CENTRE FOR AUSTRALIAN REGOLITH STUDIES

THE TERTIARY GEOLOGY AND GEOMORPHOLOGY OF THE MONARO: THE PERSPECTIVE IN 1994

Edited by

K.G. McQueen

Centre for Australian Regolith Studies
Occasional Publication No. 2
October, 1994

The Tertiary Geology and Geomorphology of the Monaro: The Perspective in 1994

Proceedings of a one day workshop organised by the Centre for Australian Regolith Studies at the University of Canberra 8th June 1994

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CENTRE FOR AUSTRALIAN REGOLITH STUDIES,
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PREFACE

The Monaro region of southern New South Wales has been the focus of geological and geomorphological interest since it was first visited and described by European explorers and scientists in the early part of last century. This volume of articles on the Monaro is the product of a one day workshop held at the University of Canberra on the 8th of June, 1994. The workshop arose from a discussion between Max Brown, Ken McQueen and Ken Sharp during the IAVCEI field trip to the Monaro Volcanic Province in September 1993. Max Brown took on the task of organising the workshop under the auspices of the Centre for Australian Regolith Studies at the University of Canberra and the Australian National University. The main aim of the workshop was to bring together as many people as possible with research interests and knowledge on the Tertiary history of the Monaro region to discuss this knowledge and present new findings. It was hoped that some consensus could be reached on the interpretation of events and processes in the area and that directions for future research could be determined.

The following is a list of participants who attended the workshop.

Dr R. Abell	Australian Geological Survey Organisation
Ms A. Britt	Monash University
Dr M.C. Brown	Faculty of Applied Science, University of Canberra
Ms R. Chan	Australian Geological Survey Organisation
Dr I. Crick	Australian Geological Survey Organisation
Dr R. Galloway	previously CSIRO
Mr G. Goldrick	Monash University
Mr S. Hill	Department of Geology, Australian National University
Dr K.G. McQueen	Faculty of Applied Science, University of Canberra
Dr J. Nott	SREM, Australian National University
Dr C. Ollier	CRES, Australian National University
Ms M. Orr	Melbourne University
Mr I.C. Roach	Faculty of Applied Science, University of Canberra
Mr K.R. Sharp	previously Snowy Mountains Engineering Corporation
Dr D. Taylor	CRA Exploration Pty Ltd.
Dr G. Taylor	Faculty of Applied Science, University of Canberra
Dr P. Wellman	Australian Geological Survey Organisation
Dr G. Wilford	Australian Geological Survey Organisation

K.G. McQueen
Co-Director, CARS
October, 1994.

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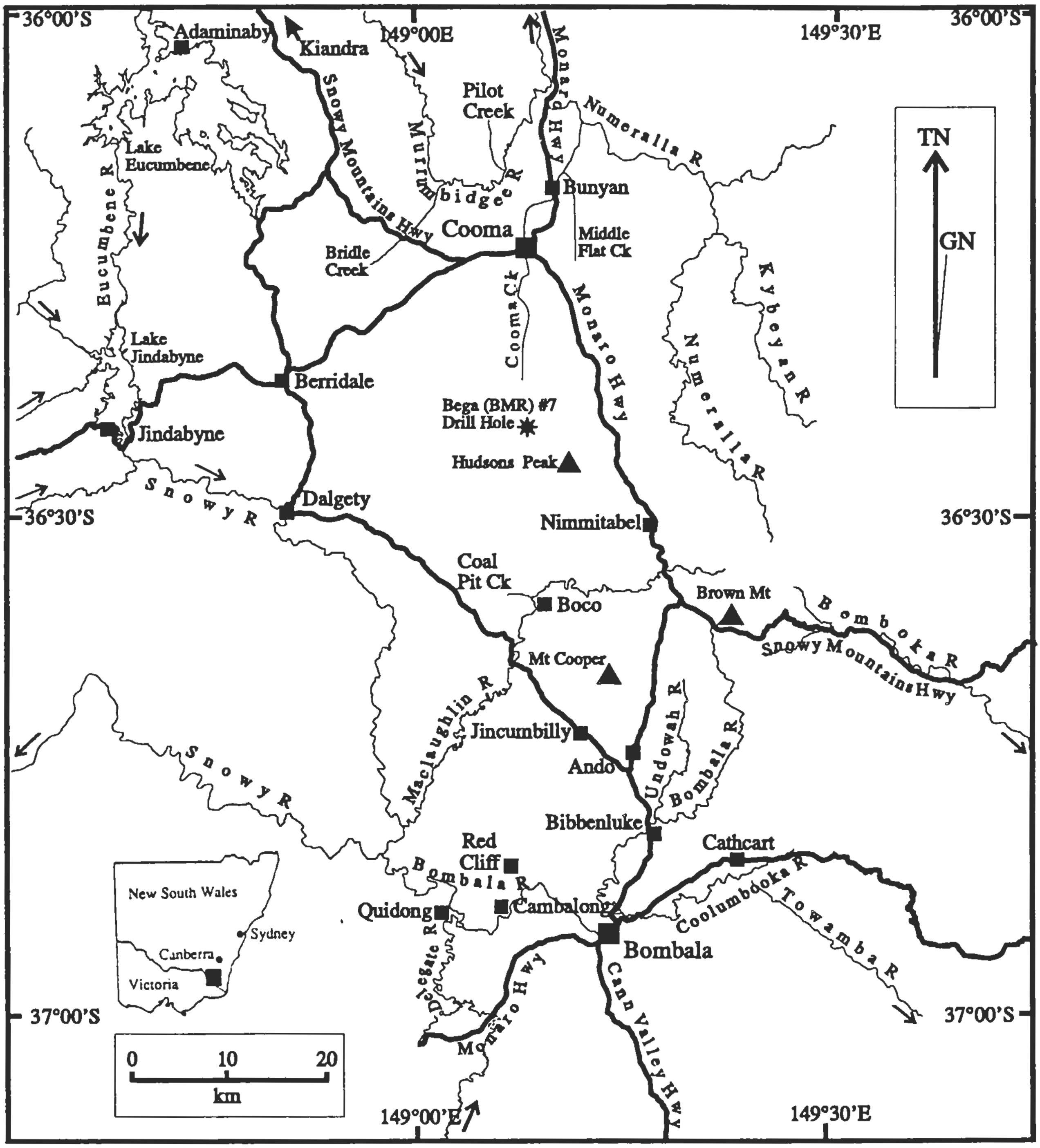

General area of the Monaro in southeastern New South Wales showing some localities and place names referred to in this publication.

A History of the Geological Exploration of the Monaro with Particular Reference to the Cainozoic and Landscape Evolution

Graham Taylor
Centre for Australian Regolith Studies, University of Canberra

What is the Monaro?

The Monaro is essentially the region of south-eastern New South Wales bounded by the Kosciusko Highland in the west, the coastal escarpment in the east and the Victorian border in the south. Its northern extremity is less clear, but for the purposes of this article it extends north to about the Bredbo/Adaminaby region. Some authors take in the whole region from Canberra to the border while others are more restrictive but cover a larger area than this summary does. For example Hancock (1972) includes the Three Counties (Fig 1); Beresford centred on Cooma, Wallace around Berridale and Wellesley including Delegate, Bombala and Nimmitabel, originally defined as the Monaro.

The name Monaro derives from an Aboriginal word and varieties used include; Monaroo, Monera, Meneiro, Meneru, Miniera, Monera (Hancock, 1972). Clarke (1851) spells it both as Maneero and Merinoo, and other spellings include Maneroo. In the fullness of time all have been subsumed by Monaro. The meaning of the name is not clear, some white people thought it meant 'women's breasts', others 'a small lake', but as no good records exist its origin must remain obscure. Old timers in the Monaro pronounce it *Mon-air-uh,* which perhaps comes closer to the original Aboriginal name, but who knows?

Aboriginal People

Although there is uncertain evidence of Aboriginal occupation of the Monaro as far back as 25,000 years ago, the most positive date comes from near Cooma and is about 8,000 years. This is from an Aboriginal burial site containing two bodies; a young man and an older woman together with a range of grave goods[1]. Included amongst the good were fragments of 'ochre' and although ochre is common on the Monaro (see bauxite summary later) the buried material is not from the region.

The Aboriginal tribes in the region include 'Ngaringo', across most of the Monaro proper, with other tribes impinging on the Monaro from around Ngaringo territory: they include Bidwell (around Delegate) and the Walgalu north of the Murrumbidgee River near Cooma.

A few points of interest concerning the Aborigines were noted by Clarke (1851/52):
- on his travels to Mt Kosciusko in early summer he reports that "..*a party of Aborigines was overtaken by a snowstorm and two were suffocated and a third crippled from frostbite...*".
- that the Aborigines frequented the Alps in early summer to catch bogong moths which they scorch by fire and then eat.
- indiscriminate use of fire by the Aborigines, coupled with their inability to extinguish a blaze is believed to account for the aridity of parts of the continent.

Investigations of many outcrops of silcrete (greybilly) around the Monaro also show considerable signs of Aboriginal working of the sites for tools. Chips and core-stones of silcrete abound at many sites.

