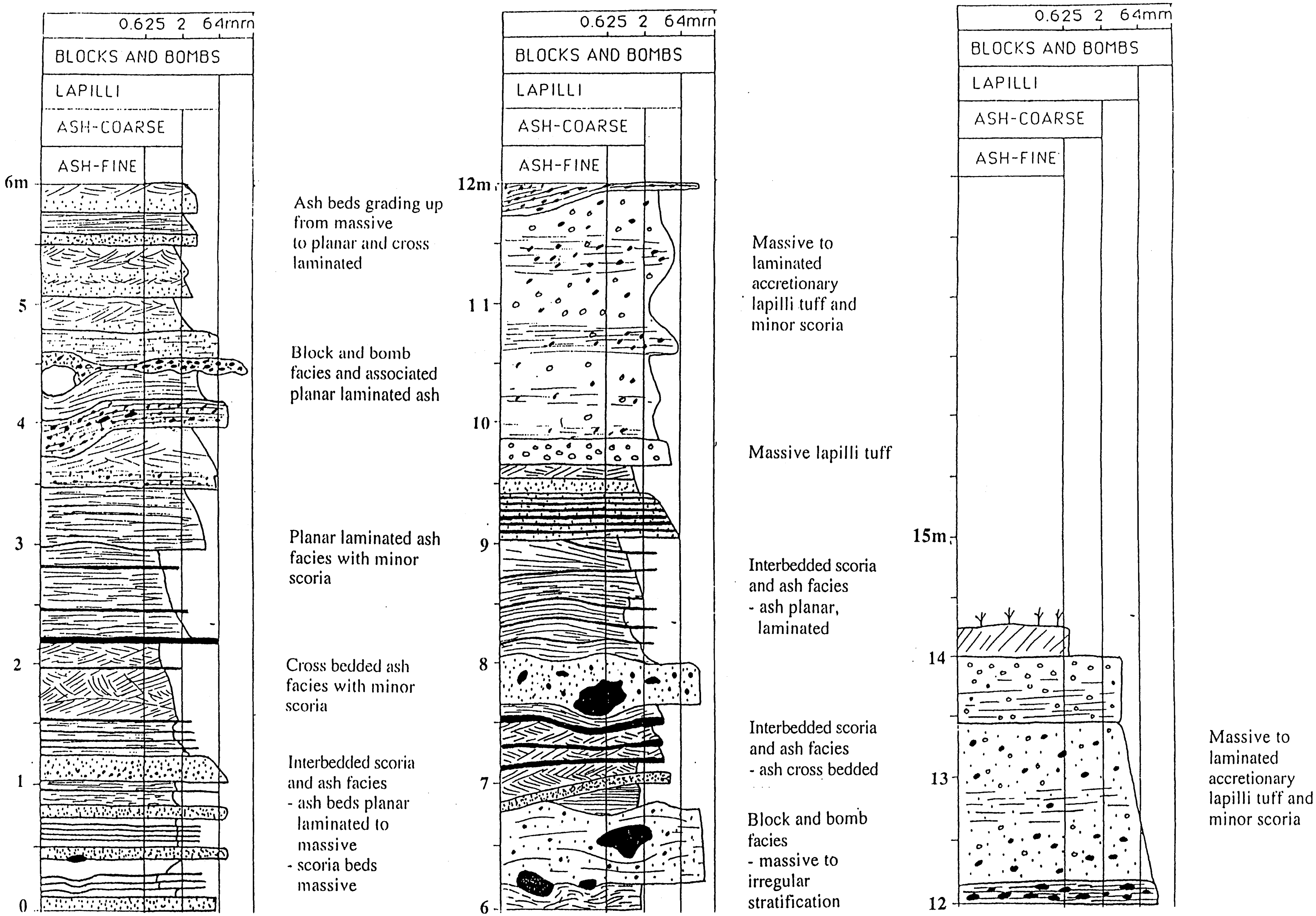

Figure 26.4 *Measured section, south wall, north quarry, Noorat-Nortlake Road, showing lower phreatomagmatic tuff ring succession.*

mainly by pyroclastic (base) surge deposition, with some contribution from air-fall processes. The majority of the tuff ring succession appears to be truncated at the eastern margin, and the truncation surface is then mantled by steeply dipping phreatomagmatic layers and thick scoria deposits.

The question is when did the truncation occur, and what was the cause of it? A simple solution would be that the crater-side margin of the tuff ring collapsed into the crater as a slide of debris during a late stage phreatomagmatic explosive phase. Contemporaneous sliding of debris almost certainly occurred, but looking closely at individual phreatomagmatic layers from the steeply dipping mantling package, it is clear that many of them slope up, and then bend into the stratified tuff ring succession from the base of the tuff ring succession up. The steep inner or crater margin of the tuff ring has clearly been steep and actively maintained throughout the history of the tuff ring. Nonetheless, some of these phreatomagmatic layers that "wrap" into the tuff ring succession, truncate lower layers. It is suggested that such truncations are the result of the erosional effects of base surges climbing up the steep inner tuff ring wall out of the crater. Initial explosive thrust and momentum would give the surges erosive capacity as they "climbed" upslope out of the crater. Once over the rim of the tuff ring, and onto the low outer slopes of the tuff ring, the surges would have decelerated and been in a depositional mode. The phreatomagmatic layers mantling the steep inner wall, would represent deposition from the low velocity tails of base surges.

The transition from phreatomagmatic tuff ring succession to strombolian scoria deposits was not instantaneous, as shown by interbedding of the two at the top of the cutting.

Finally, bombs in the scoria exposed in the upper part of the ramp road frequently contain mantle xenoliths. It is clear from the facies exposed in the cutting that the tuff ring was built up with the mantling pyroclastic deposits.

Outcrop 3

Continue up the ramp road which leads upslope through a locked gate and into an old higher scoria quarry. This quarry exposes the cone forming Massive Scoria Facies, and the Scoriaceous Proximal Block and Bomb Facies. Bombs of all shapes and sizes are to be found, as well as a variety of xenolith types. The succession represents very energetic, maintained strombolian eruptive activity, that through continuous or in several spaced phases of eruptive activity, could have produced the scoria cone complex in a matter of several days, weeks or at most several months (cf. 1973 eruption on Heimay, Iceland).

Summary

1. The Mt Noorat Volcanic Complex again illustrates the delicate balance between magmatic and phreatomagmatic explosive activity in continental maar-tuff ring complexes. Rapid and apparently random alternations in style occur.

2. Likely controls on change from one to the other style are the ability of the magma conduit to develop and maintain an impermeable basalt lining on the margins of the conduit, the recharge rate of the aquifer that is the source of the phreatomagmatic explosive interaction with the rising basalt, and fluctuations in the rise velocity of the magma through the conduit. Clearly during the final cone building stage access by the aquifer to the magma conduit had been blocked off.

3. The south wall exposure in the north pit suggests that the steep crater margin of the tuff ring was not necessarily due to gravitational sliding into the crater, but in large part was maintained as a steep slope by the erosive effects of base surges in an erosive mode, as they flowed upslope out of the crater (cf. Stop 27, Lake Purrumbete tuff ring).

STOP 27: LAKE PURRUMBETE

By W.J. Edney and R. Cas

Department of Earth Sciences, Monash University

Return to Terang, turn left (east) onto the Princes Highway, continue to Camperdown. Drive through Camperdown, and take a side road to the south about 5 km from Camperdown to Lake Purrumbete. On the eastern side take an unsealed track without a gate to the right up the outer maar slope into the old quarry (Fig. 27.1).

Lake Purrumbete, 10 km SE of Camperdown, is a simple arcuate shaped maar (2.5-3.0 km in diameter), with the crater now occupied by a 45 m deep lake (Figs. 27.1 and 27.2). The volcano has been previously described by Bull (1982) and Edney (1987). The crater walls are entirely constructed of well bedded and stratified, generally fine grained and indurated buff-brown phreatomagmatic deposits which in part overlie the older Stony rises basalt flow (Fig. 27.2). Maar rim heights range from 5-40 m, with the thickest deposit in the north-eastern sector of the crater (Fig. 27.1), which may be related to the prevailing wind direction, but no conclusive evidence of aeolian transport has been found. There is one major unconformity which was formed by penecontemporaneous faulting. No soils, only minor erosion is found at the unconformity and this may only represent an insignificantly small time break in the eruption, since inward dipping base surges overlying parts of the fault plaster up against and erode parts. Other evidence of penecontemporaneous deformation is found between deposition of different beds along the tuff scarp which surrounds parts of the maar lake.

The deposits of the Lake Purrumbete maar rim display characteristics that indicate only minimal fluctuations in the water/magma ratio during the entire period of eruption of the centre. Deposits from magmatic eruptions are absent. Individual eruptive units display little evidence for variation in water/magma ratios unlike those at Tower Hill (Stop 23). The only variability observed is that between discrete eruptive units, where there are differences in the efficiency of degree of fragmantation.

<u>STOP 27 : Lake Purrumbete Maar.</u>

<u>Locality 1:</u> The only quarry on the edge of Lake Purrumbete exposes approximately 26 m of the maar stratigraphy (Fig. 27.3, 5.1). The deposits of the Lake Purrumbete maar dip at 3-4° away from the vent.

The maar rim deposits of Lake Purrumbete display the most spectacular surge depositional structures found in the Newer Volcanics Province. The bedforms range from planar laminations and low angle truncations to climbing dunes and minor poorly developed antidunes and are all of base surge origin (Figs 27.3, 27.4). Massive to diffusely bedded deposits are rare and often show transitional or gradational contacts with cross-bedded units. Adjacent cross-beds in cross bed sets show significant grain size variations. Is each cross-bed the product of successive surges or pulsing in a single surge?

Some of the massive ashier units which mantle dune forms have been interpreted as co-surge ashes resulting from the elutriation of fines from a moving base surge and subsequent fallout (Walker, 1983;). Some diffusely bedded lapilli units also display mantle bedding and may be phreatomagmatic air-falls or surge modified fall deposits (Fig. 27.3). The coarse nature of the lapilli tuffs and relative scarcity of fine ashes, indicate relatively high water: magma mass ratios. sf-Mdf plots fall in the surge and fall fields of Walker (1971, 1983; Fig. 27.5).

At the western end of the main quarry wall just above road level, very steeply dipping (60-70°) lapilli tuffs can be found. The contact is sharp and discordant. A clue to its origin can be found at Locality 2.

<u>Locality 2</u>: At road level at the western end of the quarry, follow the track to the maar rim and then down to water level. Turn southwest to the cutting. Lower bedded lapilli tuffs are truncated by an inward dipping discordant surface (Fig. 27.6) that at its upper end also shows channelling. The tuffs and lapilli tuffs overlying the discordance thin up slope. Although apparently planar bedded, close inspection reveals subtle lensing and low angle truncations. In addition, syn-depositional faults are also common, some of them reverse. The whole succession is interpreted as largely surge in origin, planar bedded surge facies (Wohletz and Sheridan 1979) being most common. The question is whether or not the discordant surface formed through the erosive effects of surges or through sliding of part of the maar rim sequence back into the crater, probably as a result of explosive shock. The reverse faults are interpreted as resulting from explosion induced reverse faulting of the semi-consolidated maar rim sequence.

