Chapter two

Volcanic geomorphology in eastern Australia

SYNOPSIS: Running along the line of the eastern Australian highlands from north to south, a chain of heating events, associated with Tertiary extensional tectonics, fostered intraplate volcanism from about 70 Ma. The underlying thermal stress resulted in magma exploiting crustal weaknesses, with lava field and central-type outpourings of lavas. The most significant geomorphic features of the eastern Australian Cenozoic volcanic landscape developed in the form of central-type volcanoes. The study of the geomorphology of these types of volcanoes may be placed within the context of continental, regional and local scale tectonic development. Application of this approach shows that there are strong links between the geomorphology of these volcanoes and plate motion, hotspot trails, orogenesis, and drainage development.

2.1 General introduction

Volcanism is a widespread phenomenon that is not confined to the Earth. Indeed, several of the Solar System's planets and satellites have either experienced volcanic activity (for example, Mars) or are currently affected by volcanism (for example, Venus, Io). Apart from supplying new geological material, volcanoes play an important part in the development of landforms. On Earth, entire geomorphic provinces are volcanic in origin. The Ontong Java Plateau, the Columbia River Plateau in the United States, the Deccan Plateau in India, the Hawaiian and Galapagos Islands and the great basalt flows of Iceland, are among the greatest constructional features of the world.

The global distribution of volcanoes is closely related to tectonic structures, however volcanoes are not uniformly distributed. Approximately 62% of active volcanoes occur on the Pacific Rim, a further 10% occur in the Atlantic Ocean and another 22% are located in Indonesia. The remainder are located in Africa, the Mediterranean-Middle East region, the Hawaiian Islands and other mid-ocean islands (Bloom 1979). Further eruptions occur as submarine activity and are probably the greatest contributors to the generation of new lithosphere. Where not covered by thin sedimentary deposits, the topography of the ocean floor is distinctly that of a basaltic terrain, with shield volcanoes, ridges, cones and rifts adding high relief landforms to an otherwise low-relief surface.

In Australia, volcanism occurred as early as Precambrian time: sediments of this age found in the Pilbara and Yilgarn cratons (Western Australia) are interbedded with rocks of volcanic origin; Bultitude (1976) and Dunn and Brown (1969) have reported early Cambrian basic volcanic activity in the east Kimberly-Victoria River area and the Northern Territory-northwestern Queensland regions respectively; activity during the Ordovician-Silurian period occurred in the Lachlan Fold Belt; Early mid-Devonian volcanism has been reported at Yerranderie (100 km west of Sydney) by Jones *et al.* (1977); Carboniferous and Permian activity occurred in the New England Fold Belt; and Jurassic volcanism has been documented in the Gunnedah Basin (Bean 1969).

From about 70 Ma and continuing until mid-Holocene time, volcanic activity in Australia was entirely intraplate and confined to eastern Australia (Johnson and Taylor 1989). Intraplate volcanism can be triggered by a range of mechanisms: continental rifting initiated by either extensional processes or by continental collision, resulting in compressive regimes and propagating fractures; active back-arc environments and associated basin-and-range type provinces; and oceanic or continental mantle plumes, with or without relative movement of continental/oceanic crust (for example, Hawaii, Iceland and eastern Australia; Knutson *et al.* 1989). Only the first and third of these categories are considered to be of relevance here. This is because, in eastern Australia, Cenozoic volcanism is remote from plate boundaries and the magma cannot be attributed either to mid-ocean ridge activity or subduction zone processes. Neither can it be clearly attributed to upwellings along transform faults (Johnson and Taylor 1989). In intraplate volcanism, magmatism is thought to be associated with rising plumes of hot mantle material (Cattermole 1989). Wellman and McDougall (1974a) argued that Cenozoic central-type activity (Section 2.2.2) was the result of the passage of the Australian lithospheric plate over two hotspots in the asthenosphere. However, there is still considerable debate over the origin of this volcanism (Section 2.4). Regardless of the source of magma, the conditions that control the rise of large volumes of magma to the surface are similar in all tectonic settings, whether the eruptions are of plate-margin, mid-ocean ridge or intraplate volcanism (Shaw 1980; Park 1988).

2.2 Eastern Australian volcanism: distribution and classification

2.2.1 Distribution of Australian volcanism

Intraplate volcanic rocks in eastern Australia extend from Torres Strait, along the eastern highlands of Australia and into Bass Strait and Tasmania (Figure 1.1). The volcanic rocks of central-eastern Queensland range from Miocene to Quaternary in age. By contrast, the volcanic rocks of New South Wales and southeastern Queensland are entirely Tertiary in age. The volcanoes of these areas are extensively eroded but, surprisingly, still retain much of their primary volcanic form (for example, Tweed, Ebor-Dorrigo and Nandewar Volcanoes, and the Warrumbungle Complex show remnant structural and shield-forming features). In the south, the formation of the Newer Volcanics of Victoria and South Australia commenced 4.5 Ma ago. In these regions, volcanic features are well preserved and include maars, craters and lava flows. The main period of eruption in South Australia occurred in late Pliocene-early Pleistocene times, and continued until 4600 years ago (McDougall *et al.* 1966). However, the age range of volcanic activity within the Holocene in these regions is uncertain since thermoluminesence and ^{14}C dates give divergent results. Despite this widespread volcanic activity, the belt of volcanism along the eastern highlands is not continuous, and large gaps occur between individual areas. Some of the gaps are filled with minor isolated outcrops of volcanic origin while other outcrops may have been entirely eroded away. Alternatively, the discontinuous character of activity may be explained in terms of imposed compressive (quiescent) and extensional (eruptive) tectonic regimes (Johnson 1989).

The distribution of large outpourings of volcanic material require the crust and the lithosphere to have an appropriate configuration such that large volumes of magma are able to rise to the surface. The rise of magma through the crust is facilitated by the existence of an extensional stress field in the lithosphere (Shaw 1980; Cas and Wright 1987). Thus, the location of intraplate vents may be controlled, to some extent, by the location of crustal fractures. In Australia, this is evident in the alignment, at all scales, of Cenozoic eruption centres and may also be demonstrated by the alignment of fissure-vent systems (Wellman 1979a). Sutherland (1978) suggested that Australian volcanism is certainly associated with pre-existing major fracture zones and their structural intersections. During periods of maximum tension, deep structural weaknesses would have enhanced magma access

(Sutherland 1985). In addition, Sutherland (1981) proposed a strong latitudinal control in volcanic peaks with more prevalent episodes coinciding with major structures. Indeed, some of the major New South Wales volcanoes are located on major lineaments (Scheibner 1976). For example, repeated episodes of volcanism in New South Wales appear to coincide with extensions of the Nandewar and Macintyre Lineaments, and the Warrumbungle to Coastal Lineaments (Sutherland 1985). However, some fundamental fractures in volcanic belts show no significant volcanism (for example, the Palmerville Fault, Northern Queensland). The relationship between Warrumbungle volcanism and pre-existing structural configurations forms a major part of this study. This is because the structural configuration of volcanism has considerable implications for geomorphic evolution of the landscape, particularly spatial and temporal rates of denudation, relief and drainage development (Chapter 3).