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1 *ANU Reporter Vol 23 #1* for March 11 1992.

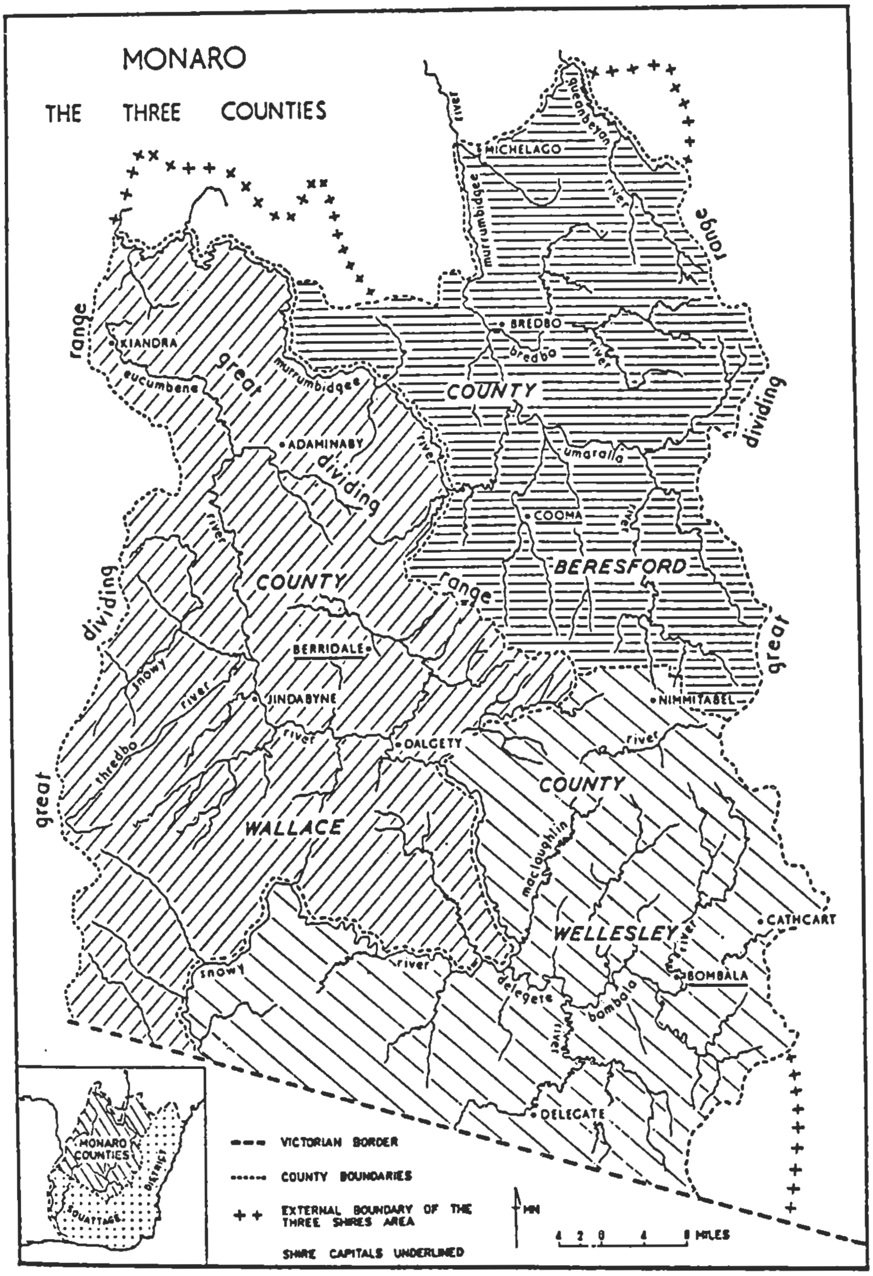

Fig. 1. The area of the Three Counties gazetted in December 1848 (reproduced from Hanccock 1972).

Early European Exploration

Between 1 and 3 June 1823 **Captain Mark John Currie (RN)** rode south from the Limestone Plains (now Canberra). On June 4th he exited fine forested lands with rocky outcrop and lofty ranges onto 'downy' country. He records the experience thus:

> *"Passed through a chain of clear downs to some very extensive ones, where we met a tribe of natives, who fled at our approach (as we learned afterwards) having never seen Europeans before: however, we soon, by tokens of kindness, offering them biscuits etc. together with the assistance of a domesticated native of our party, induced them to come nearer and nearer, till by degrees we ultimately became good friends; but on no account would they touch our horses, of which they were from the first much more frightened than ourselves. From these natives we learned that the clear country before us was called* ***Monaroo****, which they described as very extensive: this country we named* ***Brisbane Downs*** *after (and subsequently by permission of) his Excellency the Governor."*

Currie made few observations relating to the natural history of the region except that it was grassy plains.

By 1840 the Monaro was formally established as a 'Squattage District' under the control of Commissioner John Lambie of Cooma. The Monaro at this time was large (Fig 2) and extended down to Ninety Mile Beach.in what is now Victoria

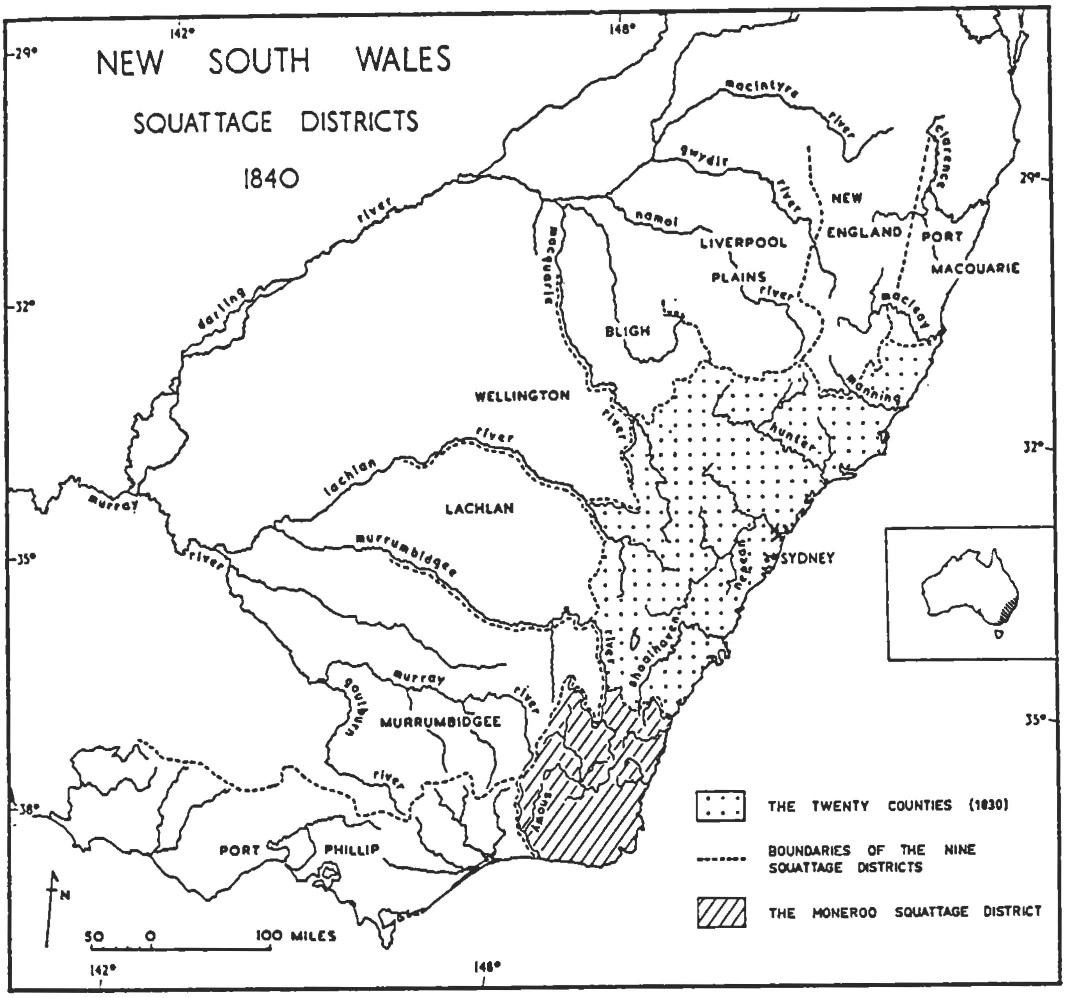

Fig. 2. The Squattage Districts of New South Wales in 1840 showing the area of the Maneroo Squattage District (reproduced from Hancock, 1972).

Early Men of Science in the Monaro

A number of botanists visited the Monaro over the years from **John Lhotsky** in the 1830's and later **R. von Lendenfeld** in 1885, **R. Helms** between 1889 and 1893 and **H.J. Maiden** between 1888 and 1889. The most recent comprehensive ecological study of the Monaro was conducted by Alec B. Costin in the late 1940's and published as a classic ecological study in 1954.