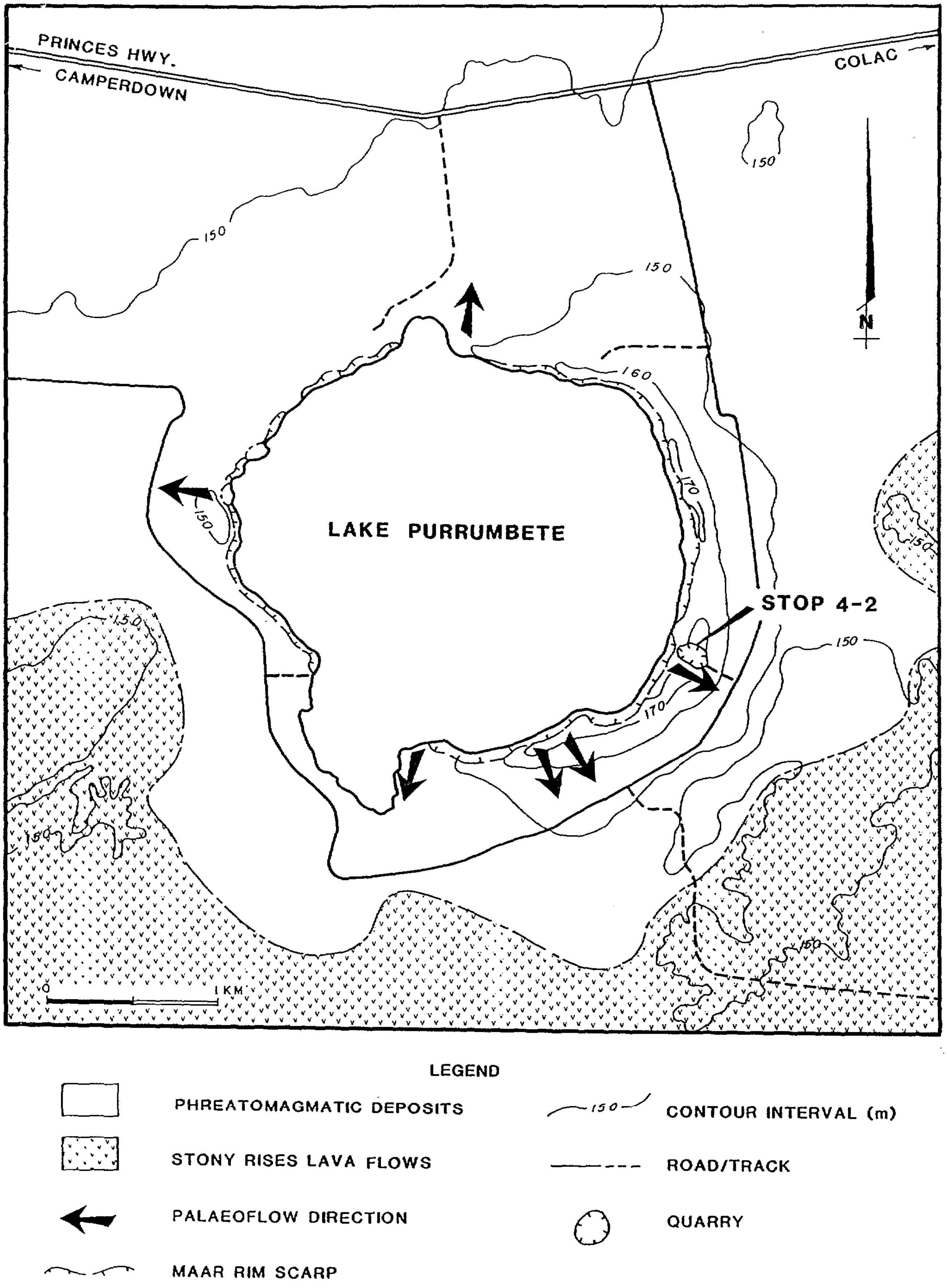

Figure 27.1 *Location map for some of the volcanic landforms in the Camperdown area.*

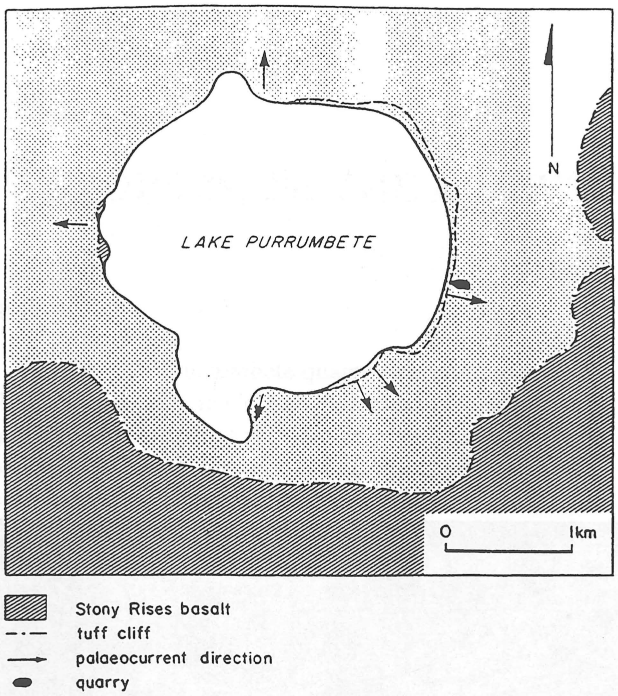

Figure 27.2 *Map of the Lake Purrumbete maar.*

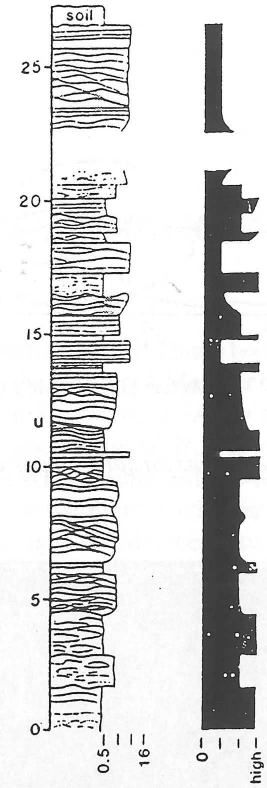

Figure 27.3 *Stratigraphic section through the phreatomagmatic deposits of the Lake Purrumbete maar.*

Figure 27.4 *Dune bedded base surge deposits, southern quarry wall.*

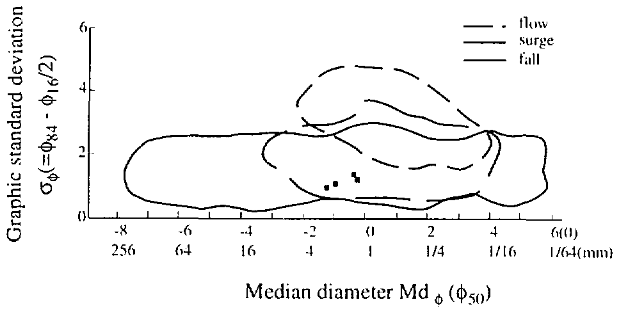

Figure 27.5 *sf-Mdf plots for surge deposits, Purrumbete maar.*

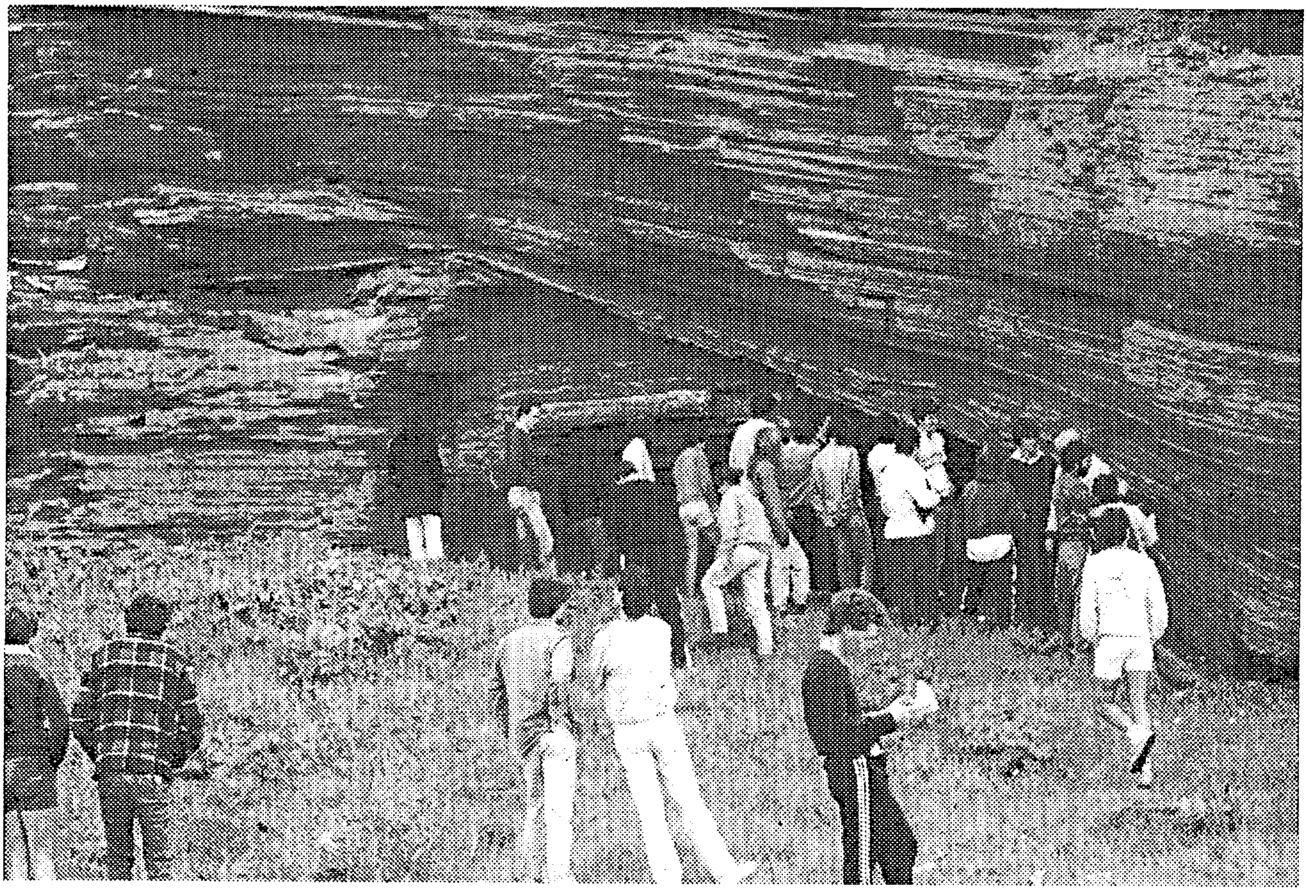

Figure 27.6 *Inward dipping beds mantling a craterward dipping discordant surface, lake level, southwest of quarry.*

STOPS 28, 29: THE AIREY'S INLET VOLCANIC COMPLEX

Introduction

From the Purrumbete quarry return to the Princes Highway and drive to Colac. 13km east of Colac take the turn south to Birregurra and Dean's Marsh to Lorne. Stay overnight in Lorne. Driving from Lorne, cross the bridge over Painkalluc Creek on the Prince Highway at Airey's Inlet, and then turn right into Painkalluc Road. Follow this dirt road 300-400m to a parking area on the right side of the road. Then walk down to the shore of the estuary to the ocean beach, following the beach north eastwards until basalt outcrops are encountered on the rock platform and coastal cliffs.