2.2.2 Classification of Australian volcanism

Wellman and McDougall (1974a) classified volcanism, on the basis of chemical and petrographic information, into three main provinces. The distribution of these provinces is shown in Figure 1.1. The classifications of central-type, lava field and leucitite provinces define the three dominant forms of igneous activity in eastern Australia. These are described below:

1. *Central-type volcanic provinces:* these provinces consist largely of basaltic rocks with occasional felsic rocks and/or mafic intrusions, lavas and pyroclasts (rhyolite, trachyte or phonolite). These types of volcanic rocks were produced from central vents (more precisely, clusters of vents; compare with Cotton 1942, 76; Section 1.6). In many cases these eruptions built up large volcanoes (more precisely, volcanic complexes). In general, the central-type volcanoes of Queensland are on, or to the east of, the Great Divide whereas most of those in New South Wales and Victoria (including the leucitite centres, see below) are on, or to the west of it.

In northern New South Wales, nine central-type volcanic provinces are recognised. The region extends from near the Queensland border south to the Hunter-Goulburn valley (Figure 2.1). The volcanism ranges in age from 70-12 Ma and exhibits both diverse morphology (reflecting eruptive processes) and petrological characteristics. While extensively eroded, central-type volcanoes exhibit distinct primary volcanic features (Chapter 3).

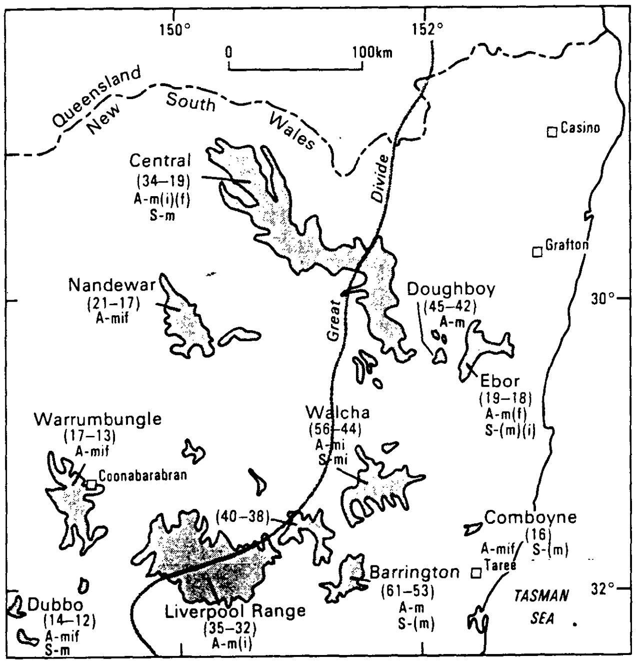

Figure 2.1: Distribution, rock types and ages (Ma, in brackets) of volcanic provinces in northern New South Wales. Rock associations: A, alkaline; S, subalkaline. Rock types m, mafic; i, intermediate; f, felsic; (m) minor mafic; (i) minor intermediate; (f), minor felsic. *Source*: Knutson 1989a.

Volcanic rocks of the central-type volcano provinces show a strong correlation between age and latitude, with apparent migration of central volcanic activity from north to south, at a rate of 65 mm a^{-1} (Duncan and McDougall 1989; Figure 2.2). Indeed, if the age and positions of central-type volcanoes which lie along the Australian volcanic lineaments are examined, it is apparent that there is a similarity in the ages of the volcanoes occurring at the same latitude (Table 2.1). This table infers that the presence of a hotspot with a regional influence of some 70 000 km^2 was the causal mechanism for this volcanism (Section 2.4). Such influence explains the areal extent of similar, near contemporaneous volcanism. (This volcanism also includes non-central-type volcanism since these types of activity are generally accepted to represent similar types of volcanic material. However, the volcanics that were extruded from areas of pipe swarms and diffuse dykes (lava fields) do not show age progression (see lava field provinces below)). This region of influence is much broader than that seen in the Tasman Seamount chains just to the east, and the lithosphere must exert a considerable control on the surface expression of volcanism over hotspots (Duncan and McDougall 1989). The variation in the age and volume of Australian central volcanoes suggests that basaltic discharge from hotspot phenomenon fluctuated by as much as an order of magnitude over tens of millions of years. Such variation in magma discharge accounts, in part, for the variation in morphology of Australian shields. Isotopic dating together with volume estimates suggest that volcanic discharge varies over time. When discharge varies, this could be reflected by fluctuations in the rate of production of new shields, the average volume of individual shields, or both.

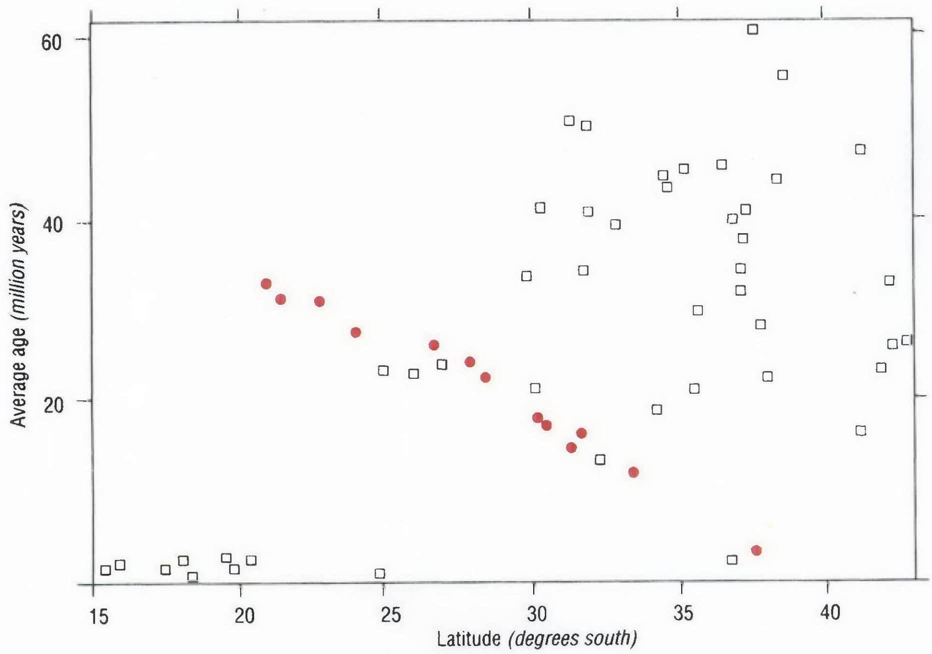

Figure 2.2: The relationship between age and latitude of central-type volcanoes (red dots) in eastern Australia. The decrease in age of central vent volcanicity from north to south is consistent with the southward migration of central-type volcanism (65 ± 3 mm a^{-1}), and the mean rate of northern drift of the continent (56 mm a^{-1}). These data support the theory of hotspot volcanism for eastern Australia. Lava field volcanism (□) shows no relationship between age and latitude. Ages for the leucitite suite follow the same trend as central-type volcanoes, but are not shown here. *Source*: Modified from Duggan and Knutson 1993.