P.E. Strzelecki, a Polish geologist arrived in Australia in 1839 and journeyed to the Monaro and the Alps soon after. He made few detailed geological observations on the Monaro, but did reflect, even if in sweeping generalisations, about soils and drought which gripped the country during his visit. He commented to Governor Gipps that on traversing Lambie's Squattage District he saw the land "aflame". He continued that squatters were land spoilers, not improvers. He denounced the use of land by squatters and suggested land-use reform was necessary and that the soil fertility should be harvested, not mined. An observation entirely appropriate for the late twentieth century.

Over the summer of 1851/2 the **Reverend W. B. Clarke** at the instigation of the Governor Sir Charles FiztRoy and the then Colonial Secretary undertook a survey of the 'Southern Goldfields' in response to the 'gold fever' sweeping the Colony. He arrived in the Monaro 'territory' in December 1851 and undertook one of the most comprehensive surveys of the geology ever done. His final report (1860) did not result in a 'rush' but it did document many of the most important geological features of the region. However, his prediction that the Muniong (Snowy) Range would prove to yield gold in commercial quantities was fulfilled in 1861 when a 'rush' began at Kiandra (Aboriginal Giandarra).

Amongst many other features Clarke reported widely on the 'trap' (stepped basalt fields) covering the Monaro and offered explanations as to their origin. He also noted two differing types of granite with a marked distribution on the Monaro. Perhaps he recognised the difference between the S- and I-type granites later defined and described by Chappell and White (1974). He noted signs of mineralisation at many sites including Quedong (now Quidong) which was later mined. Other discoveries included coal within the trap, fossil wood below the trap and the late Devonian sediments which he said were of unknown age. He makes the first mention of what we now know as silcrete and found 'precious opal'.

Clarke's work on the Monaro deserves much greater attention than is possible here, but his was doubtless one of the most comprehensive surveys ever, and it was not until the mid- to late twentieth century that his work was substantially improved upon.

R. Helms published in 1894 (see Hadley, 1915) on the evidence for glacial action around Mt. Kosciusko, but wrote nothing on the general geology of the Monaro.

It is clear that by late last century **Professor T.W.E. David** was interested in the evidence of glaciation in Australia and he published and spoke widely on the topic until his death in 1932. David (1908) in his work on the glacial geology of the Kosciusko region noted Lake Coolamatong near Berridale and attributed its origin to "down-throw" of a fault (now known as the Barneys Range Fault).

G.W. Card and **W.S. Dun** (1897) worked on the newly discovered diatomite deposits ('Fullers Earth') deposits east of Cooma and thought them to be Quaternary lake deposits in the drainage of Middle Flat Creek. Many other geologists have worked on these deposits and assigned various significances to them (see later).

The Period 1900 - 1970

The early part of this century was geologically a busy time on the Monaro. Early work was mainly related to landscape evolution, and several geologists must have been working in the region almost simultaneously.

S.A. Süssmilch (1909) published on the physiography of the Southern Tablelands of New South Wales which he saw as a relatively flat area extending from Yass through Canberra to the Victorian border. He pointed out that this flat region consists of a series of plateaux separated by abrupt differences in elevation and he thought that the stepped plateaux were fault controlled. He and David (1908) before him and Andrews (1910) concluded the Monaro was an uplifted peneplain because it is incised by the rivers (e.g. Murrumbidgee, Snowy) and contains a number of residual or relict hills (Wullwye, Gygederick, The Brothers). In 1914 Süssmilch also made mention of extensive basalts between Cooma and Bombala, but wrote little more of them. In commenting on the lakes of the Monaro he thought they arose from "down warping" of the plateaux and like David gave Lake Coolamatong as an example. This theory requires that down warping must be very recent. There is little evidence that the majority of Monaro lakes are associated with known faults, but some probably are (see below).

E.C. Andrews (1910) thought the Monaro, and other landsurfaces in eastern New South Wales were peneplains in line with the newly published Davisian ideas on landscape evolution. He suggested the lower, basalt-free surfaces were of Pliocene age while the higher and basalt topped plain (or remnants) was of Miocene age. It was this uplift which developed the newer lower plain and which he called the Kosciusko Uplift. In his words it is expressed as:

> *"In the late and post Tertiary history of Eastern Australia one important fact stands out, and that is the geographical unity of the Eastern continent.*
> *(i) The Tertiary peneplain extended from north to south across the continent. The flora was uniform and evidenced a mild tropical climate.*
> *(ii) The "leads" of Pliocene, of the "Newer Volcanics," are to be found all along the eastern continent. They are evidence of similar floras, and they all evidence subsidence accompanied by filling of the channels by similar continental deposits and final burial under floods of basaltic lava.*
> *(iii) The basalts of the "newer Volcanics" are similar in appearance along the whole eastern side of Australia.*
> *(iv) The "Kosciusko" Period is also noted for its production of similar topographic features extending from north to south Australia. So also are its rejuvenation phases.*
> *(v) A similar geographical unity characterised the movements of the Human Period."*

It is interesting to note that these ideas were taken up whole heartedly at the University of Sydney, to the extent that they persisted without challenge (with one exception) until well into the 1970's. David in his Explanatory Notes for his map 'The Geology of the Commonwealth of Australia' extended these ideas continent wide. So was born the idea of peneplains affected by at least two periods of uplift, one pre-Miocene, the other post-Miocene. These ideas owe part of their origin to observations in the Monaro, but also derive partly from the Northern Hemisphere ideas of Davis. It is fair to say that adherence to these ideas for so long has held back our understanding of the geology of the Monaro and other regions of Australia for more than half a century.

Andrews also produced some other interesting ideas in his 1910 paper. A figure illustrating the "Direction of forces producing isostatic readjustment" shows Australia moving north toward New Guinea and New Zealand moving east away from Australia against opposing forces in the Pacific. This must surely be one of the earliest tectonic models for the continent and a fairly accurate precursor to our currently accepted plate tectonic models. Andrews in the same paper argued that these forces were responsible for major faulting and in relation to the Monaro he accurately showed the Murrumbidgee Fault and the downthrown block to its east which he called the " Monaro Sunkungsfeld" after Süssmilch (1909).

T.G. Taylor (1910) was one of the first geologists to note and attempt an explanation of the peculiar drainage patterns of the Monaro. Taylor was at the time Physiographer to the Commonwealth of Australia and he was later appointed as Acting Commonwealth Geologist, in fact the first Commonwealth geologist. Süssmilch (1910) and others before him, including David, had also noted this oddity in the drainage. Taylor discussed the 'boathook' bend in some of the rivers as representing points of river capture (for example where the Crackenback joins the Snowy) and he also noted the very odd semi-circular bend in the Murrumbidgee River north of Cooma, which he attributed to capture of an earlier stream flowing southward from about Michelago by the original Murrumbidgee. The latter he asserted used to flow south through Slacks Creek to the Wullwye and Snowy. Süssmilch (1914) had a similar idea, but suggested the eastern river rose near Bredbo before capture. He suggested the capture occurred due to warping in the vicinity of the present Great Divide near Cooma Airport. Süssmilch also attributed the rivers deep incision into the peneplain as being due to the Kosciusko Uplift. Browne (1914; 1967) also pointed out similar anomalous stream patterns and adopted similar explanations. Various authors also noted the number of 'straight' reaches on many streams and attributed this to their following fault planes (e.g. the Crackenback, Snowy at Jindabyne, the Murrumbidgee, Wullwye). As will become clear in this volume there is still contention nearly 100 years later about the origins of the Monaro drainage patterns.

David (1897) in his work on the Vegetable Creek tin fields of New England had interestingly provided part of the solution to solving the mysteries of these drainage patterns. In this study he mapped out the old drainage using basalt flows and 'deep leads' to position ancient stream beds. This technique was not taken up on the Monaro until Craft's work of 20 years later. It is still a major tool used to determine the prior drainage of the region.

W.R. Browne (1914) mapped the geology of the Cooma region, and later (1943) mapped the area from Bunyan to Bredbo. He noted the widespread distribution of the basalts and the drainage anomalies. Browne also reported the widespread presence of 'greybilly' in the area, but his interpretations were somewhat odd. It was, however, the first record of their presence since the work of Clarke and the first map of their distribution on the Monaro. In this paper Browne (1944) also gave a detailed description of the diatomite deposits at Middle Flat. He made a few comments about contemporary processes of interest. For example he commented that sand dunes were migrating across the road from Queanbeyan to Cooma in places such that it made the track impassable in spots (cf. Strzelecki, 1849). Browne was working during a major period of drought in the area.

J.E. Carne and **L.J. Jones** (1919) reported for the New South Wales Geological Survey on the limestone resources of the state and in that volume they refer to the Quidong area and identified Silurian fossils. They did no mapping, nor did they record any detail of features other than the limestones, although the Palaeozoic basin is overlain by significant and interesting Cainozoic deposits. Last century gold was worked from these deposits just south of Quidong at Nelbothery Hole, and high level gravels track the former course of the Delegate River which is presently well incised into the older landscapes.

E.J. Kenny (1924) summarised earlier descriptions of the "Cooma Diatomite" and mentioned that the mine began operating in 1886 and up to 1923 had produced about 1,252 tons valued at £3,570.