The Airey's Inlet Volcanic Complex is exposed in coastal cliff and platform exposures extending from Airey's Inlet to Urquharts Bluff (Figs 28.1-4) in the Torquay Sub-basin/Embayment of the Otway Basin. The rock succession is part of the Angahook Member which has traditionally been designated as a member of the Eocene-Oligocene Demon's Bluff Formation. Basalt from the Angahook Member at Airey's Inlet has been dated at 26.5-27 Ma (Late Oligocene), and according to Abele and Page (1974), this is younger than expected. This is because the exposed contact between the Angahook Member of the Oligocene-Miocene Jan Juc Formation at Airey's Inlet has been interpreted as an unconformity. If, as argued here, that the dated basalts are syn-volcanic and syn-depositional shallow intrusives into the Point Addis Limestone Member, then clearly the Angahook Member between Airey's Inlet and Urquharts Bluff at least, is the same age, or slightly younger than the basal part of the Point Addis Limestone Member, and should be considered to be a member of the Jan Juc Formation, which is the lowest formation in the Torquay Group.

The volcanic succession includes intrusive and extrusive basalts, hyaloclastites, pyroclastic lapilli-tuffs, tuffs and locally agglomerate, as well as mass-flow resedimented and reworked volcanic sediments. Singleton and Joyce (1969), in a one line statement, recognised that part of the succession represents the remains of a tuff cone. Work by Bourton (1988) and Sato and Cas (in prep.) indicate that the preserved succession represents the remains of the successions of several discrete, overlapping eruption points. At the southeastern end of the volcanic