Table 2.1: Miocene shield volcanoes of New South Wales.

Volcano	Approximate location	Average age (Ma)	Estimated original volume of volcanic materials (km^3)
Tweed	28° 15′/153° 14′	21.9	4000
Ebor-Dorrigo	30° 22′/152° 23′	19.2	270
Nandewar	30° 15′/150° 10′	18.5	600
Comboyne	31° 37′/152° 29′	16.3	40
Warrumbungle	31° 20′/149° 00′	15.8	400
Canobolas	33° 20′/149° 00′	11.8	50

Source: Wellman and McDougall 1974a.

According to current theory, the age-latitude phenomenon can be explained in terms of migration of the Indo-Australian plate over fixed hotspots located in the mantle (Section 2.4.2). A general hotspot model successfully interprets much of the age-progressive linear relationship of central-type volcanic provinces (McDougall and Duncan 1980), but there is variation in interpretation over some of the details. For instance, in one model of age-progressive central volcanism in eastern Australia proposed by Sutherland (1983), volcanic activity is depicted as advancing in a wide longitudinal band, associated with the northward movement of the Indo-Australian plate across a single stationary east-west thermal anomaly in the upper mantle. By contrast, Wellman and McDougall (1974b) argued that age-progressive correlation is the result of the movement of the Australian plate over two hotspots in the asthenosphere. Lister and Etheridge (1989) provide a further alternative: that age progressive volcanic lines can be caused by melts segregating from the culmination of chains of mantle diapirs or convectional upwellings, whose rise was triggered by rapid uplift during a much earlier lithospheric extension event.

Those areas of east Australian volcanism which do not fit an age-progressive model of volcanism have been explained in other ways. Some of the older eruptions of eastern Victoria (20-26 Ma) and northern Tasmania (13-38 Ma) may be associated with the separation of the Australian and Antarctic plates (Johnson 1989). Johnson (1989) surmised that intraplate volcanism is related to deep upwellings of hot mantle material connected with the break-up of Gondwana. The ~25 Ma time lag here may be accounted for by lithospheric extension as a trigger for the rise of deep-seated mantle diapirs.

Obviously, the age distribution of volcanism in eastern Australia does not conform to a clear pattern. While a simple explanation for the pattern of location of individual volcanic centres is that it may have been the result of extensional strain caused by tension within the Indo-Australian plate, most of the occurrences of volcanism can be placed within a framework of northward drift during the Cenozoic when Australia was thought to have passed over as many as five hotspots, or at least centres of volcanic eruption. Two of these were offshore (the Tasmantid Seamounts) and three on land (McDougall *et al.* 1981; Section 2.4.2). By contrast, the discontinuous character of eruptive regimes may perhaps be explained in terms of imposed compressive and extensional activity (Johnson 1989). Alternatively, Middlemost (1985) proposed that Miocene central-type volcanism in New South Wales resulted from a relatively stationary, large (radius over 200 km) sub-lithospheric anomalous upper mantle degassing region, rather than from a primary heat anomaly such as a hotspot.

2. *Lava field provinces:* these consist almost entirely of basaltic lavas and are composed of extensive flows from diffuse sources. This type of volcanism is more or less randomly distributed in terms of age and latitude when compared to central provinces. Most lava fields are on, or to the east of the Great Divide (Figure 1.1), or within 100 km west of it. By contrast, central and leucitite provinces are not limited by the trace of the Divide. The lava field volcanoes of New South Wales are much older than the comparatively young volcanic areas of northern Queensland and western Victoria. Lava field volcanism dominated eastern Australia until about 35 Ma. After this time most volcanic activity was associated with central-type eruptions.

3. *Leucitite suite (high potassium-mafic provinces):* these are dominated by minor intrusions and rare lava flows of leucitite that are petrologically and spatially distinct from all other eastern Australian volcanic areas. These provinces occur in a 90 km wide band extending 640 km from Byrock, 75 km southeast of Bourke, New South Wales, to Cosgrove in Victoria (Cundari 1989; Figure 1.1).

The most important distinctions between these three province types have been petrological, although striking differences in age trends (Wellman and McDougall 1974a), geochemistry and distribution are evident. Despite these classifications, the volcanological and morphological distinctions between these three volcano types is not particularly clear (Johnson 1989). Lava fields, for example, are thought to be examples of "plains basalt" volcanism, as this group may also have been produced mainly by eruptions from central vents. In some cases, substantial shield volcanoes may have been built that were not significantly different from the mafic shields of the central-type volcanoes (Cas 1989). In addition, some volcanoes classified as central-type have no overall shield or conical shape. For example, the felsic plugs and lava residuals of the Glasshouse Mountains in Queensland do not cluster about the centre of a prominent mafic shield (Plate 2.1).

The total volume for all Australian volcanism is estimated to be at least 20 000 km^3 (Wellman and McDougall 1974a; Table 2.1). These authors concluded that the rate of total volcanism was roughly constant over the past 60 Ma, although the central and lava field types began their activity at different times, and most lava field volcanism cut out before central-type activity began.

When compared to other volcanic regions (Deccan Plateau 1 000 000 km^3; Columbia River Basalts 195 000 km^3; Moana Loa 40 000 km^3), the volume of volcanic rock in Australia is not large. However, this volume is spread along some 4000 km and is clearly a major magmatic manifestation of large-scale tectonic processes. Moreover, the volume of intraplate magmas must be considerably greater than 20 000 km^3 if magmatic underplating is a major cause of highland uplift (Section 2.3.2).

Plate 2.1: The eroded remnants of the central province type Glasshouse Mountains. While classified as central-type volcanism, this (compare with Plate 4.1a, b) feature has no overall shield shape but is petrologically distinct from lava field and leucitite-type volcanism. *Photo*: M. Timmers.

2.3 The relationship between volcanism and the eastern Australian highlands: post-Palaeozoic evolution

The eastern highlands of Australia, a complex landscape region (Figure 1.1), is dominated by Early to mid-Palaeozoic geosynclinal deep and shallow marine sediments with abundant Cenozoic basalts (Taylor 1994). Post-Palaeozoic eastern Australian highland evolution was characterised by relative tectonic stability throughout the Jurassic, with little evidence to support the contention that the eastern highlands are essentially remnants of a Palaeozoic to Early Mesozoic compressional event (Lister and Etheridge 1989). This is because the development of the region conforms to a more conventional, continental margin, plate tectonic model: arc-trench type magmatism and crustal growth result from abundant additions of newly-formed mantle-derived magma (Wyborn 1989). During the Late Cretaceous period, continental rifting off the east coast of Australia formed the Tasman Sea (between 82 and 55.5 Ma ago) through the process of sea-floor spreading (Weissel and Hayes 1977; Veevers *et al.* 1991). As yet the relationship between eastern highland history, as proposed by models of uplift (Section 2.3.2 and 2.3.3), and simple plate tectonic models has not been adequately clarified. Nor have models of highland evolution been comfortably related to volcanic activity. This is mainly because the eastern highlands are distant from the plate margin and the mechanisms thought to account for high relief zones, which are commonly associated with belts of plate convergence.