F.C. Craft (1933) undertook a study of the surface history of the Monaro. His findings were at odds with those we have discussed and he showed clearly, for the first time, that the basalts of the Monaro filled deep valleys (500 feet) in the older 'peneplain' surface. Craft also pointed out that in many areas the pre-basaltic landscapes had been exhumed, particularly around Cooma and that many of the "buried valleys have been partly exposed with remnants of basalt". Craft's summary of the post basalt history concluded:

> *"Three stages are thus revealed: the general weathering and stripping of basalt sheets from the Monaro peneplain, the cutting of valleys through the basalt and their extension by headward erosion, and a process by which the basalt was removed from the filled valleys until, with the re-establishment of formed slopes, erosion had virtually ceased."*

Of the Monaro Peneplain he reported:

> *"A consideration of the upper Murrumbidgee shows that post-basaltic erosion has tended to reproduce pre-basaltic features in detail, with some downcutting in the Cooma district."*

After reviewing the information about the origin of the Monaro drainage from Clarke (1860), David (1908), Süssmilch (1909), Taylor (1910) and Browne (1928) Craft concluded:

> *"Süssmilch (1909) and Taylor (1910) have suggested that the upper Murrumbidgee originally flowed to the Snowy, whence it was diverted northward by capture following warping and basalt flows. The balance of both pre- and post-basaltic erosional features on either side of the Main Divide does not favour the idea and there is no certain evidence of considerable warping. Moreover, the Umaralla* (now Numeralla) *appears to have discharged northward over a very long period of time, and there are no features rising above the level of the Monaro peneplain between it and the Murrumbidgee, and no suggestion of an old divide. Considering the profiles of the main streams (Text-fig 4.), it will be seen that they are very similar over parts of the courses, in which the streams flow on opposite sides of the Monaro ridge, ... The existing divide has been an essentially stable feature over a long period of time, antedating the basalt flows considerably."*

Much of Craft's work suggested the conventional wisdom of the time, based on the Davisian Cycle, was not necessarily correct. As the Macleay Fellow of the Linnean Society in Geography at The University of Sydney, his conclusions did not meet with ready acceptance. His career at The University was more or less over at this stage and he went school teaching after a short but insightful career working on landscape evolution in the Monaro and the Shoalhaven Valley. His work was largely ignored, as indicated by the uncritical acceptance of earlier wisdom by White *et al.* (1977) in their much later explanatory notes to the Berridale 1:100 000 Geological Sheet (see later).

In 1937 **B.E.V. Skvortzov** wrote on the diatoms making up the diatomite deposits from Cooma. The samples were sent to him by Mr M.F. . of the N.S.W. Department of Mines, Sydney. In the work he quotes geological details of the site described by Browne (1914). He dated the deposit as probably mid-Tertiary, but, 30% of the material he determined to be from the Lower Tertiary. While he recognised that most of the species were freshwater he reported three distinct marine taxa and was not sure whether these were "accidental" in otherwise freshwater lacustrine deposits.

E.S. Hills (1941) examined and described Murray Cod (*Maccullochella macquariensis*) from the Cooma diatomite amongst those from other deposits. This clearly demonstrated that the area of the lake in which the diatoms were deposited at Cooma was connected to the inland river system in which the cod existed. He concluded that the remains were not older than Pliocene, but that the fossils *"do not give a decisive age"*.

C.StJ. Mulholland (1938; 1941) undertook a preliminary geological survey along the western margin of the Monaro in preparation for what was to become the Snowy Mountains Hydro-electric Scheme (SMH) in 1949.

In 1947 **Irene Crespin** described the diatomite deposits of Australia including those of Middle Flat. She identified the major species present and summarised their importance in the total Australian context.

The Cooma Metamorphic Complex was first systematically described by **Germain A. Joplin** in 1948 and although not directly relevant in this context it was a hall-mark study on regional metamorphism carried out on the Palaeozoic rocks of the Monaro.

H.M. McRoberts (1948) is one of the few to have worked in the southern Monaro. She mapped the area immediately surrounding the township of Bombala. In relation to Tertiary geology she made several valuable observations. She noted that many of the contemporary river systems have not yet eroded their valleys to the base of their Tertiary fills (sediment or basalt) even though they have eroded through basalt and silcrete (greybilly) capping sediment fills. She noted a pre-Tertiary sediment relief of at least 200 m in the vicinity of Bombala. McRoberts also described metamorphosed weathering or soils (bole) within the flows and she concluded that this was good evidence for more than one flow.

McRoberts (1948) still referred to the 'Monaro peneplain' despite her observations discussed above. Is it possible that as a Commonwealth Research Student at the University of Sydney she was discouraged, as others before her had been, from taking these observations further? I have no answer to this but she was on the verge of a breakthrough in understanding the Tertiary evolution of the Monaro, but did not continue. In her summary she writes *"Tertiary sediments and basalt cover much of the area and give promise of useful results on detailed study."*

A.B. Costin in 1954 published a major ecological study of the Monaro. His direct contribution to geology was minimal as he essentially relied on the earlier work described above. Costin considered many of the Quaternary features of the Monaro and nearby regions, including solifluction and other mass flow deposits, soil distribution, and the relationships between geological and soils features and the ecosystems.

Costin's treatise on the ecology of the Monaro was a landmark publication in Australia and led the way for most similar studies since. His novel integration of geology, soils, climate and biota provided important new insights. He was meticulous in using the most recent and up to date information in all areas of his study.

In his work on mapping and describing the soils of the Monaro Costin made several observations of particular interest with respect to the Tertiary geology. He noted pre-Oligocene (ref. Table 1) 'laterite' developed on alluvial materials relict on the highest points in the landscape. Additionally he recognised a second 'laterite' on the younger and lower Pliocene surface, again particularly in valley-fill alluvium but he also noted their development in basic rocks. Other cemented materials observed and mapped by Costin included silcrete and calcrete.

Weathering profiles between basaltic lava flows were noted by Costin. He also described very fine-grained clays from near Bunyan which he suggested were soils formed on lacustrine deposits.

Table 1 is a summary of the geological history of the Monaro and High Country as it was known up to about 1950 and as set out by Costin.

C.L. Adamson (1955) undertook preliminary geological surveys in the northern Monaro for the SMH. He reported on the presence of widespread basalt, silcrete and Tertiary sediments in the vicinity of Adaminaby, Bridle Creek west of Cooma, Caddigat and the western reach of the Murrumbidgee.

Also at about this time **E.D. Gill** and **K.R. Sharp** (1957) published an early paper using accurate geological mapping to interpret the landscape evolution at the Kiandra goldfields, just north-west of the Monaro. While this area is not strictly within my definition of the Monaro, theirs was the next piece of work after Craft to bring into question the ideas of earlier workers. They concluded the pre-basaltic drainage in the area was developed on a landscape dating from the Cretaceous, that the basalts were Lower Cainozoic and Upper Cainozoic, and finally that the Kosciusko Uplift of Andrews (see above) must have taken much longer than visualised by earlier geologists.

Table 1. A tentative chronology of some significant Post-Cretaceous physiographic features and events (from Costin 1954).

Period	Sub-division	Tectonic movements	Physiographic features	Lakes and rivers	Significance
			TERTIARY		
pre-Oligocene			Oldest peneplain residuals.	Ancient lake & river systems.	Prolonged still-stand & peneplanation. Drainage pattern different from that of today. Moist climate.
Oligocene		General uplift.			Commencement of new cycle of erosion with incipient peneplanation. River piracy & changes in river patterns. Moist climate.
Miocene	Early				Continued peneplanation. Moist climate.
	Middle		General peneplain surface.		Prolonged still-stand & peneplanation. Moist climate.
	Late	General uplift.			Commencement of new cycle of erosion. Moist climate.
Pliocene	Early				Continued erosion. Moist climate.
	Middle		Broad valleys.		Development of mature topography. Moist climate.
	Late	Commencement of Kosciusko Uplift.			Commencement of new cycle of erosion. Moist climate.
			QUATERNARY		
Pleistocene	Early	Completion of Kosciusko Uplift.	Differentiation of Monaro into present tracts. Fault scarps & rift valleys. Youthful topography. Glacial topography of the first series of Kosciusko valley and cirque glaciations. Youthful topography.	Old Lake Jindabyne.	Vigorous erosion. Climate differentiation. Minor adjustments to drainage pattern. Moist climate. Acceleration of erosion. Increased physiographic & climatic diversity. Cold moist climate.
	Middle		Youthful topography.	Drainage of Jindabyne Lake.	Continued erosion. Moist climate.
	Late		Glacial topography of second series of Kosciusko glaciations. Youthful topography.	Glacial lakes of cirque glaciation.	Acceleration of erosion. Increased physiographic and climatic diversity. Cold moist climate, with brief warmer interglacial phase.
Recent		Minor tectonic adjustments.	Youthful topography.		Continued erosion. Warmer and drier climate.