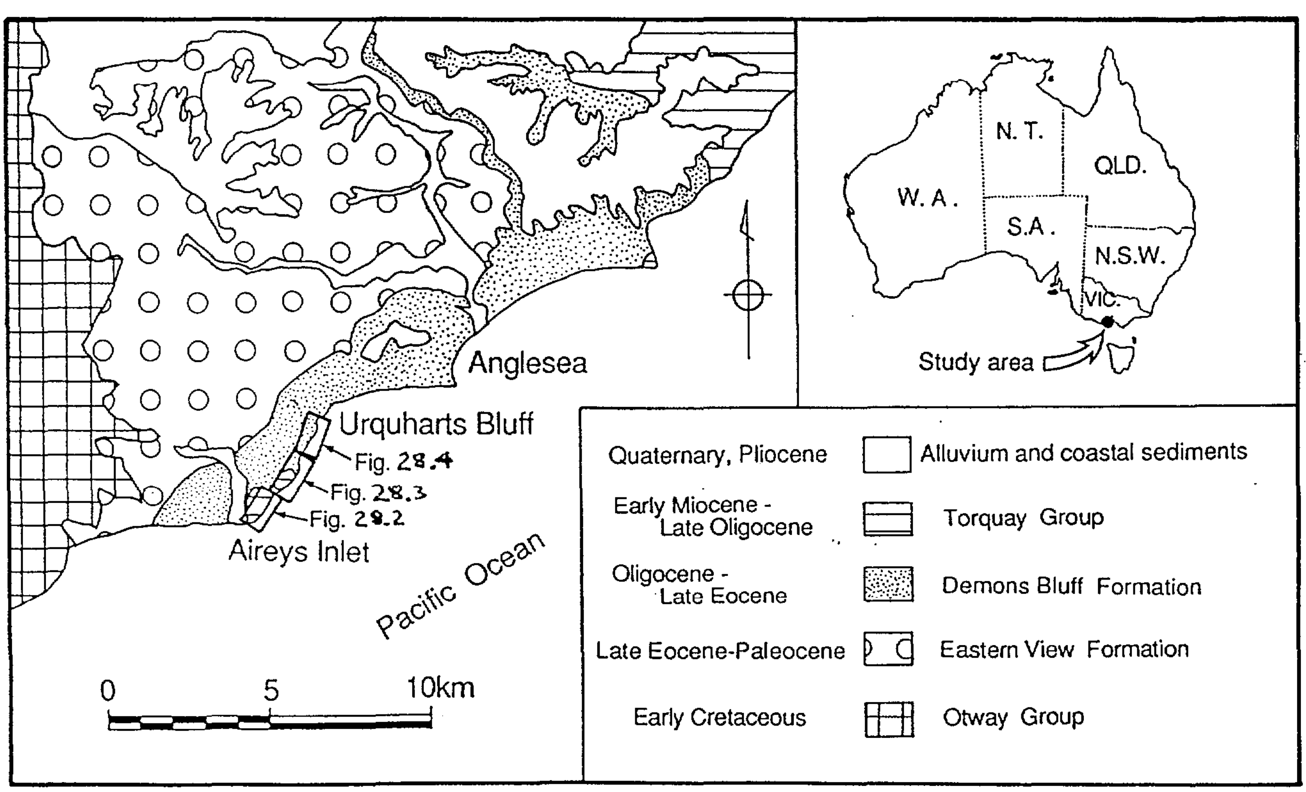

Figure 28. 1 *Geological setting of the Angahook Member*

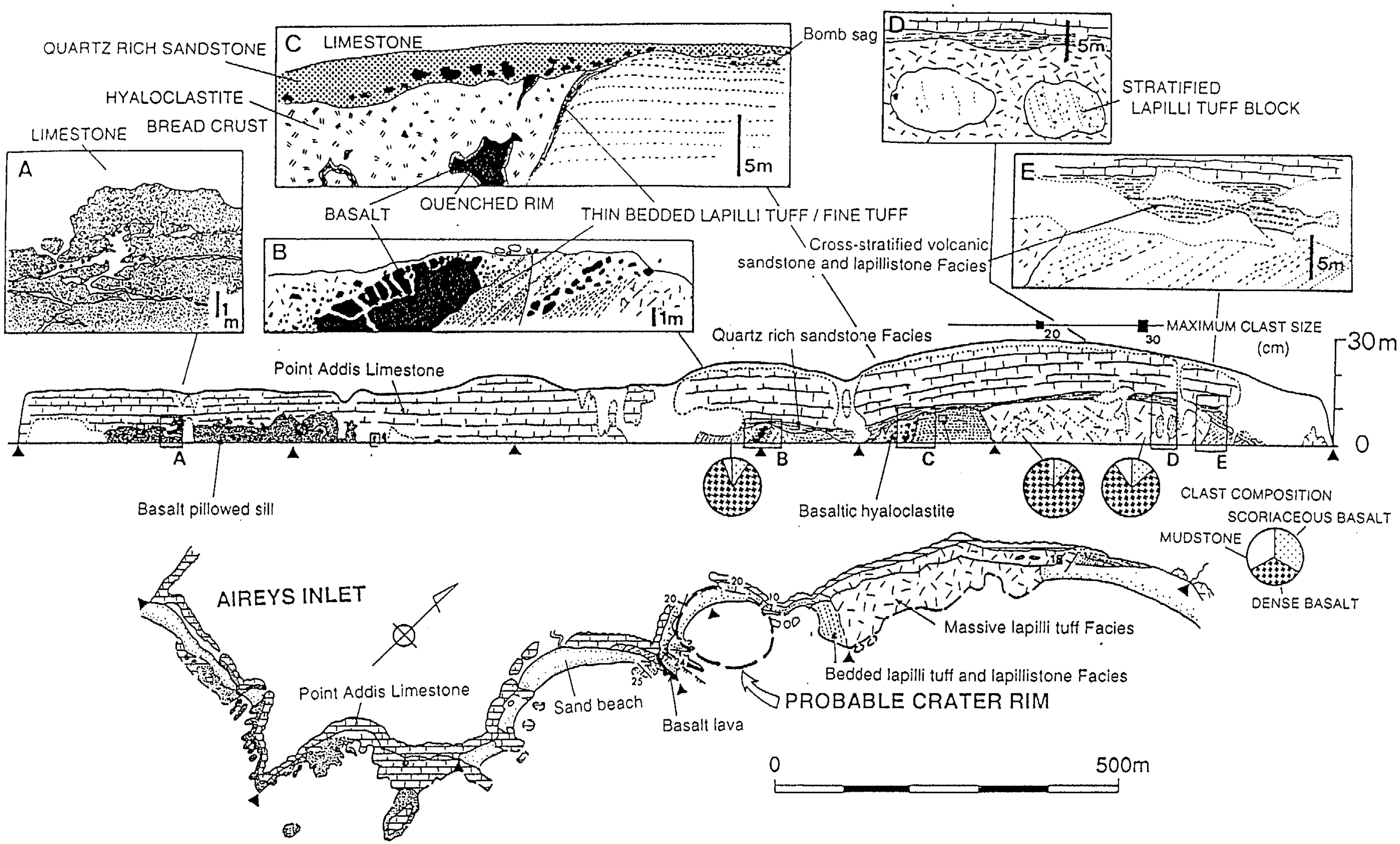

Figure 28.2 *Map and cross section, Angahook Member, Airey's Inlet south*

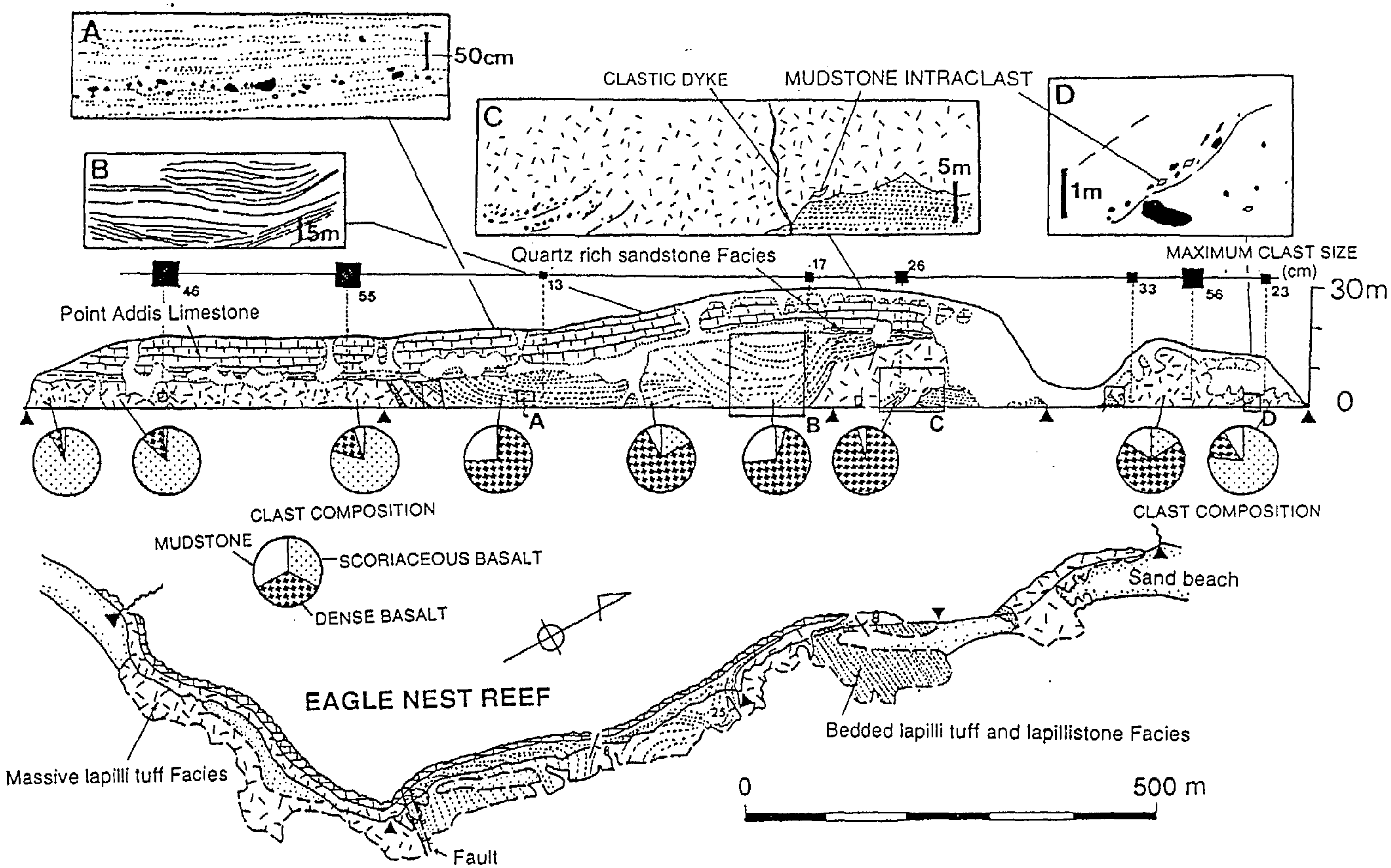

Figure 28.3 *Map and cross section, Angahook Member, Airey's Inlet north*

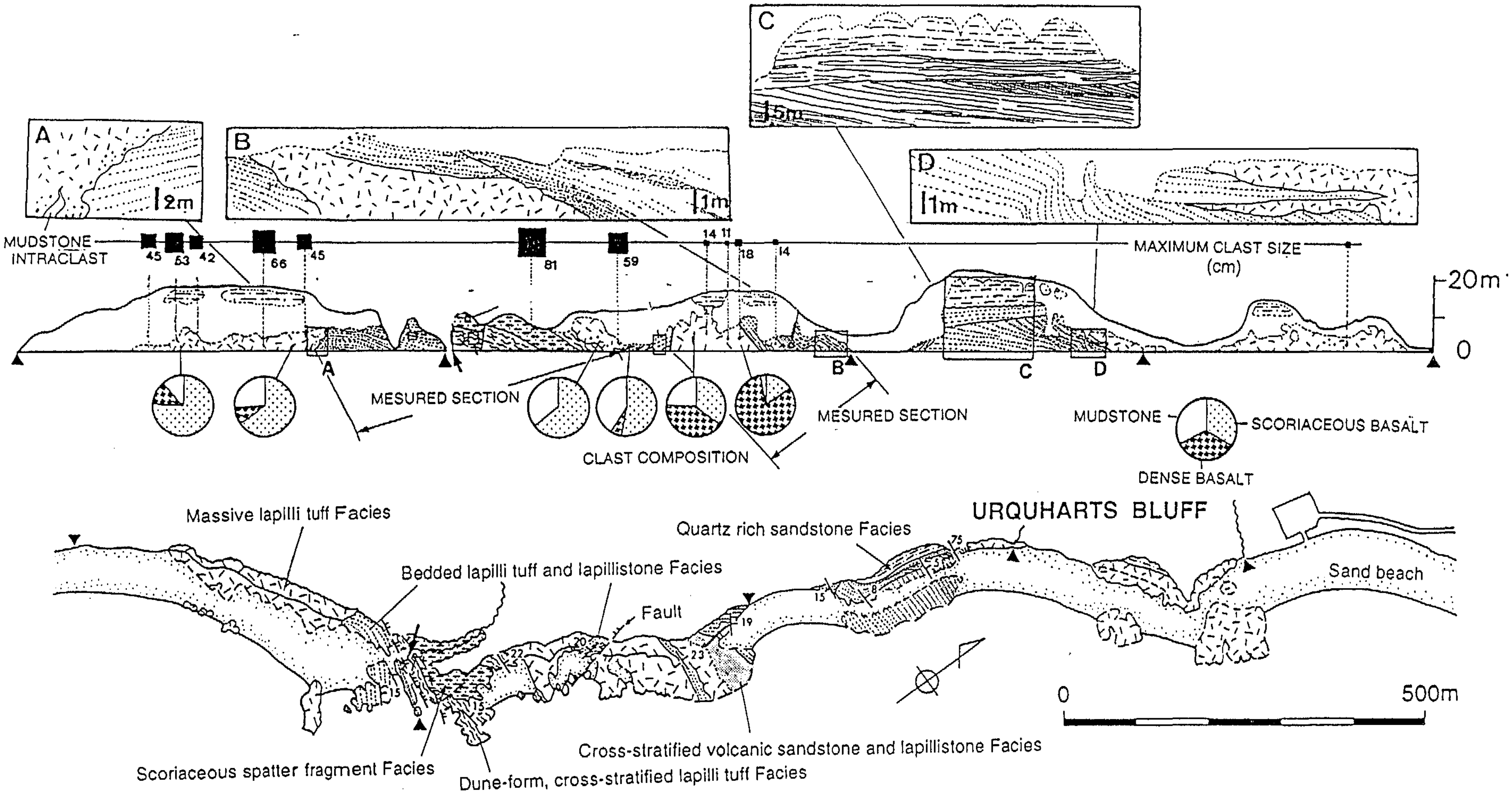

Figure 28.4 *Map and cross section, Angahook Member, Airey's Inlet north to Urquharts Bluff*

belt at Airey's Inlet outcrops are dominated by intrusive basalt. Northeastwards basalt boulders in the limestone testify to the emergence of some of the basalt on the seafloor, and reworking by current activity. Further to the north east closely associated lavas, hyaloclastite and bedded lapilli-tuffs appear to represent the remains of a small cone. The northeastern half of the coastal outcrop belt appears to represent the remains of two or more shallow marine surtseyan tuff cones, including bedded lapilli tuff successions.

The waterdepths in which eruption occurred appear to have been relatively shallow. The Point Addis Limestone Member is a coarse calcarenite containing bryozoan, gastropod, bivalve, echinoid and foraminiferal debris, all consistent with a subwave base offshore shelf setting. Cross-stratification and scour and fill sedimentary structures also indicate shallow water currents and environments. Within the volcanics, the only palaeoenvironmental indicators are hyaloclastite, suggesting subaqueous eruption and/or emplacement, a reworked shoreline volcanic sandstone sequence with symmetrical ripples, representing a localised beach-shoreline on an emergent tuff cone, marine fossils in debris flow deposits, and pyroclastic surge deposits in the northern tuff cone successions, indicating the growth of tuff cones above sealevel.

STOP 28. Lighthouse coastal section, Airey's Inlet

Outcrop 1

At low tide, exposures on the rock platform reveal an irregular relationship between basalt and calcarenite. The irregular surface of the basalt has previously been interpreted as an irregular unconformity (Abele and Page, 1974) and the calcarenite in hollows between basalt highs has been interpreted as infilling crevices in the eroded basalt surface. Close examination of the contact suggests that bedding in the calcarenite at the contact dips at up to 60-70^{o}. This is significantly higher than angle-of-reponse (25-30^{o}) that would be expected from sedimentary draping of a coarse cohesionless clastic sediment.

Outcrop 2

In the cliff exposures behind the rock platform and further along to the northeast, the irregular contact between the Angahook Member basalt and the bioclastic calcarenite of the Point Addis Limestone Member is exposed in section (Figs 28.2, 28.5). Irregular lobes of basalt protrude up into the base of the bedded calcarenite. At one point, the contact can be reached up a small rocky promintory. The basalt surface consists of several "pillow-like" lobes enclosed by calcarenite. The surface of the basalt lobes consists of a thin chilled skin about 1cm thick with small closely spaced radially arranged cooling fractures in section, and a breadcrust texture on the surface. These lobes have clearly never been subject to erosional

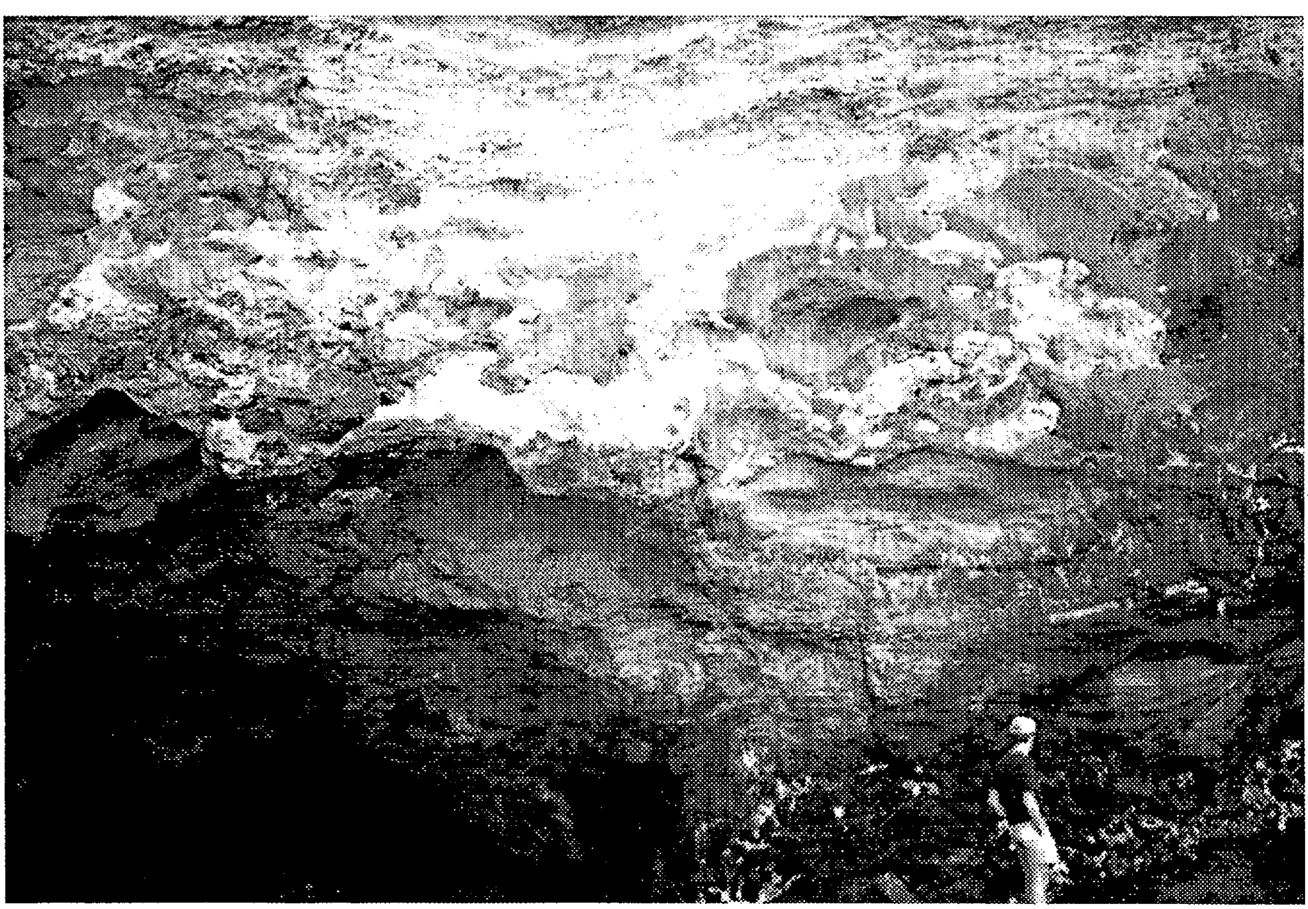

Figure 28.5 *Irregular upper contact of syndepositional basalt sill and bioclastic limestone, below lighthouse, Airey's Inlet*

action. In the adjacent cliff embayment, large, highly irregular basalt lobes at the top of the basalt are connected to the main basalt below by very narrow necks (Fig. 28.5). Such relationships are not consistent with an erosional origin as small sea stacks. The basalt lobes should clearly have collapsed and been incorporated as detached boulders in the calcarenite, which they are not.