Numerous hypotheses have been proposed to explain the history of the eastern highlands. Early interpretations were dominated by the concept of cycles of uplift and erosion in which periods of uplift are succeeded by phases of erosion and peneplanation (for example, Davis 1899; Woolnough 1927; Voisey 1958; Browne 1969 and Warner 1971). Broadly, these interpretations suggested very recent (Plio-Pleistocene) surface uplift of one or more erosion surfaces. Deeply incised valleys cutting headward from the coast appear to support the idea that uplift had been recent. The questioning of cyclical interpretations of landscape history grew as radiometric dates of Cenozoic lavas distributed along the highlands were obtained. These dates, combined with the increasing awareness of the role of lithological control on highland evolution (provided by essentially horizontally bedded sediments and low relief), suggest that land surfaces are much older than cyclical models propose (Section 1.5). The importance of the growing understanding of lithological controls was that they led to the inference that the low relief surfaces of the highlands were not necessarily formed close to sea level.

2.3.1 Eastern highland relief

The elevation of the eastern highland belt is not great. It is generally less than 1000 m in most of New South Wales and Queensland, and less than 2000 m even in the highest areas, except in the Victorian and New South Wales Alps. The surface relief of the highlands tends to be low, characterised by occasional high residuals of granitic rock. The major relief of the highland belt is associated with a steep fall from the upland plateau surfaces to the coastal plain. This *Great Escarpment* appears to be primarily an erosional feature, presumably formed as a result of scarp retreat from a new continental edge created by continental rifting. Ollier (1982b) suggested that the geomorphic evolution of the Great Escarpment did not occur in cycles of erosion as suggested by Davis (1899) and others, but is instead related to global tectonics and is a unique feature rather than a cyclical one. Ollier (1982b) postulated that tectonic uplifting, associated with the rifting, warped a pre-existing plain in the Late Mesozoic. On the steeper eastern slopes, erosion carved gorge-like valleys which coalesced into a continuous escarpment. By contrast Jones and Veevers (1982), Lambeck and Stephenson (1986) and Wellman (1987) proposed that the divide has been stable since at least Late Mesozoic times.

In numerous places the Great Escarpment intersects, and can be dated by, volcanic flows and these may give some clues to ages of uplift or scarp retreat. Some younger volcanoes, such as the Tweed Volcano, were erupted about 20 Ma ago on the plains created by the retreat of the Escarpment, and are now considerably eroded themselves. In this location the Escarpment is pre-Tweed in age. Pisanu and Gale (1994) suggested that the Escarpment is also pre-Main Range in age, citing evidence that the lavas of the Main Range Volcano and the Tweed Volcano overlap in both age and location. Further, they suggested that Main Range lava outliers capping plateau surfaces below the adjacent Tablelands indicate that they were erupted onto a surface across which the Great Escarpment had already retreated. This means that the eruptions from both of theses volcanoes must have taken place onto the same surface across which the Escarpment had already retreated. This contradicts Ollier's (1984a) proposal that the Main Range Volcano was erupted across the tablelands and was subsequently eroded by the headward retreat of the Great Escarpment. The Great Escarpment also cuts across the 19 Ma Ebor-Dorrigo Volcano, so here the Escarpment is post-19 Ma. The age difference in these locations along the Great Escarpment occurs because the softer Jurassic sediment of the Clarence-Moreton Basin around the Tweed Volcano was easier to erode than the Palaeozoic sediments and granites of the New England Block. Only one lava flow cascades over the Escarpment, near Innisfail (Queensland), and is about 3 Ma old, so here the Escarpment was in existence at this time (Ollier 1991).

2.3.2 Volcanism and uplift

A relationship between eastern highlands uplift and volcanic activity has often been inferred due to the clear spatial relationship between Cenozoic volcanism and the eastern highlands. Both Wellman (1979a, 1987) and Jones and Veevers (1982) have proposed a causal link between igneous activity and uplift, both of which are thought to be related to the breaking of the lithosphere as the Australian continent and the Lord Howe Rise rifted apart and formed the Tasman Sea. Two specific mechanisms have been proposed regarding this relationship: one, whereby uplift results from thermal expansion at or near the source of melting (Wellman 1979a), the other by which it results from the isostatic effect of underplating the crust with large volumes of mantle-derived magmas (Wellman 1979b; 1987). However, such assumptions must be validated given that none of the intraplate analogues in India, Africa or South America have volcanicity associated with uplifted rims. Why then is Australian morphotectonic development so different to these analogues which, like Australia, are bounded by spreading zones?

Thermal-mechanical modelling of intraplate continental regions has previously been based on analogues of oceanic intraplate regions. If the eastern highlands are comparable to the Hawaiian Ridge, then the amount of heat needed to account for the eastern highlands (as a thermal expansion effect) can only be injected into the crust if the heat source was at least as large as that of the Hawaiian Ridge (Lambeck and Stephenson 1986). While there also appears to be a clear spatial association between Tertiary igneous activity and the eastern highlands, the volume of Tertiary volcanic material is small and cannot account for a thermal event large enough to produce the observed uplift (Wellman 1979b, 1987; Wellman and McDougall 1974a). In addition, there is no clear spatial relationship between the age of the dominant volcanic rocks and their elevation. For example, Keen (1985) suggested that the largest volume of volcanic rock in eastern Australia occurs in central to western Victoria, where the elevation is lowest. This means that the movement of the Indo-Australian plate over the heat source must have been relatively slow given the amount of uplift demonstrated by the presence of the eastern highlands.

The issue becomes more complex when hypotheses of uplift are based on active rifting or passive margin models (Johnson 1989). In active rifting models (where the lithosphere thins as a result of mantle upwelling), the zone of uplift may be remote from the rift axis, whereas in passive rifting (resulting from lithosphere stretching), the elevated region is restricted to the area of stretched and rifted lithosphere. However, if secondary convection occurs the spatial extent of uplift may be similar to that experienced during active rifting. The difference between models of continental uplifting and passive margin evolution is geomorphically distinct; while both models can produce uplift, they differ in the height of elevated lithosphere and areal extent that they predict. It appears, then, that more information is required on the initial phase of lithosphere development in eastern Australia, since early rifting is crucial in influencing the overall magnitude and spatial distribution of uplift, especially in the case of passive margin uplift. Since models of active and passive uplift are poorly constrained (because of their assumptions about lithospheric properties and the amount of associated crustal extension), estimates of uplift will vary from a few tens of metres to hundreds of metres or more. To date, little attention has been given to any geomorphological evidence (with some exceptions, for example, Ollier 1982b; Bishop 1988) that might indicate which, if any, of the proposed models is applicable to the evolution of the eastern Australian passive margin. Nevertheless, the role of passive margins in long-term landscape development is important.