Ian B. Lambert and **Allan J.R. White** (1964) writing on the Berridale Wrench Fault showed it to be mobile through the Tertiary as it clearly displaces the basalts and they argued that it had a significant northwesterly-facing scarp during much of the Tertiary. They also reported the first "volcanic plug" recorded from the Monaro at "Hazeldean", and they refer to a nearby "metamorphosed soil" composed predominantly of alumina, titania and ferric oxide with minor plagioclase. This clearly showed the basalts were deeply weathered prior to extrusion of the covering flow and then metamorphosed. Although Lambert and White did not recognise the widespread occurrence of these inter-flow weathering profiles this is the first recorded evidence for such materials.

In 1967 **Len R. Hall, G. (Toby) Rose** and **Denis J. Pogson** published the Bega 1:250,000 Geological Sheet which was the first detailed compilation of the geology of the Monaro. Prior to this many local studies had been completed but never synthesised.

C. Herbert (1968) reported again on the Cooma diatomite. He concluded the diatomite was associated with fluvial sediments deposited on the surface of glacial outwash plains during the decline of the last Kosciusko glaciation. He also reported the deposit was laminated throughout with laminae about 0.5 mm thick and that the sequence was deposited over about 10,000 to 4,000 years.

The Period 1970 Onwards

Renewed interest in silcrete during the late 1960's to early 70's resulted in a symposium at the University of Sydney convened by Professor Trevor Langford-Smith. At about the same time **W.R. Browne** (1972) published his paper on "greybilly" which included a number of Monaro sites. Because the silcrete (greybilly) generally occurs as sub-basaltic sheets and lenses its origin had been the subject of debate for some time. Ideas ranged from magmatic fluid origins for the cementing solutions (**Williamson**, 1957; **Browne**, 1972: **Langford-Smith**, 1978) through release of silica from basalt weathering (**Ollier**, 1978; **Lambert**, 1963) to intraformational origins (**Taylor** and **Smith**, 1975). Browne (1972) summarised the Monaro silcrete (greybilly) occurrences and in his discussion and conclusions made some interesting observation, some of which have had major geological implications both on the Monaro and outside it. Most importantly he reinforced the concept of "the vanished basalt": He wrote:

"It is considered that the alterations - both silicification and leaching - have been effected by solutions emanating from the basalt, and that where the basalt has been entirely removed by erosion, the existence of any alterations indicates its former presence. Thus the greybilly association may be important in regard to palaeogeography."

This view persisted for some time both on the Monaro and across Australia where authors took the view that the presence of silcrete indicated the former presence of basalt (e.g. Galloway and Gunn, 1978; Exon *et al.*, 1970). More importantly Browne (1972) made some inferences about landscape evolution on the Monaro based on his data on greybilly. These were:

"(1) The earlier Tertiary drainage-pattern was in many places very similar to that of the present day.

(2) The earlier Tertiary topography was gradually buried under basalt over a considerable time-interval to a depth of at least 1,200 feet above some of the valley floors.

(3) Later, possibly in early Pliocene times, prolonged erosion removed much of the basalt and to a large extent restored the landscape to its pre-basalt condition but left some evidences of its previous presence, particularly in the river valleys.

(4) Later again, but still in the Pliocene, erosion was succeeded by deposition in the exhumed valleys and the deposits were in turn somewhat dissected.

(5) The arterial rivers - Eucumbene, Snowy, Murrumbidgee and Umeralla - participated in these happenings, but subsequent erosion has removed the evidences more thoroughly than in the tributaries."

These findings are interesting given the earlier apparent influence Browne had on the interpretation of the landscape evolution suggested by Craft (1933) and McRoberts (1948). Except for the chronology of events, his conclusions are very similar to those of the present, even if for reasons not in accord with present thinking. It must be remembered that his work was all done prior to isotopic dating.

One of the most significant events which helped in our understanding of the Cainozoic and particularly Tertiary geology of eastern Australia was the dating of the basaltic rocks using radiometric techniques. **Peter Wellman** and **Ian McDougall** (1974) were the first to publish a series of dates from the major eastern Australian basalt provinces using the K/Ar dating technique. Included in their dates were nine from the Monaro proper and nine from the adjacent Snowy Province, including one from Kiandra. Some of their dates are summarised in Table 2.

Table 2. K/Ar dates from Wellman and McDougall (1974). The dates are as published and not corrected for presently accepted decay constants.

Altitude & Locality	**Age (Ma)**	**2 s.d.**
Snowy Province		
2 km NW Kiandra	21.5	0.6
8 km NNE Kiandra	20.4	0.6
5 km N Cabramurra	21.7	0.4
Monaro Province		
1300 m, 9 km SE Eucumbene	36.0	0.9
970 m, 5 km E Toll Bar	38.8	1.0
1230m, Hudsons Peak	39.5	1.0
1230m, Hudsons Peak	37.2	1.0
	38.5	1.0
	40.2	1.6
1190m, Hudsons Peak	45.1	0.8
1040 m, 20 km SW	46.8	1.2
Hudsons Peak	46.7	1.2
820 m, SSW Hudsons Peak	47.4	1.2
	50.0	1.2
900 m, 11 km NNE Hudsons Peak	53.1	1.2
905 m, 10 km NNE	52.7	0.9
Hudsons Peak	54.4	1.0

Of the Monaro Province they concluded that there may be a relatively young plug at Hudsons Peak, and that within the Province there were three periods of volcanism; about 53 Ma, 49-45 Ma and 39-36 Ma. Wellman and McDougall used their data to reinterpret some of the earlier tectonic dating estimates and to comment on landscape evolution. They estimated the age of uplift of the Eastern Highlands as mid-Cretaceous to Late Oligocene with another lesser uplift after the mid-Miocene to the present. To do this they used the relationships between dated basaltic flows and the topography.

Sue Kesson (1973) published a paper on the petrogenesis of the Monaro volcanics in which she identified the bulk of the Monaro Province volcanics as basanites, basalts, olivine nephelinites and phonolites with minor teschenite. She concluded, on the basis of geochemical data, that they originated as partial melts from a heterogeneous mantle source.

Graham Taylor and **Ian E. Smith** (1975) in response to the idea of the "vanished basalt", based on the premise that the silcrete was somehow chemically and genetically related to the basalt, re-examined some of Browne's (1972) silcrete sites. The Symposium 'Silcrete in Australia' held in 1973 at The University of Sydney was also a major impetus to Taylor and Smith, as many of the authors adhered to concepts which they could not agree with. In their detailed geochemical and petrographic study of three Monaro silcrete sites, they concluded there was no evidence, chemical or morphological to genetically connect silcrete with basalt, and they explained the apparent field association of the two by suggesting the silcretes significantly post-dated the basalt and that the basalt simply capped quartzose deep-lead aquifers in which cementation occurred by intraformational silica mobility.

In 1977 **Allan J.R. White, Ian S. Williams** and **Bruce, W. Chappell** published a 1:100,000 geology map and explanatory notes for the Berridale area. The major contribution of this work was to the understanding of granite geochemistry and petrogenesis. They also summarised the Tertiary geology as it was known, but made few new or significant contributions in this area or to knowledge of landscape evolution.

Bradley J. Pillans (1977) working 2 km south of Bredbo palaeomagnetically dated a truncated deep-weathering profile as Palaeocene-Eocene, but because of the low number of samples Pillans generalised the date to early Tertiary.

In 1979, **Peter Wellman** threw the whole question of the uplift of the Eastern Highlands into question again when he suggested the Highlands began uplifting about 90 Ma ago and that they have been doing so at a constant rate since about 45 Ma ago. While this is not the place to review the history of perceptions about the Highland uplift, the uplift history does impact significantly on the Cainozoic geology of the Monaro, and this study more than any other rekindled this debate, not only about uplift, mechanisms and processes, but also about the interpretation of the geomorphic processes used to interpret uplift and landscape evolution in general in this area.

The diatomite deposits of Middle Flat were briefly described and their ecology discussed again by **D. P. Thomas** and **R.E. Gould** in two papers in 1980.

Cliff Ollier (1982) finally debunked the concept of the Kosciusko Uplift, although not using data from the Monaro. The implications for understanding the Cainozoic geology of the region were none-the-less very significant. Also in 1982 Ollier showed the eastern boundary to the Monaro, part of what he called the "Great Escarpment", was a major and ancient feature in the landscapes of eastern Australia. He dated the escarpment formation as around 50 Ma.

The same year **Phil W. Schmidt, Graham Taylor** and **Pat H. Walker** showed the weathering profile previously dated by Pillans (1977), as well as another near Middle Flat, to be Late rather than Early Tertiary. They palaeomagnetically dated ironstones overlain by late Tertiary lacustrine sediments deposited along the Murrumbidgee and its tributaries upstream of Bredbo.

Also in 1982 **Jim R. Tulip, Graham Taylor** and **Elizabeth M. Truswell** published a paper on the palynology of these lake deposits. They clearly showed the deposits to be Miocene (12-21 Ma) as well as showing the flora to be *Nothofagus* dominated with significant podocarpaceous pollen and lesser amounts of myrtaceous pollen and rare proteaceous pollen. The also showed the region was lacking the indicative subtropical rainforest elements found elsewhere at the time and indicated cooler and perhaps drier conditions on the Monaro than in surrounding areas during the Miocene.