Irregular pockets of calcarenite are also found *within* the massive body of the basalt, and at several spots, very irregular, highly vesiculated clasts of basalt occur totally suspended in the calcarenite, and some connect back continuously to the adjacent basalt. Again, these relationships are inconsistent with an erosional relationship between the basalt and calcarenite.

Outcrop 3

Clambering around the next headland, provides further exposures of the contact. At several localities, irregular lobes of basalt again protrude up into the calcarenite. As at outcrop 2, they are in places connected to the underlying massive basalt by narrow delicate necks, and preserve original radial cooling fractures and breadcrust textures. Several are strikingly vertical in their orientation.

Interpretation

It is suggested that the basalt, rather than being older than the Point Addis Limestone Member calcarenites, is contemporaneous with the calcarenites or marginally younger. We suggest that the irregular lava lobes that protrude up into the calcarenite are intrusive apophyses from a syn-sedimentary basalt sill. If the basalt surface were an erosional surface these lobes would have to be erosional stacks. Erosion would not preserve delicate breadcrust textures and the narrowness of some interconnecting necks would have led to the collapse of those stacks. Lateral intrusion of the sill appears to have occurred along a very coarse, originally porous bioclastic layer.

Alternatively, the lobes could represent a pillow lava surface. Pillow lavas however are more regular, sausage-like and cylindrical in form, and never protrude up. They drape underlying pillows in a regular manner, producing a stack of pillows with upper convex margins, and lower re-entrants.

A syn-depositional intrusive origin explains:

(a) the steep dips of calcarenite in contact with basalt lobes on the platform. These dips would have originated from updoming of originally horizontal bedding beyond angle of repose as individual intrusive lobes protruded up into the semi-consolidated calcarenite from the underlying sill.

(b) preservation of breadcrust and cooling jointed chilled rims of basalt lobes. As basalt lobes intruded up into unconsolidated-semi-consolidated water-saturated calcarenite, chilled margins would have formed. Further injection of magma into the lobes from the host sill, would have caused the chilled skin to expand and crack, forming breadcrust texture.

(c) the irregular form of the basalt lobes. When basalt intrudes unconsolidated sediment, irregular shapes develop because of heterogeneities exists in the intruded sediment, and because the intruded sediment has no strength.

(d) the irregular variably vesiculated clasts of basalt in calcarenite. These are interpreted as quench fragmented hyaloclastite debris, spalled off the adjacent intruding basalt surface, and mixed into the adjacent calcarenite by fluidisation induced mixing (Kokelaar 1982, Cas and Wright 1987), producing local aggregates of peperite.

Walking further around the coastline to Split Point, local pavements are encountered of rounded basalt clast conglomerates, and at Split Point, of basalt clasts mixed into calcarenite. Both these features suggest that somewhere, the intruding basalt breached the seafloor and was reworked by bottom currents, again indicating magmatism contemporaneous with deposition of the Point Addis Limestone Member.

Outcrop 4

Walk past Split Rock and along three small sandy beaches past a staircase to the first outcrop of bedded phreatomagmatic lapilli tuffs. Bedded lapilli-tuffs, dipping 25° to the south, pass downwards into ?autobrecciated-massive basalt, then further bedded lapilli-tuffs, with a coarse block bed. Walking further north(east)wards, dips swing to the northwest and north. At this northern exposure a blocky basaltic clast breccia, including several very large, irregular clasts occur. Some of these "clasts" appear to be relics of thin dykes, others spalled pillow lava rims. All clasts appear to have chilled margins. Jigsaw-fit or near jig-saw fit textures exist, and the breccia appears to be a hyaloclastite breccia. This basalt may have been part of the small crater fill succession.

This area of outcrop, with the radially outward clips, is intepreted to be the remains of a small surtseyan tuff cone. The lapilli-tuffs are planar bedded, and appear to be largely fall deposits, or surge-modified fall deposits. There is no evidence that this cone emerged above sea level. The outward dipping lapilli tuffs represent cone flank deposits, the hyaloclastite and inward dipping lapilli tuffs, crater fill facies.

To the north diffusely bedded (including undulating folded bedding) lapilli-tuffs become massive and unbedded, and include clasts of bedded lapilli-tuff. This succession is interpreted as a slide and debris flow deposit, resulting from sector collapse of a surtseyan tuff cone.

Walk back to staircase, climb to top, turn left along road past lighthouse. Continue down hill and return to vehicles.

STOP 29 Boundary Road to Urquharts Bluff

Drive back to Princes Highway and turn right. Drive up the hill and continue to Boundary Road. Turn right and continue to car park at the end. Walk to northern end of car park and find walking path through bush and winding down beach at the left hand end of Figure 28.4.

The rock platform and cliff exposures to the south (Fig. 28.3) have consisted of variably dipping phreatomagmatic lapilli-tuffs, sometimes with discordances and (?surge) channels, and intervals of massive unbedded lapilli-tuff. Bedding in the lapilli-tuffs is sometimes undulating, and in places fills and drapes channel-like mechanism (surge or surge modified fall deposits). Irregular basalt blocks and bombs are localised along some horizons, indicating ballistic explosive events. The massive lapilli-tuffs in places have clastic dykes of lapilli-tuff cross-cutting them, and their margins are in places clearly erosional into the underlying bedded lapilli-tuffs. They are also interpreted as slide-debris flow deposits resulting from sector collapse of surtseyan tuff cone(s). Rare occurrences of fossils indicate submarine deposition, as do highly irregular mudstone intraclasts.

Outcrop 1

From the base of the path head north along the beach (Fig. 28.4). Some of the first rock platform-exposures, variably covered by beach sand, consist of fine-medium, well sorted basaltic sandstone. The outcrop is bedded, with sandstone occurring in broad, low angle, upward concave laminated-thinly bedded sets that truncate each other at low angles. Symmetrical wave ripples are visible in some sets. This outcrop is interpreted to represent a fossil beachface on the slopes of a surtseyan tuff cone.

Outcrop 2

Continuing northeastwards for 300-400m, the platform and cliff exposures (Fig. 28.4) consist of massive, variably bouldery lapilli-tuff. Some boulders were scoriaceous bombs, others appear to have been pillow lava clasts. The matrix is poorly sorted lapilli-tuff. A notable feature of this facies is the frequent occurrence of subvertical clastic dykes of lapilli-tuff, and subvertical cylindrical clastic pipes. The infills of these dykes and pipes is frequently multilayered, with a marginal fine-grained fine volcanic siltsone succeeded inwards by course lapilli-tuff of one or more generations. These structures are interpreted as dewatering structures, resulting from the compaction and dewatering of massive slide-debris flow deposits of bouldery lapilli-tuff following sector collapse of a surtseyan tuff cone.

Outcrop 3

At the northern end of the outcrop of massive facies there is an abrupt contact with soft sediment folded and faulted bedded lapilli tuffs, thought to represent the in situ remains of the host tuff cone.

Cross the tidal channel if the tide is low enough. Carefully climb onto the seaward platform. On the south-western side on a ledge above water level is an interval of cross-stratified lapilli-tuff. Is this a primary pyroclastic surge succession or a reworked interval of volcanic sediment?

Climbing to the top of the rock platform, and looking into the tidal surge channel and tunnel, bombs with asymmetrical impact sags, and low angle cross-stratification with surge dime bed-forms are visible in the northern wall. Both impact sags and surge dune cross-stratification indicate that the vent was to the west to northwest.

A measured section (Fig. 29.1, location shown on Fig. 28.4), from the massive unit for 700 metres along the coast, and representing 110m of stratigraphic thickness are represented. Facies include bedded lapilli-tuffs (falls and surges?), dune-form, cross-stratified lapilli-tuff facies (pyroclastic base surges), cross-stratified volcanic sandstone and lapillistone facies (reworked or surge?), scoriaceous fragment facies (hawaiin strolmbolian fall or mass-flow), and massive lapilli-tuff facies (sector collapse debris flow deposits).

(Fig. 29.2). There are some problems in distinguishing surge cross-stratification from cross-stratification resulting from reworking. The presence of surge deposits is important indicating emergence of tuff cone(s) above sea level. In addition, intervals of hawaiian-style spatter deposits suggest a fire fountaining phase of eruption. Subaerial eruption is implied, and the magmatic style of eruption (cf. phreatomagmatic), suggests the vent and conduit were isolated from the sea. Lining of the magma conduit by chilled magma, and growth of cones above sea-level would have achieved this.

Outcrop 5

High cliff exposures past the end of the measured section reveal several major discordant surfaces in the bedded lapilli-tuff succession (Fig. 28.4). These represent erosional surfaces, and therefore breaks in eruptive activity, and/or the superimposition of tuff cone building successions from several nested cones.

Either return to Boundary Road carpark or to carpark at beach northeast or Urquhart's Bluff.

Summary

The Airey's Inlet Volcanic Complex appears to represent the remains of a multiple eruption point shallow marine basaltic volcanic complex (Fig. 29.3) which at the southern end produced basaltic lavas and syn-depositional intrusives, whereas to the north produced multiple, in

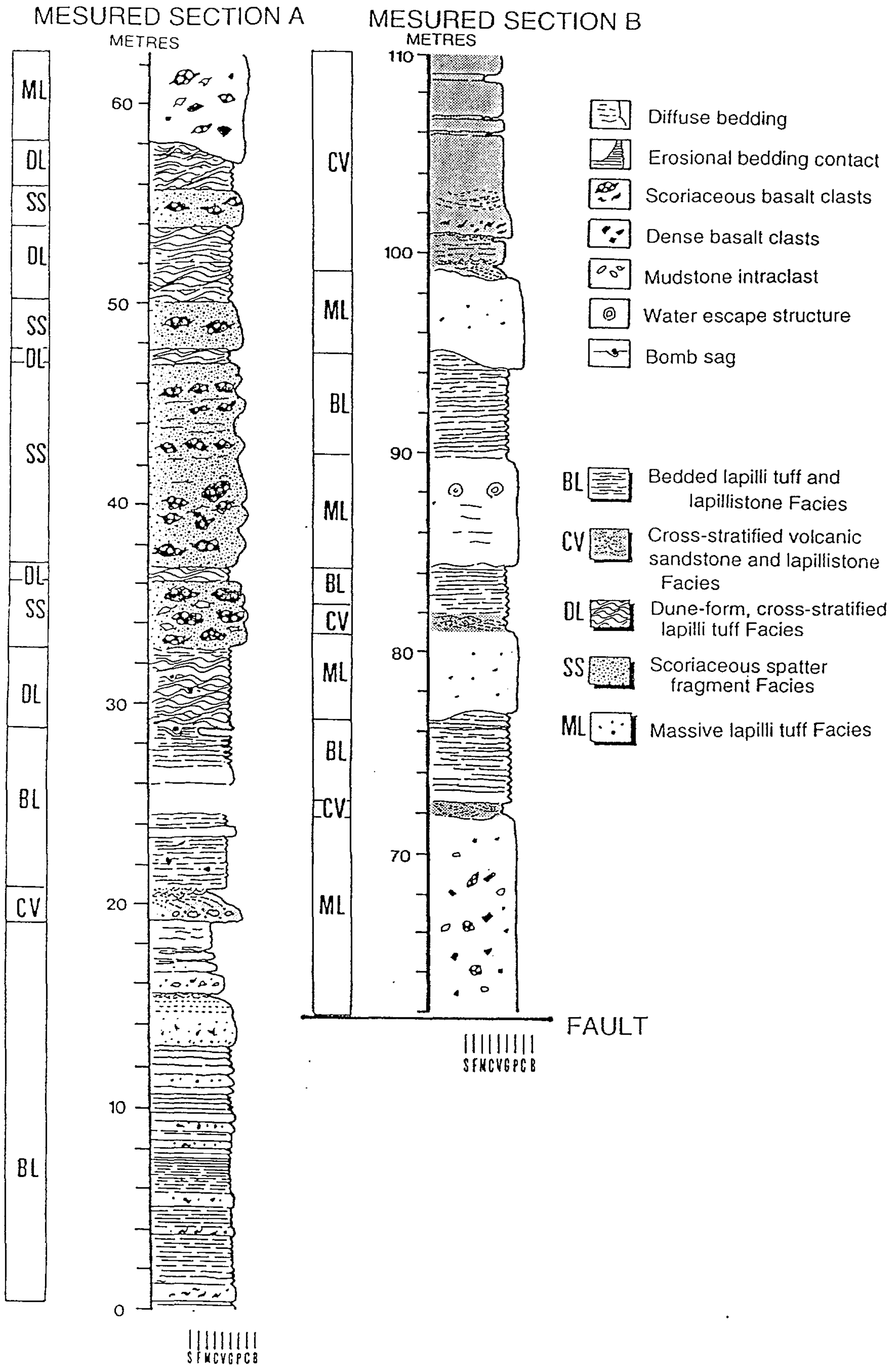

Figure 29.1 *Measured section through surtseyan tuff cone, Boundary Road to Urquhart's Bluff; see Figure 28.4 for location*