2.3.3 Timing of uplift

Tertiary volcanism is almost wholly confined to the eastern highlands, and because some of the volcanic rocks exhibit an age-progressive relationship (Section 2.2.2) it has been postulated that thermal-mechanical models of uplift may be relevant to eastern Australia. While such models appear to offer a simple explanation, there are numerous other hypotheses concerning the timing of uplift of parts of the highlands. These are summarised in Table 2.2.

Table 2.2: Timing and evidence for highland evolution.

Period	Highland evolution	Reference
Mainly Late Cenozoic	Uplift of eastern highlands	Andrews 1911; Browne 1969
Early mid-Tertiary	Formation of the southern New South Wales highlands	Young and McDougall 1982
Late Mesozoic	Deposition of sediments derived from the southern highlands began in the Gippsland and Otway Basins.	Veevers 1984
Pre-Mesozoic	Uplift of southern highlands.	Bishop *et al.* 1985; Lambeck and Stephenson 1986
Eocene	Southern highlands ≥ 600m, probably 800 m. Deposition of sediment derived from the southern highlands began in the Murray Basin.	Ollier 1977; Veevers 1984
Pre mid-Cenozoic	Uplift of eastern highlands	Craft 1933; Young and McDougall 1982
Paleocene	Southern highlands ≥ 500 m.	Taylor *et al.* 1985
Late Cretaceous-Cenozoic	Semi-continuous uplift of the eastern highlands	Hills 1940; Wellman and McDougall 1974b; Ollier 1978
Late Cretaceous-Paleocene	Sediment deposited in basins along the northern coast of Tasmania	Williams 1989
Late Paleozoic	Continuous passive isostatic rebound	Lambeck and Stephenson 1986

Jones and Veevers (1982) suggested that the maximum age of the eastern highlands is 95 Ma. This was supported by Wellman (1987), who attempted to demonstrate that there was periodic Cenozoic uplift associated with volcanism, which was accompanied by sea level fluctuations and sedimentation in the flanking basins after this time. The northern portion of the eastern highlands have Mesozoic sediments preserved on summits, which suggests that uplift was after the Early Cretaceous in Queensland and after the Triassic near Sydney (Wellman 1987). Veevers (1984) has suggested that the 90 Ma old sediment in the Eromanga Basin indicates that the highlands did not exist until after this time, although it is possible that this sediment could be eroded from some expression of the highlands despite the lack of evidence. Nevertheless, the balance of evidence suggests that the southern eastern highlands are probably older than their northern counterparts. Lambeck and Stephenson (1986) and Bishop *et al.* (1985) argued that the southern highlands were uplifted prior to the Mesozoic. Such a model is contradicted by the Triassic sediments which form the highest geological components of the area. As regards to a minimum age, Wellman (1987) indicated that there is now a general agreement that tectonic uplift in the southeastern highlands cannot be Late Cenozoic since mid-Tertiary basalt flows occur deep within the valleys of this area.

From the above, it can be seen that the uplift/evolution of the eastern highlands has four possible components which each have a maximum age of 100 Ma. Wellman (1987) has shown that the two earlier components were due to rifting along the present eastern margin of the Australian continent to form the Tasman and Coral Seas by asymmetric lithosphere stretching or lithosphere extension, mainly along low-angle detachment faults. This is supported by Jones and Veevers' (1982) age of 95 Ma for the opening of these Seas. Uplift at this time occurred by crustal underplating and by upper lithosphere heating. During the Cenozoic, uplift continued as a response to isostatic rebound caused by denudation of the highlands. Wellman (1987) argued that additional uplift occurred in conjunction with this in the form of isostatic uplift as a result of underplating (and possible heating of the crust) at the time of Cenozoic highlands volcanism.

Some of the questions remaining on the timing and causes of uplift may be addressed if the surface of eastern Australia prior to volcanism and uplift is investigated. The bulk of the evidence suggests that the surface was reasonably flat. Subsequent geomorphic and tectonic activity has rendered the *palaeoplain* buried or highly dissected. Woolnough (1927) suggested that "... throughout almost the whole of Australia, in or about Miocene time, there existed a peneplain [palaeoplain] of almost ideal maturity of development ...". However, estimates of palaeo-relief (for example, Pain 1983; Schön 1989) have made it clear that relief was not uniform and Korsch (1982) has demonstrated that most of the high relief was on granite residuals that may have been intruded at high levels and remained above the surrounding plain for eons.

It is possible to gain a clearer knowledge of the pre-volcanic topography, and expand the current knowledge of the picture of volcanic-tectonic relationships, by mapping sub-volcanic plateau remnants. In this study, consideration is given to the topography of the pre-volcanic surface in order to provide an insight into the effects of Warrumbungle volcanicity. Thus, sub-volcanic topography and palaeo-drainage is considered with a view to establishing the organisation and subsequent modification of drainage as it was affected by volcanic activity (prior to volcanic activity in Australia, Taylor (1911) considered that palaeoplain drainage was from east to west across the present highlands). Currently, westerly drainage of the highlands occurs via the low-gradient, long rivers of the Murray-Darling system and Lake Eyre Basin. These rivers have delivered sediment from catchment areas of about 1 000 000 km^2 throughout much of the Tertiary to the sedimentary basins of the interior of the continent. Bishop (1986) concluded that the river systems of central and southern New South Wales are probably Early Tertiary in age. Easterly drainage of the highlands consists of generally low-gradient upper and lower reaches, on the highland plateau and coastal plain, respectively. Where the streams fall across the Escarpment, gradients are steeper (Ollier 1982b). One of the main characteristics of drainage in eastern Australia is the evidence of many river modifications. These have been attributed to warping in the vicinity of the Great Divide. Although some of these are controversial, there seems to be a general consensus that the palaeoplain of eastern Australia has been warped since the palaeodrainage was established (Ollier 1986).

More significantly, much of Australia was covered by shallow seas in the Cretaceous. Oscillating sea levels at this time (Vail *et al.* 1977) affected much of the continent and demonstrates that it was already well planated. When the Cretaceous seas withdrew, they left plains covered with marine sediments on which new drainage developed. The withdrawal of these seas is of great importance for the interpretation of Tertiary events because the extension of rivers across marine sediments means that palaeodrainage is of different ages in different places. On balance, therefore, the eastern highlands are probably of considerable antiquity, but the age of geomorphic process has not been adequately clarified, with all models are critically dependent on initial assumptions (Bishop 1989). The history of incision of highland river systems and the forces driving incision are essential to understanding the evolution of the eastern highlands, including passive and dynamic tectonics, as well as erosion as a part of landscape development. Unfortunately, there is no clear agreement on the time of the beginning of this incision owing to the wide disagreement about the genesis of the uplift of the highlands.