1986 saw the compilation of some earlier data and results from new work on the lake sediments along the Murrumbidgee corridor by **Graham Taylor** and **Pat H. Walker**. This was published in two papers on Lake Bunyan. Lake Bunyan was shown to be an extensive and long lived Miocene lake in which a variety of facies were deposited including diatomite (*cf.* Card and Dun 1897, Browne 1914, Kenny 1924, Skvortzov 1937, Herbert 1968) and coal. The lake was open for most of its history and was dammed by movement on the Murrumbidgee Fault near Bredbo. The discovery of the lake, and the damming at its northern end reopened the question of drainage evolution on the Monaro calling into question the hypotheses of Taylor (1910) and Süssmilch (1909). **Graham Taylor** and **students** published the results of this drainage study in 1985. They essentially concluded there had been little change since the eruption of the basalts except for minor warping and faulting in some places.

Small lake basins on basaltic rocks are a major landscape feature of much of the Monaro. They are generally restricted to the higher regions and have been the subject of considerable speculation but no definitive studies. **Bradley J. Pillans** and **Pat H. Walker** (1987) showed these lakes have, at least a partially deflational origin and are associated with prominent down-wind lunettes and/or thin clay shadows.

Apart from the work of those who studied the glacial and periglacial features of the Monaro and adjacent high-country there has been little detailed work on the Quaternary deposits of the Monaro except for the seminal work of Costin (1954). During 1988 **Angela C. Davis** (1989) began a study of the Quaternary deposits and their contained fauna, along Pilot Creek. These deposits had been discovered by a University of Canberra student (**Chris Foudoulis**) in 1982 during the study of sub-basaltic topography, published by Taylor *et al.* in 1985. Work on these Quaternary deposits culminated in the publication of a paper by **W. David L. Ride, Graham Taylor, Pat H. Walker** and **Angela C. Davis** in 1990. They described in detail the Quaternary stratigraphy of two fossil-bearing sites on Pilot and Cooma Creeks.

In 1988 **Cliff Ollier** and **DennisTaylor** reported their ideas on the origins of the Monaro Province basalts and proposed that Brown Mountain formed the centre of a large shield volcano from which lava flows and drainage radiate. They went on to argue that the eastern half of the volcano has been eroded by retreat of the Great Escarpment and concluded that the escarpment must therefore post-date the basalts (i.e. <55 Ma). From this they concluded that uplift of the area must also post-date the basalts. **Graham Taylor, Ken McQueen** and **Max C. Brown** discussed this paper in 1989 and questioned the validity of some of the basic assumptions. They presented evidence to indicate that the basaltic province had formed as an irregular lava field rather than a circular, central shield volcano. They discussed other features of the pre-basaltic topography, also documented in later publications (see Table 3).

The Lake Bunyan study led to several other more detailed studies on ultra-fine-grained clay (**Pat H. Walker, Graham Taylor** and **Richard A. Eggleton,** 1989) and diatomites (**Graham Taylor, Francoise Gasse, Pat H. Walker** and **Peter J. Morgan**, 1990).

During 1985 the **University of Canberra** made the geological mapping of the Bombala 1:100,000 Sheet a departmental project and over the ensuing five years staff and students worked to complete the task. Members of the New South Wales Geological Survey, including **Winston Pratt** and **Peter Lewis** also had some input into this major project. During the project a number of separate but related studies were completed, many on features of the Cainozoic geology. These are summarised in Table 3.

The mapping work of the University of Canberra has been included in the new Bega 1:250,000 Geological Sheet. The 1:100 000 Bombala geological map and accompanying notes are currently in draft form and are to be published soon.

Table 3: List of published work related directly to the University of Canberra Bombala Mapping Project.

Author/s	**Brief Title/Subject**	**Date**	**Publication**
McQueen *et al.*	Cambalong regional metamorphic complex.	1985	Proc. Linn. Soc. NSW
Brown *et al.*	Early Tertiary volcanism.	1988	Geol. Soc. Aust. Abs
McQueen	Quidong area & mineralisation.	1989	Mineralium Deposita
Taylor *et al.*	Discussion of Ollier & Taylor's Brown Mt. volcano notion.	1989	BMR J. Aust. Geol. Geophys.
McQueen *et al.*	Teaching, research and regional geological mapping.	1990	J. Geol. Educ.
Taylor *et al.*	Early Tertiary palaeogeography, landform evolution and palaeoclimates on the southern Monaro.	1990	Palaeogeography. Palaeoclimatology. Palaeoecology.
McQueen *et al.*	Field training and geological mapping.	1991	Geol. Soc. Aust. Abs
Roach *et al.*	Petrology and geochemistry of volcanic plugs.	1992	Geol. Soc. Aust. Abs
Brown *et al.*	Core through the Monaro basalts.	1992	AJES
Taylor *et al.*	Cool climate bauxite formation.	1992	J. Geol.
Pratt *et al.*	Monaro Volcanics.	1993	Quat. Notes Geol. Surv. NSW.
Roach *et al.*	Petrology and geochemistry of the Monaro Volcanic Province.	1993	IAVCEI Abs.
Brown *et al.*	Excursion guide and notes for Monaro Volcanic Province.	1993	AGSO Rec.
McQueen *et al.*	Lake and hyaloclastite deposits of the Monaro.	1993	IAVCEI Abs.
Taylor	Excursion guide for clays and lateritic bauxite of the Monaro.	1993	10th Int. Clay Min. Assoc. Conf.
Roach *et al.*	Tertiary basaltic eruption sites.	1994	AGSO J. Aust. Geol. Geophys.

Summary and Observations

Geological interest in the Monaro region dates from the mid-nineteenth century and the impetus for this interest was, like in so many other areas, gold.

The above brief summary of research on the Monaro follows a pattern which I suspect is very common. Many of the early workers recorded detailed observations on the nature and distribution of the rocks and other earth materials, and when they interpreted them, they did so, obviously, in the light of contemporary knowledge.

It never ceases to amaze me how much some of these early investigators saw and noted, and of the very early ones, how often their interpretations were similar to present ones. It is also not surprising that many of the interpretations of the geology and particularly the landscape evolution, made from observations on the Monaro, as elsewhere in Australia, were based on theories developed in the Northern Hemisphere. As it has turned out, many of these have been wrong, mainly because of fundamental differences in the age of landscapes in Europe and North America. These imported theories have blinkered Australian geologists for too long. It is only over the last 20 years that we have begun to see that northern ideas do not fit here. There are a few visionaries, Frank Craft, for example who were ahead of their time, but presumably, because their ideas did not fit contemporary thinking their ideas were not seen for what they were.

We must all therefore argue full-steam for our ideas, maintain our iconoclasm, and when faced with defeat accept the more plausible explanation if our science is to progress more rapidly than it has in the past.

It is interesting to look at this history, or probably that of any other region, and examine the parallels between scientific progress, individual personalities, and the reluctance on the part of many to step outside the conventional contemporary bounds of methods and thinking. An understanding of this is becoming increasingly important as the National resource base depletes and as our profession begins moving increasingly into newer areas of community concern (e.g. environmental problems, land management, sustainable agriculture).

Let us learn from the past and keep our minds open, our research careful, and look for new opportunities to apply our special knowledge for the good of our community and country.

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The Morphotectonic Setting of the Monaro Region

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Argument continues between exponents of change and supporters of continuity in the linked topics of highland uplift and drainage pattern evolution in south eastern Australia. In favour of continuity, careful fieldwork in several areas has shown that major changes either have not taken place, or occurred much earlier than previously thought (e.g. Bishop, 1986; 1988; Young, 1983). As an advocate of change and evolutionary geomorphology, I believe that major changes have occurred, but on a long time scale. Landscape formation is on the same time scale as plate tectonics and the formation of continental margins. Physiographic evidence must be supported by data from the sedimentary basins flanking the highlands, and consideration of the nature of the continental margin, especially the break-up unconformity.

The Monaro region consists of an ancient plain, a palaeoplain, commonly known as the Monaro Tableland. This is of great age, and Hills (1975) described it thus:
"After the disappearance of the Permian ice sheets, an extensive and stable land area continued to exist throughout Triassic and Jurassic time, and a widespread palaeoplain was developed which may conveniently be identified as the Trias-Jura palaeoplain."

At that time Australia was still part of the supercontinent, Gondwana. The approximate relationships of neighbouring masses are shown in Fig. 1. In the Jurassic, drainage of this greater landmass was generally towards the Eromanga-Surat Basin, which was later to be roughly the Great Artesian Basin. Other basins such as the Murray, Otway and Gippsland Basins had not yet been created. In southeast Australia the ancient drainage was essentially from the south and south east (Fig. 2), and the major rivers flowed to the southernmost lobe of the Surat Basin, the Coonamble embayment.

Then a series of rifts isolated the Australian mainland. The breakup probably started like a rift valley, and the rifts grew wider and gave way to seafloor spreading. The actual faults are now mainly offshore. The palaeoplain was downwarped beneath sea level to form the breakup unconformity, where younger marine sediments overlie the tectonically complex Palaeozoic rocks (Fig. 3). The downwarp to the sea was matched by uplift along a warp axis inland, which created a new divide and disrupted older drainage. On the inland side the rivers are beheaded, while on the coastal side rivers are reversed, and the pattern still shows in some major rivers (Fig. 4). A complication in southern New South Wales is that some of the old drainage ran sub-parallel to the Tectonic axis, giving river reversals, river captures or tilt overflows a rather complicated pattern (Fig. 5).