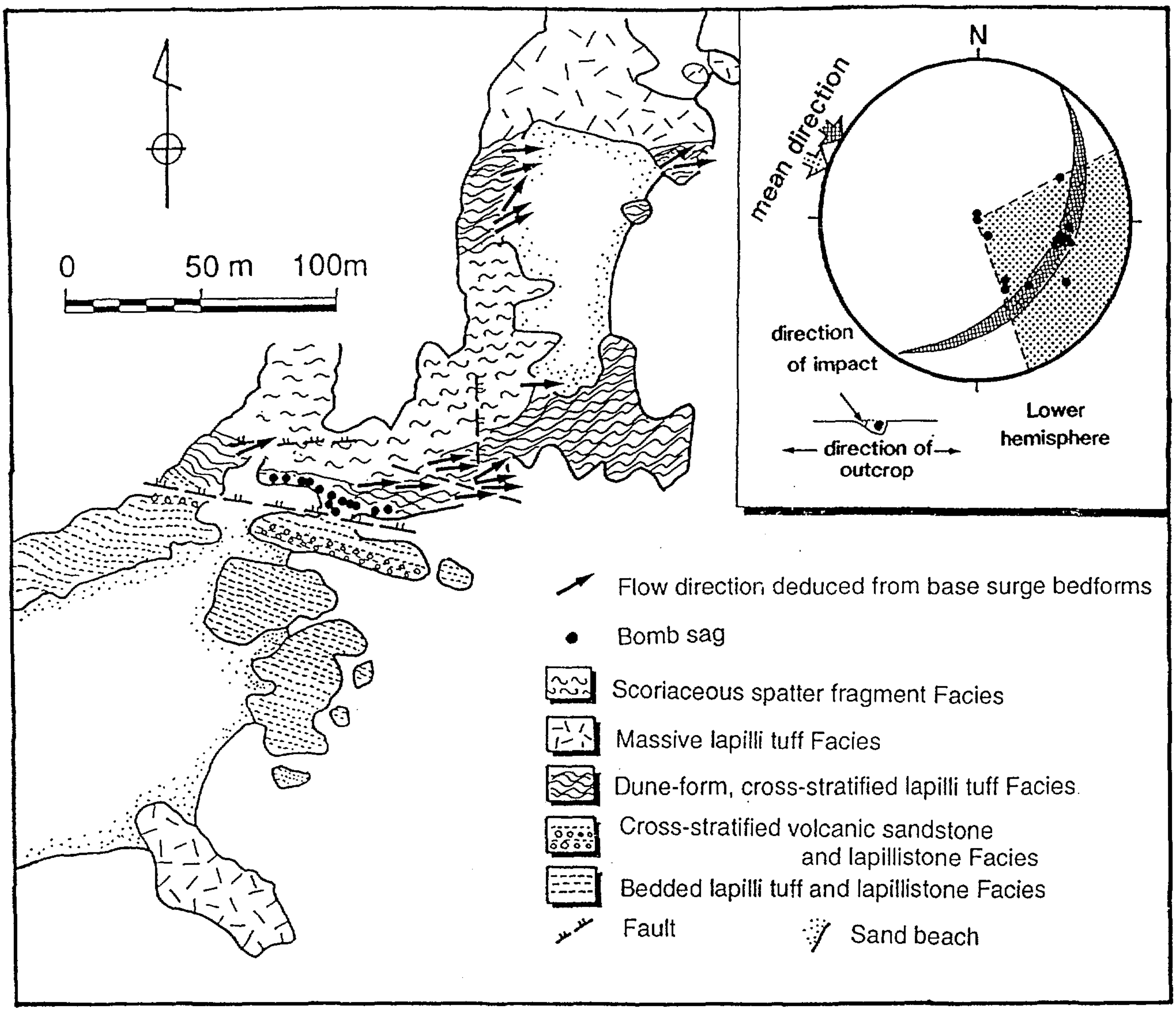

Figure 29.2 *Surge and ballistic transport directions, surtseyan tuff cone, Boundary Road to Urquhart's Bluff section*

places nested overlapping surteseyan-type phreato-magmatic tuff cones. Distinctive intervals of base-surge dune bedforms and hawaiian-style spatter deposits indicate that some cones emerged above sea level. Frequent occurrences of massive lapilli-tuff deposits that are locally many metres thick indicate that frequent collapse of parts of cones occurred, forming slides and debris-flow deposits (cf. Cas & Landis, 1987). These may have been triggered by explosive shock, shoreline erosion and undercutting, or simply gravitational collapse of oversteepened cone slopes. Although the coastal exposures are heavily weathered and altered the original vesicularity of the juvenile lapilli debris (30-60%) suggests that the erupting magma was at times at least quite gas rich. Explosions were therefore probably fuelled by a combination of magmatic gas expansion and superheating of seawater flooding the vent, as was the case with Surtsey in 1967 (Thorarinsson *et al.*, 1967). Vents appear to have lain to the west, and the occurrence of multiple vents parallel to the present northeast trending coastline suggests that development of this multiple eruption point complex may have been related to northeast trending crustal fracture system which acted as a fissure vent.

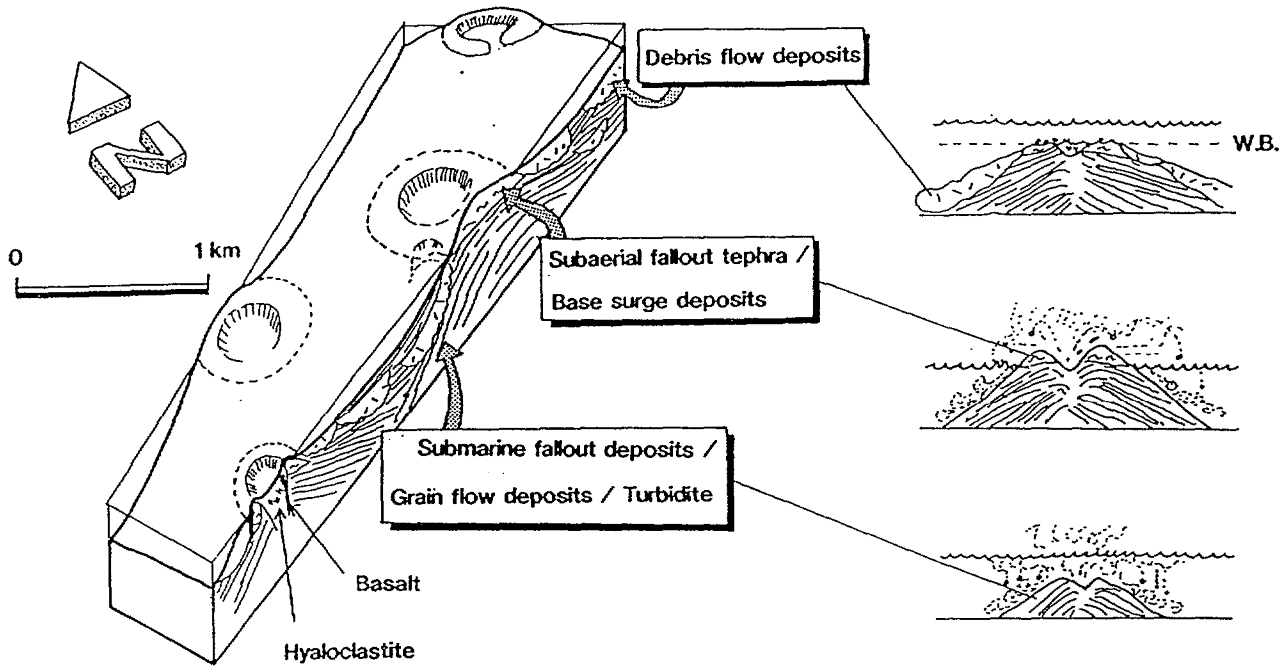

Figure 29.3 *Schematic reconstruction of the multivent Airey's Inlet Volcanic Complex*

REFERENCES

Abele, C. and Page, R.W., 1974. Stratigraphic and isotopic ages of Tertiary basalts at Maude and Airey's Inlet, Victoria, Australia. *Proceedings of the Royal Society of Victoria*, **86**, 143-150.

Allen, J.R.L., 1982. Sedimentary Structures: their character and physical basis. *Developments in Sedimentology. 30b.* Elsevier, Amsterdam.

Aziz-ur Rahaman and McDougall, I., 1972. Potassium-argon ages on the Newer Volcanics of Victoria. *Proceedings of the Royal Society of Victoria*, **86**, 143-150.

Barbetti, M. and Sheard, M.J., 1981. Palaeomagnetic measurements from Mounts Gambier and Schank, South Australia. *Geological Society of Australia. Journal*, **28** (4), 385-394.

Blackburn, G., Allison, G.B. and Leaney, F.W.J., 1982. Further evidence on the age of the tuff at Mount Gambier, South Australia. *Royal Society of South Australia. Transactions*, **106**, 163-167.

Blackburn, E.L., Wilson, L. & Sparks, R.S.J. 1976. Mechanisms and dynamics of strombolian activity. *Geological Society of London, Journal.* **132**, 429-440.

Bourton, S., 1988. *Shallow marine basaltic volcanism and sedimentation, Oligocene Demons Bluff Formation, Otway Basin, Victoria.* Unpubl. B.Sc. Honours thesis, Monash University, Australia. 151p.

Boutakoff, N. 1963. The geology and geomorphology of the Portland area. *Geological Survey Victoria, Memoirs.* **22**, 172p.

Bryan, S.E., in press. An extensional model for Cretaceous volcanism in northeastern Australia based on an integrated structural and volcanic facies analysis. *Bulletin of Volcanology.*

Bull, S. W., 1982. *The geology of Lake Purrumbete, a maar volcano of the Western Districts, Victoria.* Unpubl. 3rd year project, Department of Earth Sciences, Monash University, Australia.

Cas, R.A.F. 1983. *A review of the paleaogeographic and the tectonic development of the Lachlan Fold Belt of southeastern Australia.* Geol Soc. Aust. Spec. Publn, no.10.