2.4 Heat sources for eastern Australian intraplate volcanism: introduction

While there is a reasonable understanding of how interactions at plate boundaries give rise to major morphological features on the continents, current knowledge of the tectonic processes operating in plate interiors is, by comparison, poorly understood. There are many occurrences of volcanic activity in areas remote from plate margins (Figure 2.3); the Yellowstone region in Wyoming; the chain of peaks that make up the Hawaiian Islands; and the volcanoes of the East African rift system, are examples from both continental and oceanic regions. Such areas of volcanism, which are not related to processes of subduction or normal oceanic ridge spreading, are thought to arise from hotspot activity. The broad,

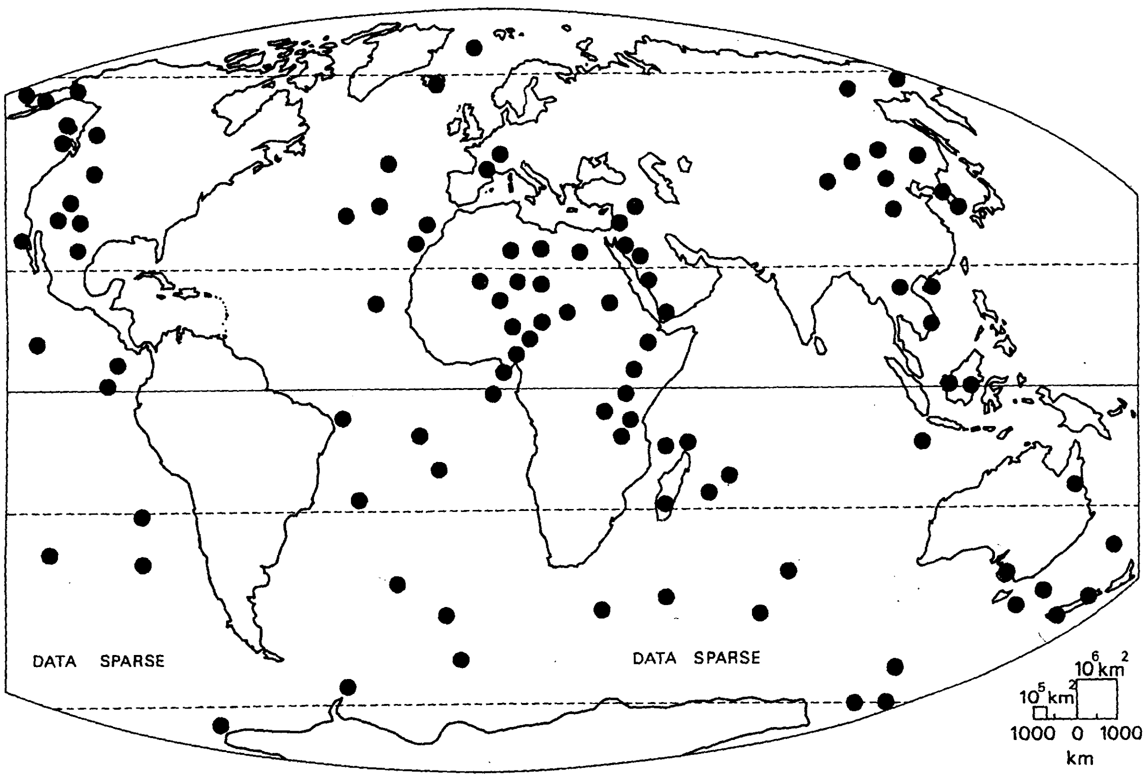

Figure 2.3: The global distribution of main hotspots. Distribution is irregular due to the problems of identifying individual hotspots, especially since it is difficult, in some areas, to determine whether adjacent centres of volcanism are associated with a single, or several, hotspots. This means that estimates of the total number of hotspots may vary from around 40 to more than 100. *Source*: Vogt 1981; Summerfield 1991.

arc-like trend of Cenozoic volcanism in eastern Australia (Figure 1.1), is quite different to the narrower, linear-like trends of volcanism defined by oceanic hotspot traces such as that of the Hawaiian-Emperor Seamount chain. Despite this, most explanations of Australian Cenozoic volcanism have been proposed within the framework of hotspot/hotline models and some of these are discussed below. Such theories are primarily based on the interpretation of controls of igneous activity, particularly through mechanisms of uplift (Section 2.3.2) as a result of rifting and/or thermal activity. However, the nature of east Australian volcanism is problematic and no single mechanism can account for all the volcanism of this area.

2.4.1 Heat source models

In order for large intraplate outpourings of magma to occur there must be an ample supply of magma which corresponds to a significant sub-surface heat source (hotspot/hotline trail). A hotspot arises from the presence of unusually hot mantle at the base of the lithosphere.

There are two main heat source models that have been hypothesised in order to explain intraplate volcanism through the presence of hotspot/hotline trails: *diapirism* and *crustal re-heating*.

Lui *et al.* (1991) described a possible source of heat (diapirism) to explain episodic hotspot volcanism, based on the development of diapiric structures in the upper mantle due to phase transition. These authors suggested that when a deep mantle plume rises towards phase boundaries in the upper mantle, changes in local heat capacity and thermal buoyancy, coupled with the latent heat associated with polymorphic solid-state phase changes at a depth of 670 km, tend to pinch off the plume head from the feeding stem and form a diapir. Such a mechanism may explain episodic hotspot volcanism as seen in eastern Australia. Indeed, if the temporal and spatial relationships of volcanism in the eastern highlands reflect the time constant of mantle processes (triggered by the rapid extension of the lithosphere beneath the upper plate), Lister and Etheridge (1989) considered that the rapid uplift of the thermal lithosphere caused by stretching induces uplift of the asthenosphere at greater depths (if there is anomalous hot asthenosphere at depth). This rapid uplift may have initiated chains of mantle diapirs or elongated plumes rising along relatively hot adiabats until partial melting takes place. These chains of solid state diapirs must rise from depths of 400-200 km. Rising at rates of 5-10 km/Ma, Lister and Etheridge (1989) suggested that the diapirs will reach the mantle solidous anywhere from 200-100 Ma after the extensional event that initiated their rise, and extensive partial melting will begin. This may be reflected by similarities in igneous activity between Australia and Marie Byrd Land (Antarctica), suggesting upper mantle-crust (upper plate) volcanism. The break-up of eastern Gondwana in the Late Mesozoic is the common link between intraplate volcanism in eastern Australia, Antarctica and New Zealand according to Johnson (1989).

Alternatively, hotspot volcanism may occur through localised reheating (crustal re-heating) at shallower depths in the mantle. Crough (1978) proposed that the gentle rises surrounding mid-plate hotspot volcanoes such as the Hawaiian group and the Cape Verde, Bermuda, and Cook-Austral Rises are caused by a broad scale re-heating of the lithosphere above the hotspots. Such a model accounts for observed relationships between geoid and swell heights, suggesting that if heat is intruded, then it rises vertically from the asthenosphere. Summerfield (1991) suggested that the source of heat is likely to be as wide as the surface relief of the swell (hotspot swells are typically several hundred kilometres across and may rise one kilometre or more above the surrounding terrain). Wellman (1986) has suggested that, for volcanoes in stable intraplate regions, the space for the underlying crustal intrusive complex is likely to be created solely by the uplift of the country rock above and surrounding it. The resultant doming of the upper crust is an important modification to local relief, since some Australian central-type volcanoes have been locally updomed by some 0.3-0.6 km (Wellman 1986). In the case of the Warrumbungle Complex, Wellman (1986) has claimed that the basement has been updomed by some 0.3 km. Given the potential effects of updoming on landscape development, one of the aims of this study is to determine whether there has been significant updoming of basement material in the Warrumbungle Complex and, if so, whether it has had any effect on the geomorphic development of landscape components.