The first basin to be formed was the Otway-Gippsland Basin, and the associated east-west Victorian Divide. Rivers such as the Cann and Genoa which originally flowed north to the palaeo-Murrumbidgee and then to the Surat Basin were reversed to their present southerly course. The Gippsland Basin has Lower Cretaceous sediments (Strzelecki Group), mainly non-marine sediments derived from volcanoes (now lost) to the east. Sediment was not derived from the north, suggesting it was still low-lying. Then in the Lower Cretaceous the volcanogenic sediments are replaced by quartz-rich sediments (Latrobe Group) suggesting that a deeply weathered continental area had been uplifted. Marine sedimentation became dominant only in the Cainozoic.

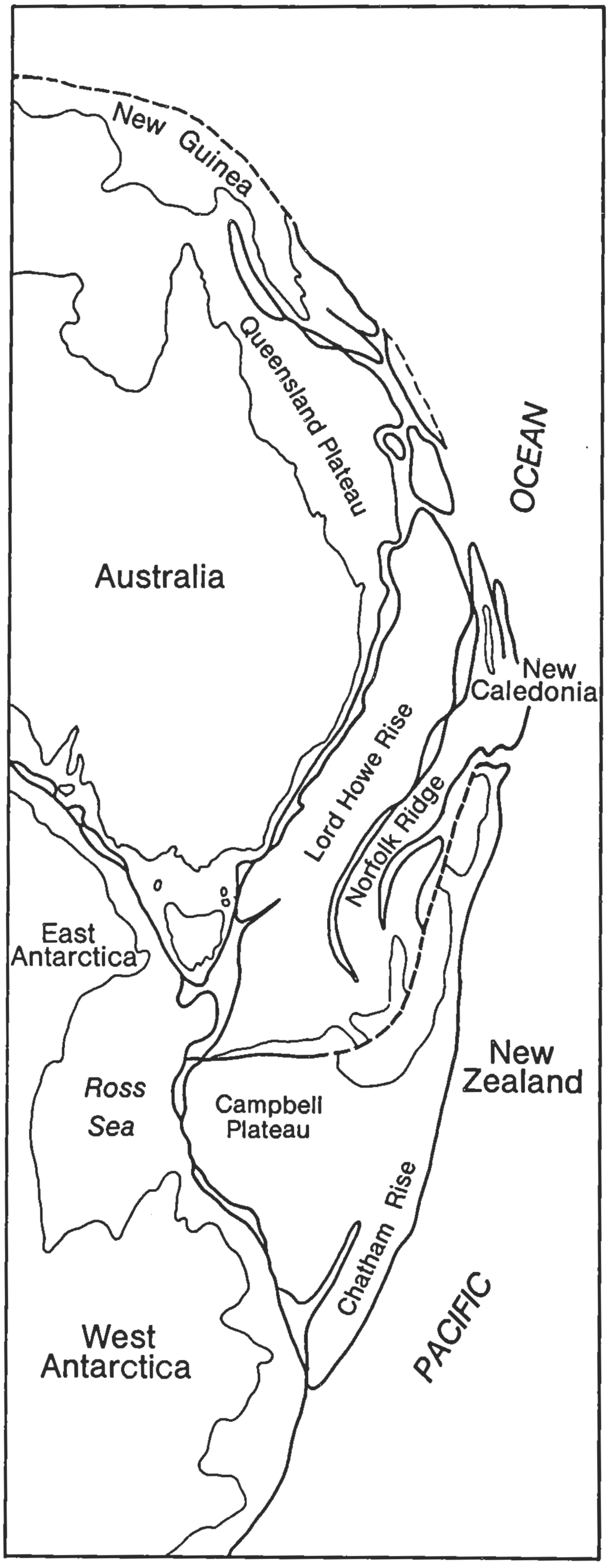

Fig. 1. The position of southeast Australia before the breakup of Gondwana (after Griffiths, 1971).

Next came the opening of the Tasman Sea, the formation of the Great Divide of New South Wales running NNE, and the downwarp of the palaeoplain off the New South Wales coast. Sedimentation has been described by Davies (1975). Major rivers such as the Clarence, Hunter, and Shoalhaven, were reversed on the eastern side of the Great Divide.

The formation of the uplifted divides close to the tectonically subsided coasts is typical of passive margins in many parts of the world. Some general geomorphic aspects are presented by Ollier (1985), and some geophysical speculations about them is in a special section of the Journal of Geophysical Research, vol. 99, of June 10, 1994. The continental margins are attacked by erosion, especially on the seaward facing side, creating large escarpments known as Great Escarpments. In New South Wales there is a single Great Escarpment in most places (Ollier, 1982a), but the older Victorian Divide has been attacked from both north and south for a longer time, and is reduced to a series of High Plains such as the Dargo High Plain.

The Monaro Tableland is bounded by steep escarpments that are the southernmost part of the New South Wales Great Escarpment. It runs for a while as a south-facing escarpment (Fig. 6), but gives way to the east to the Victorian High Plains.

The two major axes - the Victorian Divide and the Great Divide - intersect in the Monaro area, which is therefore a place of major morphotectonic significance in Australia. Lester King noted this intersection of axes, and pointed out that it was similar to the intersection of the Natal monocline and the Cape Province monocline intersect at Compassberg, the highest point in Cape Province, and also by the intersection of the East Brazil monocline and the Paraiba monocline at Pico da Bandiera, the highest mountain in Brazil. Of course the highest mountain in Australia, Mt Kosckiusko, is close to the intersection of the two main axes of uplift in Australia, but the Monaro Tableland is somewhat to the east.

Volcanoes follow both axes of uplift in a general way (Fig. 7), and near the intersection of the two volcanic trends lies a large patch of basalt. Ollier and Taylor (1988) called this the Monaro Volcano, centred on Brown mountain. They later suggested that it was a complex volcano with many eruption points like Mt Etna of today (Ollier and Taylor, 1989). The original mass was sufficiently symmetrical to develop radial drainage. Others regard the volcanic pile as a volcanic complex or lava field (e.g. Wellman and McDougall, 1974; Taylor *et al.*, 1989).

In a fairly late stage of landscape evolution there was a phase of major faulting (Fig. 8), and the block south of the Long Plain Fault was uplifted by up to a kilometre and tilted to the southeast. The movement may have been as young as 20 million years ago, and it is possibly this movement that gave rise to the myth of the Plio-Pleistocene Kosciusko Uplift. The faulting must be at a very high angle to account for their straightness over many kilometres, but when studied in detail they turn out to be low angle reverse faults. The reverse faults may be gravity release faults after high uplift (Ollier and Wyborn, 1989). Ollier and Taylor (1988) have suggested that reversal of rivers associated with this faulting and tilting may account for the strange courses of the rivers in the region, including the hook at the start of the Murrumbidgee River.

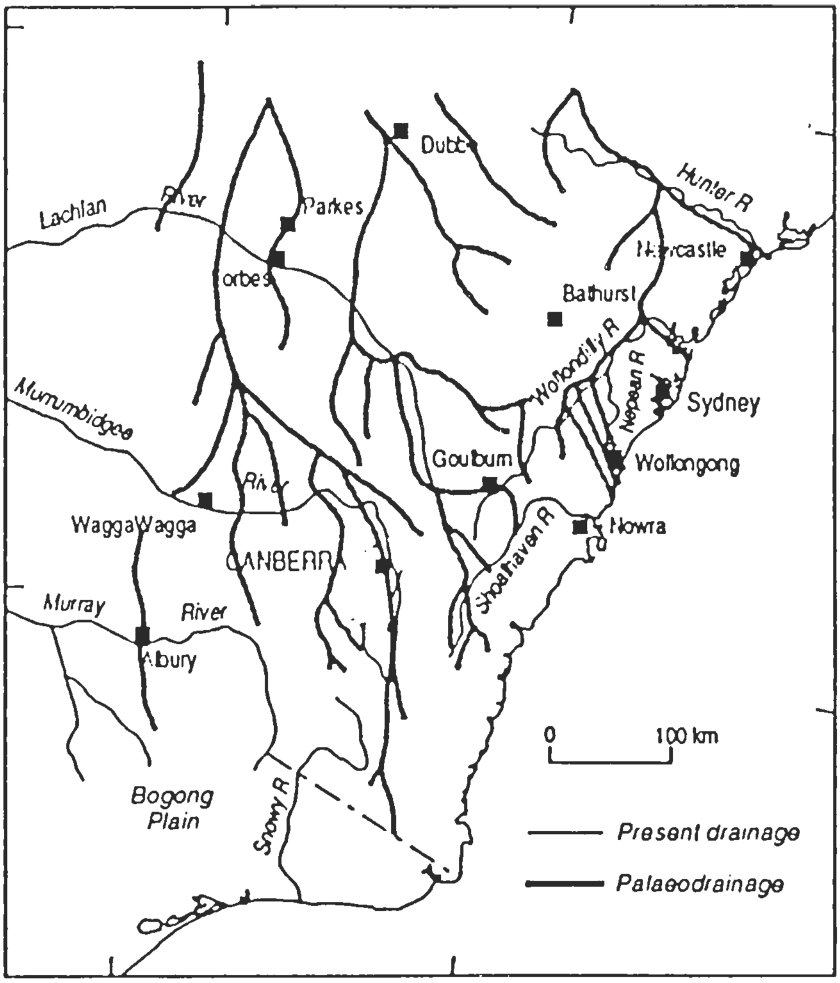

Fig. 2. Palaeodrainage in southeast Australia. There is no simple "palaeodrainage" awaiting discovery, for it evolved over a long time, and the diagram shows some former connections that may not represent an exact point in time.