Cas, R.A.F., 1989a. Regional influences on magma emplacement. In R.W. Johnson and S.R. Taylor (eds.) *Intraplate volcanism in Australia and New Zealand.* Cambridge University Press. 40-42. 408p

Cas, R.A.F., 1989b. Physical Volcanology. In Johnson, R.W., Knuston, J. and Taylor, S.R. (eds.) Intraplate Volcanism in Eastern Australia and New Zealand. Cambridge University Press, 132-135., 55-88. 408p.

Cas, R.A.F., 1991. *Nomenclature of Volcaniclastics.* Newsletter No. 4, IAVCEI Commission for Volcanogenic Sediments, 3-6.

Cas, R.A.F. and Landis, C.A., 1987. A debris flow deposit with multiple plug-flow channels and the associated side accretion deposits. *Sedimentology*. **36**, 901-910.

Cas, R.A.F. and Wright, J.V., 1987. *Volcanic Successions modern and ancient.* George Allen and Unwin, London.

Cas, R.A.F., Landis, C.A., and Fordyce, R.E., 1989. A monogenetic Surtla-type, surtseyan volcano from the Eocene-Oligocene Waiareka-Deborah volcanics, Otago, New Zealand : A Model. *Bulletin of Volcanology*, **51**, 281-298.

Chappell, B.W., White, A.J.R. and Hine, R. 1988. Granite Provinces and basement terranes in the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences.* **35**, 505-521.

Chivas, A.R., Barnes, I., Evans, W.C., Lupton, J.E. and Stone J.O., 1987. Liquid carbon dioxide of magmatic origin and its role in volcanic eruptions. *Nature.* **326**, 587-589.

Chough, S.K. and Sohn, Y.K., 1990. Depositional mechanics and sequences of base surges, Songaksan tuff ring, Cheju Island, Korea. *Sedimentology.* **37**, 1115-1135.

Colgate, S.A. & Sigurgeirsson, T. 1973. Dynamic mixing of water and lava. *Nature* . **244**, 552-554.

Cooper, J.A. and Green, D.H., 1969. Lead isotope measurements on lherzolite inclusions and host basanites from Western Victoria; Australia. *Earth Planet. Sci. Letters* . **6**, 69-76.

Coulson, A., 1941. The Volcanoes of the Portland district. *Proceedings of the Royal Society of Victoria*, **53**, 394-402.

Crawford, A.J. and Keays, R.R., 1978. Cambrian greenstone belts in Victoria: marginal sea-crust slices in the Lachlan Fold Belt of Southeastern Australia. *Earth Planet. Sci. Letters.* **41**, 197-208.

Crowe, B.M. & Fisher, R.V. 1973. Sedimentary structures in base-surge deposits with special reference to cross-bedding, Ubehebe Craters, Death Valley, California. *Geological Society of America, Bulletin.* **84**, 663-682.

Dasch, E.J. and Green, D.H., 1975. Strontium isotope geochemistry of lherzolite inclusions and host basaltic rocks, Victoria, Australia. *American Journal of Science.* **275**, 461-69.

Day, R.A., 1983. *Petrology and geochemistry of the Older Volcanics, Victoria (distribution, characterisation and petrogenesis).* Unpubl. Ph.D. thesis, Monash University, Australia.

Day, R.A., 1989. Victoria and South Australia - Volcanic Geology. In Johnson, R.W., Knuston, J. and Taylor, S.R. (eds.) *Intraplate Volcanism in Eastern Australia and New Zealand.* Cambridge University Press, 132-135, 408p.

Dodson, J.R., 1974. Vegetation history and water fluctuations at Lake Leake, Southeastern South Australia. I. 10,000 B.P. to present. *Australian Journal of Botany.* **22**, 719-741.

Edney, W.J., 1984. *The geology of the Tower Hill volcanic centre, Western Victoria.* Unpubl. M.Sc. (Prelim.), Monash University, Australia.

Edney, W. 1987. *Facies contrasts and their origins in scoria cones, maars and tuff rings of the Newer Volcanics Province, Western Victoria, Australia.* Unpubl. B.App. Sc. thesis, Monash University, Australia 123p.

Ellis, D.J., 1976. High pressure cognate inclusions in the Newer Volcanics of Victoria. Contrib. *Mineral. Petrol.*. **58**, 149-180.

Evans, J.A., 1980. *Some volcanological aspects of the Camperdown area, Victoria.* Unpubl. B.Sc. Honours Thesis, Melbourne University, Australia.

Fisher, R.V. & Waters, A.C. 1970. Base surge bedforms in maar volcanoes. *American Journal of Science.* **268**, 157-180.

Fisher, R.V. and Schmincke, H-U. 1984. *Pyroclastic rocks.* Berlin, Springer-Verlag.

Forster, E.N. 1983: *The eruptive history and eruptive mechanisms as determined by the deposits, sedimentary structures and structure of the Lake Coragulac deposits, a maar of the Red Rock Volcanic Complex, western Victoria.* Unpubl. 3rd Year project., Monash University, Australia.

Frey, F.A. and Green, D.H., 1974. The mineralogy, geochemistry and origin of lherzolite inclusions in Victorian basanites. *Geochim. Cosmochim. Acta.* **38**, 1023-1059.

Frey, F.A., Green, D.H. and Roy, S.D., 1978. Integrated models of basalt petrogenesis: a study of quartz tholeiites to olivine melilitites from southeastern Australia, utilizing geochemical and experimental petrological data. *Journal of Petrology.* **19**, 463-513.

Gill, E.D., 1967. The evolution of the Warrnamboll-Port Fairy coast and the Tower Hill eruption, Western Victoria. In J.N. Jennings and J.A. Mabbutt (eds.) *Landform studies from Australia and New Guinea.* 340-64, A.N.U. Press.

Gill, E.D. 1978: Radiocarbon dating of the volcanoes of western Victoria, Australia. *Victorian Naturalist.* **95**, 152-158.

Gill, E.D. and Elmore, L.K.M., 1973. Radiocarbon dating of Mt. Napier eruption, western Victoria. *Victorian Naturalist.* **90**, 304-6.

Gill, E.D. and Elmore, L.K.M., 1974. Importance of the Mt. Napier volcanic complex near Hamilton, Victoria. *Victorian Naturalist.* **91**, 167-74.

Greeley, R. 1977. Basaltic 'plains' volcanism. In R. Greeley & J.S. King (eds.) Volcanism of the eastern Snake River Plain, Idaho : a *comparative planetary geology guidebook.* 23-44. Washington, DC:NASA.

Greeley, R. 1982. The Snake River Plain, Idaho : representative of a new category of volcanism. *Journal of Geophysical Research.* **87**, 2705-2705.

Green, D. H., Morgan, J.W. and Heier, K.S., 1968. Thorium, uranium and Potassium abundance in peridotite inclusions and their host basalts. *Earth Planetary Science Letters.* **4**:2, 155-166.

Heiken, G.H. 1972. Morphology and petrology of volcanic ashes. *Geological Society of America, Bulletin.* **83**, 1961-1988.

Heiken, G.H. & Wohletz, K.H. 1986. *Volcanic Ash.* University of California Press, Berkeley. 246p.

Hodgson, A.J., 1982. *Stratigraphy and geology of Mount Leura volcano, Newer Volcanics Province, Western Victoria.* Unpubl. 3rd year project, Monash University, Australia.

Houghton, B.F. and Wilson, C.J.N., 1989. A vesicularity index for pyroclastic deposits. *Bulletin of Volcanology.* **51**, 451-462.

Hulme, G. 1974. The interpretation of lava flow morphology. Geophys. J. R. *Astr. Soc.* **39**, 361-383.

Irving, A.J., 1974. Pyroxene-rich ultramafic xenoliths in the Newer Basalts of Victoria, *Australia. N. Jb. Mineral., Abh.* **120**, 147-167.

Irving, A.J., 1971. *Geochemical and high pressure experimental studies of xenoliths, megacrysts and basalts from southeastern Australia.* Unpubl. Ph.D. thesis, Aust. National University.

Irving, A.J. and Green, D.H., 1976. Geochemistry and petrogenesis of the Newer Basalts of Victoria and South Australia. *Geological Society of Australia, Journal,* **23**, 45-66.

Johnson, R.W., 1989. Towards a general model. In Johnson, R.W., Knuston, J. and Taylor, S.R. (eds.) Intraplate Volcanism in Eastern Australia and New Zealand. Cambridge University Press, p.289, 408p.

Johnson, R.W., Knuston, J. and Taylor, S.R. (eds.), 1989. *Intraplate Volcanism in Eastern Australia and New Zealand.* Cambridge University Press.

Joyce, E.B., 1971. A study of maars in the post-Miocene volcanoes of southeastern South Australia. *43rd ANZAAS Congress, Brisbane, May 1971. Abstracts* p.72.

Joyce, E.B. 1975. Quaternary volcanism and tectonics in southeastern Australia. In R.P. Suggate & M.M. Cresswell (eds.) *Quaternary studies. Roy. Soc. N.Z., Wellington, Bulletin.* 13, 169-176.

Joyce, E.B. 1976. Lava channels and associated caves in Victoria, Australia. In W.R. Halliday (ed.) Proceedings of the International Symposium on *Vulcanospeleology and its extraterrestrial applications.* Nat. Speleological Soc., Seattle, 51-57.

Joyce, E.B., 1980. Layered-lava channels and the origin of lava caves. *Proceedings of the 13th Biennial Conference of the Australian Speleological Federation, Melbourne.*

Joyce, E.B., 1985. A type of volcano intermediate between the scoria cone and maar of an areal basaltic province. In *Otway 85- Earth Resources of the Otway Basin Conference, Mount Gambier, 1985. Summary papers and excursion guides.* Geological Society of Australia, 55-57.

Joyce, E.B. 1988. Newer Volcanic Landforms. In J.G. Douglas and J.A. Ferguson (Eds.). *Geology of Victoria.* Victorian Division of the Geology Society of Australia, 419-426.

Joyce, E.B. & King, R.L. (eds.) 1980. *Geological features of the National Estate in Victoria.* Victorian Division, Geol. Soc. Aust. Inc., Melbourne, 208p.

Kokelaar, B.P., 1982. Fluidisation of wet sediments during the emplacement and cooling of various igneous bodies. *Geological Society of London, Journal.* **139**, 21-33.

Kokelaar, B.P., 1983. The mechanism of Surtseyan volcanism. *Geological Society of London, Journal.*. **140**. 939-44.

Leach, J.H.J. 1977.*Geology of the eastern Corangamite region and the fossil fauna of Bald Hill, near Foxhow.* Unpubl. Honours thesis, University of Melbourne. Australia.

Leys, C.A. 1982. *Volcanic and sedimentary processes in phreatomagmatic volcanoes.* Unpubl. Ph.D. thesis, Leeds University.

Lorenz, V., 1973. On the formation of maars. *Bulletin of Volcanology.* **37**, 183-204.

Lorenz, V., 1986. On the growth of maars and diatremes and its relevance to the formation of tuff rings. *Bulletin of Volcanology.* **48**, 265-274.

MacDonald, G.A. 1972. Volcanoes. Prentice-Hall.

McDougall, I., Allsopp, H.L. & Chamalaun, F.H. 1966. Isotopic dating of the Newer Volcanics of Victoria, Australia, and geomagnetic polarity epochs. *Journal of Geophysical Research.* **71**, 6107-6118.

Marker, M.E., 1975. *The lower southeast of South Australia: a karst province.* University of Witwatersand. Department of Geography and Environmental Studies. Johannesburg. Occasional paper **13**.

Moore, J.G. 1967. Base surges in recent volcanic eruptions. *Bulletin of Volcanology.* **30**, 337-363.