2.4.2 Hotspot traces in eastern Australia

A review of hotspot/hotline models by Johnson and Taylor (1989) attempted to synthesise a simple geodynamic model for the Cenozoic volcanism in eastern Australia. They suggested that the east Australian hotspot trace represents the unusual case of a hot fold belt at a continental margin that has produced lava field volcanism as a result of intraplate deformation, and overriding a hotspot that has created a substantial continental volcanic trace of central-type volcanism (Figure 1.1) down the length of this fold belt. Johnson and Taylor (1989) concluded that intraplate volcanism is related to the influence of deep upwellings of hot mantle connected with the break-up of Gondwana.

Wellman (1983) has suggested that some individual igneous provinces in eastern Australia show an apparent migration with time that is consistent with models of lithosphere movement (migration) relative to a fixed hotspot reference frame. Further to this, several authors have attempted to relate hotspots to specific reference points in an effort to calculate relative plate movements, the only assumption in the analysis of plate motion relative to the mantle being that hotspots, identified by age-progressive, linear volcanism (Section 2.2.2), do not move relative to each other, and therefore provide a reference frame for plate motion. However, according to Molnar and Stock (1987) hotspot traces do not define a fixed reference frame. Indeed, there is evidence to suggest that hotspots can migrate relative to each other at velocities of up to 20 mm a^{-1} (Summerfield 1991). This means that hotspots can move under 'stationary' lithosphere. This, for example, throws into doubt assumptions about the rate of motion of the African Plate, because its past positions have been, in part, determined with respect to a reference frame of supposedly fixed hotspots. However, a series of submarine volcanoes off the coast of eastern Australia, known as the Tasmantid Seamounts, form a line over 1300 km long and range in age from Early to Late Miocene. These seamounts, like the terrestrial central provinces, show a systematic younging of volcanism from north to south and provide strong evidence of stationary hotspot track(s) moving relative to a stationary lithosphere, influencing Australian volcanism as the continent drifted north (Figure 2.4).

Like the African plate, there are other exceptions to migratory models. For example, in Australia Early Cenozoic and Mesozoic volcanic activity is evident in some of the older eruptions of eastern Victoria and northern Tasmania. The issue is further compounded by Pleistocene and Late Tertiary volcanic activity in the Nulla Province (McBride, Sturgeon and Chudleigh Fields) in northern Queensland which is inconsistent with the single trail, age progressive hotspot model. Neither the hotspot hypothesis or Johnson's (1989) Gondwanic break-up sufficiently explain the Pleistocene activity in the Nulla Province, Queensland, which does not 'fit' a single hotspot explanation, and is further compounded by variations in lava chemistry and composition (Stephenson 1989). The basic debate as to the nature of these anomalies lies in the origin of volcanicity: is it related to hotspots or diapirs, developing ocean rifts, or invasions of the lithosphere by hot fluids and gases? Regardless, it appears that lithospheric extension may trigger the rise of mantle material that generate protracted histories of volcanism visible in the overlying migrating lithosphere as hotspot trails.

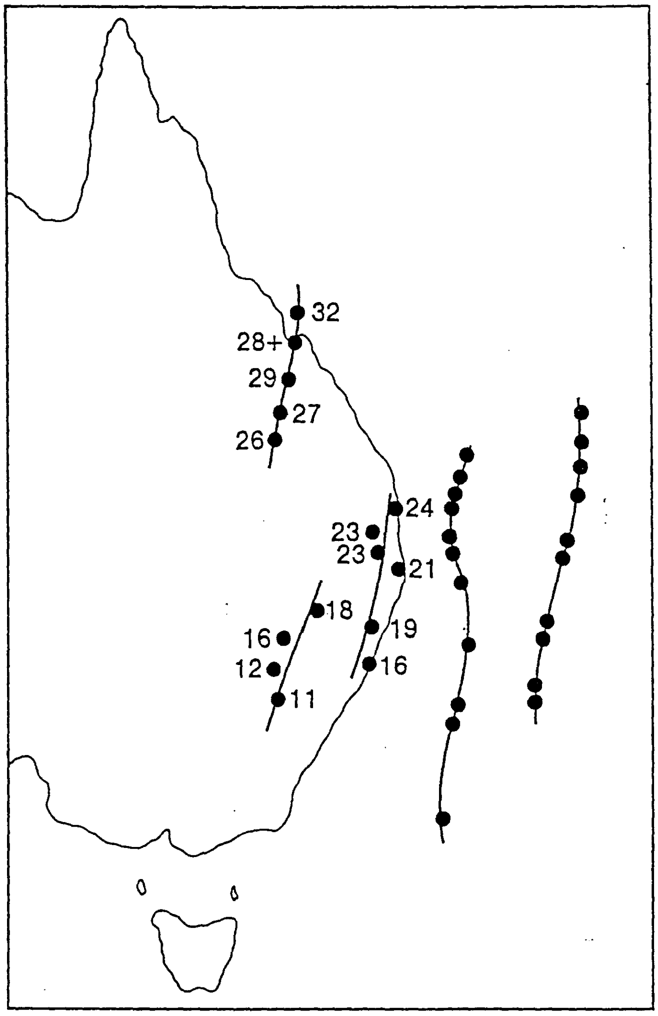

Figure 2.4: Hotspot traces in eastern Australia and the Tasman Sea. Each dot represents a central-type volcano. The numbers give the average age of the volcanoes in millions of years. *Source*: Ollier 1991.

Other discrepancies in hotspot modelling also require attention. If the central-type volcanoes arose from a single hotspot trace, how does the hotspot account for the observed 45° change in direction of the volcanic trace? (This change in trace direction also happens to coincide with a change in direction of the eastern Australian coastline). Sutherland (1981) accounted for this by relating major Australian volcanic centres to the movement of the continent over former spreading anomalies of the Coral Sea system. He suggested that all eastern Australian volcanism younger than 55 Ma was caused by seven hotspots, arguing that the majority of eastern Australian basaltic volcanism may be related to trails formed by the northward drift of the continent over several magma sources in the mantle which were associated with sea-floor spreading, extending from southeast New Guinea and the Coral Sea into the Tasman Sea. Sutherland (1981) also proposed that the spacing of volcanic episodes was controlled by the thickness of the lithosphere, plate movements and regional stress fields generated by zonal flow within the asthenosphere. Thus, either several heat sources are required to account for this anomaly, or the Tertiary volcanism is controlled by the state of stress in the continent (Pilger 1982) with a possible overprinting by Wellman and McDougall's (1974b) single hotspot trace. However, both Sutherland (1983) and Wellman (1983) rejected Pilger's model that suggested changes in tensional and compressive stress fields were responsible for volcanism rather than hotspot traces on the basis that such a model does not match detailed eastern Australian evidence. This returns to the question (for which there is no definitive answer): what is the origin of the heat source for hotspot volcanism? While a comprehensive review of these models is not appropriate in this study, Table 2.3 shows that there are many models to account for the origin and distribution of Cenozoic activity. Clearly, intraplate volcanism in eastern Australia can be related to a range of plate-tectonic mechanisms. However, no single mechanism can account for all of the volcanism (Section 2.4). Nevertheless, the geometry of volcanism, although diffuse, and the convincing age-progressive sequence of central-type activity is consistent with the general hotspot model.

Table 2.3: Origins ascribed to Cenozoic volcanism, eastern Australia-Tasman Sea.

Basaltic-felsic fields	Basaltic fields	Leucititic fields	Tasman Seamounts and islands	References
(Central volcano provinces)	(Lava field provinces)	(High K provinces)	(West chain) (East chain)	
No clearly defined relationship to systematic Tasman Seamounts	No clearly defined relationship to systematic Tasman Seamounts	No clearly defined relationship to systematic Tasman Seamounts	Migration south by lithosphere motion over fixed mantle source	Vogt and Conolly 1971
Migration south by plate motion over asthenosphere magma source(s)	Migration westwards with band of tension along eastern highlands			Wellman and McDougall 1974a
Migration south by plate motion over multiple asthenosphere sources related to Coral Sea spreading	Mostly migration south by plate motion over multiple asthenosphere sources related to Tasman Sea margin	Probably migration south by plate motion over an asthenosphere source related to Coral Sea spreading	Probably migration south by plate motion over fixed mantle sources, with different ages between chains	Sutherland 1978, 1981
			Migration south, with Lord Howe Island younger than equivalent Australian migration	McDougall *et al.* 1981
Migration south, marking change to comprehensive stress field	Older activity related to earlier tensional stress field		Possibly migration south, related to change in stress field	Pilger 1982
Migration south over linear asthenosphere magma source	Random eruption, with some coinciding with linear source	Migration south over asthenosphere magma source	East chain unrelated in age to Australian linear magma source	Wellman 1983
Migration south by plate motion over multiple, dying magma sources related to Coral Sea spreading	Largely migration south by plate motion over multiple magma sources related to Tasman Sea spreading	Migration south by plate motion over dying magma sources related to Coral Sea spreading	Migration south by plate motion over dying magma sources related to Coral Sea and D'Entrecasteau Basin spreading	Sutherland 1983, 1985
Migration south, marking change to comprehensive stress field	Related to episodes of uplift in the eastern highlands			Veevers 1984
Migration south over fixed mantle sources	Westward migration over lateral thermal pulse from Tasman rifting			Karner and Weissel 1984

Table 2.3 continued: Origins ascribed to Cenozoic volcanism, eastern Australia-Tasman Sea.

Basaltic-felsic fields	Basaltic fields	Leucititic fields	Tasman Seamounts and islands	References
(Central volcano provinces)	(Lava field provinces)	(High K provinces)	(West chain) (East chain)	
Migration south by plate motion over asthenosphere degassing source giving vortex-like magmatism				Middlemost 1985
Arc-like emplacement, not easily correlated with migration south of astheno-sources	Arc-like enclosures, differing in pattern to central volcano emplacement			Harrington and Korsch 1985
Migration south by plate motion passing out of a hot zone over a moving regional mantle upwelling	Eruption where plate overlies a hot zone over a moving mantle upwelling			Miyashiro 1986
Migration over broad stationary hotspot sources, related to onset of fast Southern Ocean opening	Problematic, but related to intraplate tensional stress	Migration over broad stationary hotspot sources	Migration over two separate stationary hot spot sources	Duncan and McDougall 1989; McDougall and Duncan 1988

Source: Sutherland 1991.

2.5 Synthesis for eastern Australian volcanic geomorphology

Continental-scale tectonic forces, in this case plate motion, may exert a fundamental control on volcanism and uplift of the passive margin and their subsequent geomorphic development. In eastern Australia, there is a clear spatial association between Cenozoic volcanism and the eastern highlands: most of the volcanic provinces are clustered near or along the antiformal divide (Lister and Etheridge 1989). This association has led to proposals for links between igneous activity and uplift, of which parts of eastern highlands uplift have been ascribed to underplating and related thermal expansion. This uplift has been partially attributed to a mantle plume, or hotspot, over which the Indo-Australian plate has been migrating through much of the Cenozoic. However, the absence of a clear relationship between local elevation of the highlands and the time at which the plume passed beneath any particular location are arguments against it causing all of the uplift of the highlands. In addition, attempts to link both uplift and igneous activity to the formation of the passive continental margin along eastern Australia have been problematic.

Thus, many workers have found it difficult to establish a realistic and dynamic model of the interaction between mantle plume(s), the asthenosphere, lithosphere, the crust and igneous volcanic activity. This is because of the relative paucity of information concerning plume upwellings and their interactions with the mantle-crust, as well as the uncertainties of uplift mechanisms, sources of magma generation, and the compositional diversity of Cenozoic basalts. In addition, models of east Australian igneous activity are poorly constrained in terms of their assumptions about lithospheric properties (Johnson 1989). Furthermore, the development of an adequate model of Tertiary volcanism in eastern Australia poses considerable difficulty given the lack of agreement in the literature regarding eastern highlands evolution and its association with igneous activity. There are primary differences of opinion concerning the timing (Mesozoic or Cenozoic) and the type of uplift of the eastern highlands (underplating, thermal expansion or rifting, denudational isostatic rebound), the degree of influence of Tertiary volcanism on highland evolution and the mechanisms by which this volcanism was emplaced. Further conclusions are hampered by evidence of Pleistocene volcanism in Queensland and Early Oligocene-Miocene activity in Tasmania, and the role of the breakup of Gondwana in the intraplate volcanism of Australia, Antarctica and New Zealand for which any "hotspot" age/latitude explanation is too simplistic.

2.6 Conclusion

The precise controls and origin of volcanism in eastern Australia are extensively debated. This has made it difficult for researchers to devise a suitable explanation for the nature and dynamism of eastern Australian volcanism. This uncertainty produces some problems for accounts of landscape development in eastern Australia. However, the central-type volcanism that gave rise to the main shield volcanoes in eastern Australia may shed some light on the development of features such as the eastern highlands. They have the potential to provide information on the geomorphic development of regional and localised landscape evolution, including structural elements, despite the length of time since their eruption. Geomorphology can help provide some constraint on large-scale tectonic development. The investigation of the geomorphic evolution of the Warrumbungle Complex may be of use in providing a partial understanding of evolution of landscapes over large temporal and spatial scales. This is particularly the case with this Complex as it has considerable potential to determine relationships between sub-basement structure, pre-volcanic physiography and the evolution of drainage patterns. In turn, this may lead to a greater understanding of the causes, and nature, of Cenozoic volcanic activity and its influence on landscape development in eastern Australia. The following chapter therefore provides a review of volcanic landscapes and the agencies that influence their development with a view to unravelling the geomorphic history of the Warrumbungle Complex, which follows in Chapter 4.