Nicholls, I.A. and Joyce, E.B., 1989. Newer Volcanics. In Johnson, R.W., Knuston, J. and Taylor, S.R. (eds.) *Intraplate Volcanism in Eastern Australia and New Zealand.* Cambridge University Press. 137-141, 408p.

Ollier, C.D., 1964. Tumuli and lava blisters of Victoria, Australia. *Nature.* **202**, 1284-1286.

Ollier, C.D. 1967a. Landforms of the Newer Volcanic Province of Victoria. In J.N. Jennings & J.A. Mabbutt (eds.) *Landform studies from Australia and New Guinea.* A.N.U. Press, Canberra, 315-339.

Ollier, C.D., 1967b. Maars: their characteristics, varieties and definition. *Bulletin Volcanologique*. **31**, 45-73.

Ollier, C.D. 1969. Volcanoes. A.N.U. Press, Canberra, 177p.

Ollier, C.D. 1974. Phreatic eruptions and maars. In L. Civetta et al. (eds.) *Physical Volcanology.* Developments in Solid Earth Geophysics No. 6, Elsevier, Amsterdam, 289-311.

Ollier, C.D. 1985. Lava flows of Mt. Rouse, western Victoria. *Proceedings of the Royal Society of Victoria.* **97**, 167-174.

Ollier, C.D. & Brown, M.C. 1964. The Byaduk lava caves. Victorian *Naturalist.* **80**, 279-290.

Ollier, C.D. & Brown, M.C. 1965. Lava caves of Victoria. *Bulletin of Volcanologique.* **28**, 215-233.

Ollier, C.D. & Joyce, E.B. 1964. Volcanic physiography of the Western Plains of Victoria. *Proceedings of the Royal Society of Victoria.* **77**, 357-376.

Ollier, C.D. & Joyce, E.B. 1967. Geomorphology of the Western District volcanic plains, lakes and coastline. *Excursions Handbook, 39th Cong. Aust. N.Z. Assoc. Advmt. Sci. Sect. C,* 55-68.

Ollier, C.D. & Joyce, E.B. 1973. Geomorphology of the Western District volcanic plains, lakes and coastlines. In J. McAndrew & M.A.H. Marsden (eds.) *Regional Guide to Victorian Geology.* University of Melbourne, Australia, (2nd Ed.), 100-113.

Orth, K., 1988. Geology of the Warrnambool 1:50 000 Map. *Geological Survey Report*. **No. 86.** 83p.

Peckover, R.S., Buchanan, D.J. & Ashby, D. 1973. Fuel-coolant interactions in submarine vulcanism. *Nature*. **245**, 307-308.

Polach, H.A., Head, M.J. and Gower, J.D., 1978. A.N.U. *Radiocarbon date list VI. Radiocarbon 20.* **(3)**, 360-385.

Pope, C., 1983. *Palaeovolcanology of the Cape Bridgewater Volcano, Portland area, Western Victoria.* Unpubl. Honours thesis, Monash University, Australia.

Price, R.C., Gray, C.M., Nicholls, I.A and Day, R.A., 1988. Cenozoic volcanic rocks. In Douglas, J.G. and Ferguson, J.A. (eds.) *Geology of Victoria.* Geological Society of Australia, Victoria Division, 439-452.

Rawling, T., 1990. *The Geology of the Mt. Noorat Scoria Cone, Western Districts, Victoria.* Unpubl. Third year project report, Monash University, Australia, 49p.

Schmincke, H-U., Fisher, R.V. & Waters, A.C. 1973. Antidune and chute and pool structures in the base surge deposits of the Laacher See area, Germany. *Sedimentology*. **20**, 553-574.

Sheard, M.J. 1978. Geological history of the Mount Gambier Volcanic Complex, southeast South Australia. Trans. R. Soc. Sth. Aust. 102, 125-139.

Sheard, M.J., 1980. Quaternary volcanism in south eastern South Australia. South Australia. Department of Mines and Energy. *Unpublished report, 80/80.*

Sheard, M.J., 1983a. Volcanoes. In; Tyler, M.J., Twidale, C.R., Ling, J.K. and Holmes, J.W. (Eds.), *Natural History of the Southeast. Royal Society of South Australia.* Occasional Publications, **3**, 7-14.

Sheard, M.J., 1983b. *Volcanoes of the Mount Gambier area. South Australia. Department of Mines and Energy.* Mineral Information Series.

Sheard, M.J., 1985a. Late Tertiary to Quaternary volcanism in the Otway Basin. In *Otway 85- Earth Resources of the Otway Basin Conference, Mount Gambier, 1985. Summary papers and excursion guides.* Geological Society of Australia, p.52-54.

Sheard, M.J., 1985b. A volcanological examination of Mounts Gambier and Schank. In *Otway 85- Earth Resources of the Otway Basin Conference, Mount Gambier, 1985. Summary papers and excursion guides.* Geological Society of Australia, p.76-88.

Sheard, M.J., 1986. Some volcanological observations at Mount Schank, southeast South Australia. *South Australia Geological Survey. Quarterly Geological Notes.* **100**, 14-20.

Sheard, M.J., 1990. A guide to Quaternary volcanoes in the Lower south-east of South Australia. *South Australia, Department of Mines and Energy, Mines and Energy Review.* **157**, 40-50.

Sheridan, M.F. & Updike, R.G. 1975. Sugarloaf Mountain tephra : a Pleistocene rhyolitic deposit of base-surge origin in northern Arizona. *Geological Society of America, Bulletin.* **86**, 571-581.

Sheridan, M.F. & Wohletz, K.H. 1981. Hydrovolcanic explosions : the systematics of water-pyroclast equilibration. *Science.* **212**, 1387-1387.

Sheridan, M.F. & Wohletz, K.H., 1983. Hydrovolcanism: basic consideration and review. *Journal of Volcanology and Geothermal Research.* **17**, 1-29.

Singleton, O.P. & Joyce, E.B. 1969. Cainozoic volcanicity in Victoria. *Geological Society of Australia, Special Publ.* **2**, 145-154.

Skeats, E.W. and James, A.V.G., 1937. Basaltic barriers and other surface features of the Newer Basalts of western Victoria. *Proceedings of the Royal Society of Victoria.*, 49, 245-92.

Smith, G.C., 1988. Oil and Gas. In Douglas, J.G. and Ferguson, J.A. (eds.) *Geology of Victoria.* Victorian Division of Geological Society of Australia Incorporated, 514-546.

Smith, B.W. and Prescott, J.R., 1987. Thermoluminescence dating of the eruption at Mount Schank, South Australia. Australian Journal of Earth Sciences, 34:335-342.

Sohn, Y.K. and Chough, S.K., 1989. Depositional processes of the Suwolbong tuff ring, Cheju Island (Korea). *Sedimentology.* **36**, 837-853.

Solomon, M., 1951. The volcanic rocks of southeast South Australia. *South Australia. Department of Mines. Unpublished report, 77/50.*

Sparks, R.S.J. 1978. The dynamics of bubble formation and growth in magmas : a review and analysis. *Journal of Volcanology and Geothermal Research.* **3**, 1-37.

Sparks, R.S.J., Pinkerton, H. and Hulme, G., 1976. Classification and formation of lava levees on Mt. Etna, Sicily. *Geology.* **4**, 269-71.

Sprigg, R.C., 1952. The geology of the southeast province, South Australia, with special reference to Quaternary coast line migrations and modern beach developments. *South Australia. Geological Survey. Bulletin.* **29**, 30-62.

Sprigg, R.C., 1959. Presumed submarine volcanic activity near Beachport, Southeast South Australia. *Royal Society of South Australia. Transactions.* **82**, 195-203.

Sutherland, F.L., 1985. Regional controls in eastern Australian volcanism. In: Sutherland, F.L., Franklin, B.J. and Waltho, A.E. (eds.), *Volcanism in eastern Australia, with case histories from New South Wales.* Geological Society of Australia, New South Wales Division, Publication 1, 13-31.

Thorarinsson, S.T., 1967. *Surtsey: The new island in the North Atlantic.* New York: The Viking Press.

Thorarinsson, S.T., Einarsson, T., Sigvaldson, G.E., and Ellison, G. 1964. The submarine eruption off the Vestmann Islands. *Bulletin of Volcanology.* **27**, 435-445.

Van Tatenhove, A. 1983: *A girl and her volcano.* Unpubl. 3rd year project Report, Monash University, Australia.

Verwoerd, W.J. and Chevallier, L., 1987. Contrasting types of Surtseyan tuff cones on the Marion and Prince Edward islands, southwest Indian Ocean. *Bulletin of Volcanology.* **49**, 399-413.

Veveers, J.J., 1984. Phanerozoic earth history of Australia. Claredon Press, Oxford.

Veveers, J.J., 1986. Break-up of Australia and Antarctica estimated as mid Cretaceous (95±5 Ma) from magnetic and seismic data at the continental margin. *Earth and Planetary Science Letters.* **77**, 91-99.

Walker, N.C., 1967. A review of post-Miocene volcanic centres in South Australia. *Mining Review, Adelaide.* **126**, 152-155.

Walker, G.P.L., 1971. Grainsize characteristics of pyroclastic deposits. *Journal of Geology.* **79**, 696-714.

Walker, G.P.L. 1973. Explosive volcanic eruptions : a new classification scheme. Geol. Rundsch. 62, 431-446.

Walker, G.P.L., 1983. Characteristics of dune bedded pyroclastic surge bedsets. *Journal of Volcanology and Geothermal Research.* **9**, 281-96.

Walker, G.P.L. and Croasdale, R., 1972. Characteristics of some basaltic pyroclastics. *Bulletin of Volcanology.* **35**, 303-17.

Wass, S.Y. and Irving, A.J., 1976. *XENMEG. A catalogue of occurrences of xenoliths and megacrysts in basic volcanic rocks of eastern Australia.* The Australian Museum Sydney.

Webb, J.A., Joyce, E.B. and Stevens, N.C., 1982, Lava caves of Australia. In *The Proceedings of the Third International Symposium on Vulcanospeleology, Oregon.*

Wellman, P., 1983. Hotspot volcanism in Australia and

New Zealand: Cainozoic and mid-Mesozoic. *Tectonophysics*. **96**, 225-243.

Wellman, P. and McDougall, I., 1974. Cainozoic igneous activity in eastern Australia. *Tectonophysics*. **23**, 49-65.

Wilson, L. 1980. Relationships between pressure, volatile content and ejecta velocity in three types of volcanic explosion. *Journal of Volcanology and Geothermal Research*. **8**, 297-313.

Wilson, L. & Head, J.W. 1981. Ascent and emplacement of basaltic magma on the earth and moon. *Journal of Geophysical Research*. **86**, 2971-3001.

Wohletz, K.H. 1983. Mechanisms of hydrovolcanic pyroclast formation : grainsize, scanning electron microscopy, and experimental studies. *Journal of Volcanology and Geothermal Research*. **17**, 31-63.

Wohletz, K.H., 1986. Explosive magma-water interactions: Thermodynamics, explosion mechanisms, and field studies. *Bulletin of Volcanology*. **48**, 245-264.

Wohletz, K.H. and Sheridan, M.F., 1979. A model of pyroclastic surge. In Chapin & Elston (1979), *Geological Society of America Special Paper 180*, 177-94.

Wohletz, K.H. and Sheridan, M.F., 1983. Hydrovolcanic explosions II. Evolution of basaltic tuff rings and tuff cones. *American Journal of Science*. **283**, 385-413.

Wood, C.A., 1980. Morphometric evolution of cinder cones. *Journal Volcanology and Geothermal Research*. **7**. 387-413.