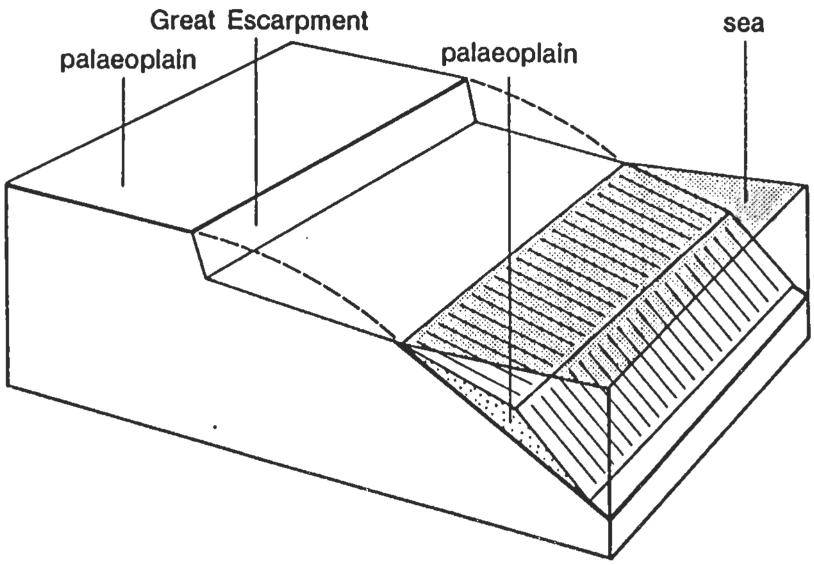

Fig. 3. The downwarp of the palaeoplain to form the breakup unconformity. Erosion on land creates the Great Escarpment, and deposition offshore builds a sediment wedge above the breakup unconformity.

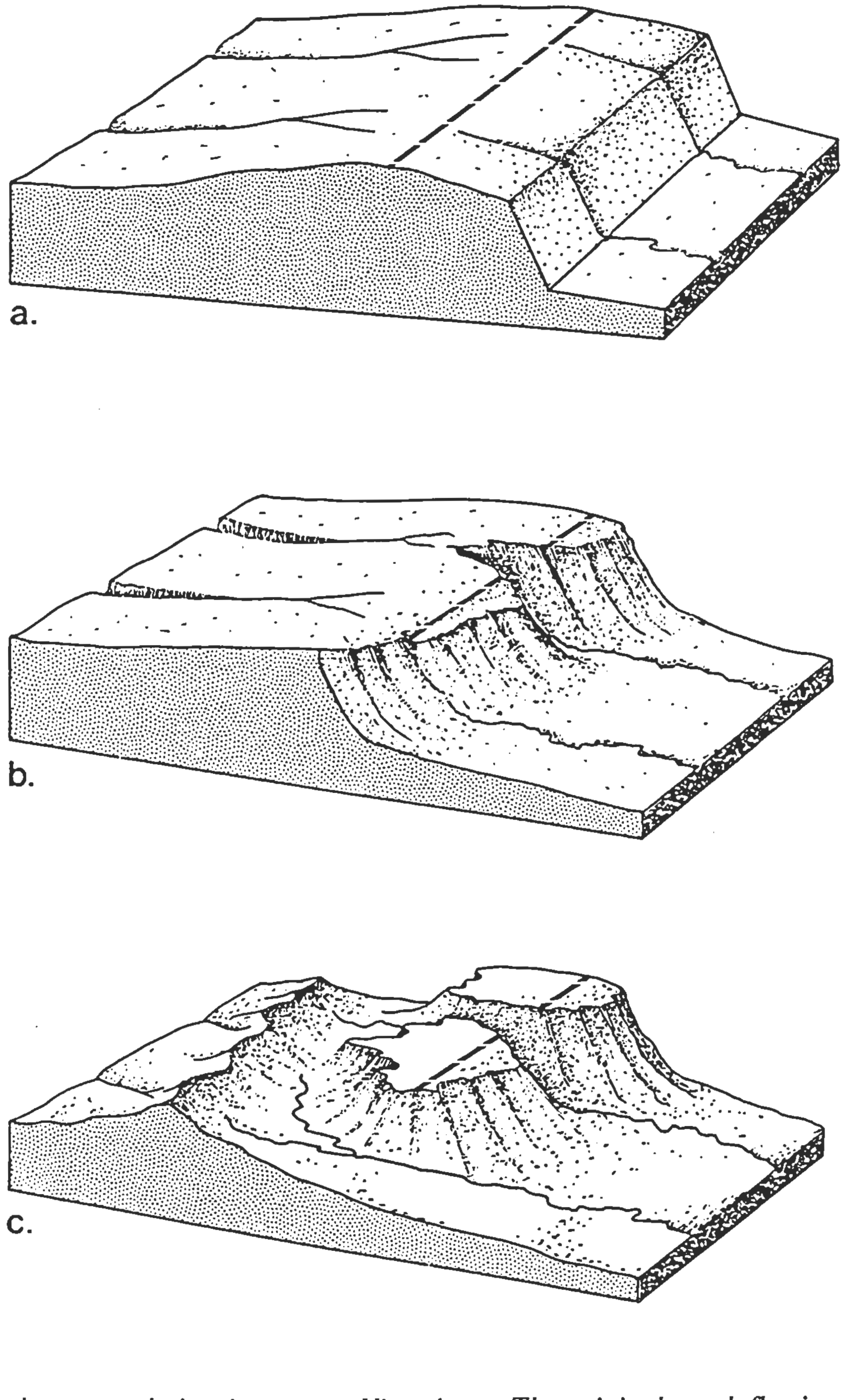

Fig. 4. Landscape evolution in eastern Victoria. a. The original north-flowing rivers have been affected by a warp, with reversal of rivers on the south. Rivers on the steeper, southern side have cut back faster than those to the north. b. a hypothetical stage of development. c. Intersection of valleys forms the Great Divide, which is north of the highest land - the High Plains. The dashed line shows the original axis of upwarp, which no longer corresponds to the Great Divide.

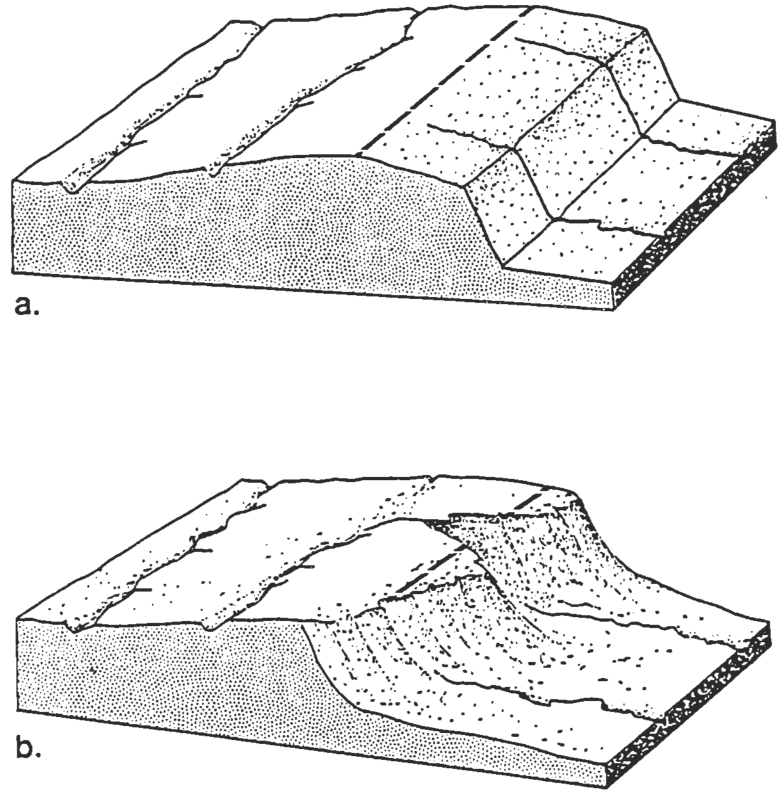

Fig. 5. Retreat of the Great Escarpment in southern New South Wales. The structural grain is roughly parallel to the coast and the escarpment, and north flowing rivers may be captured or diverted to the coast.

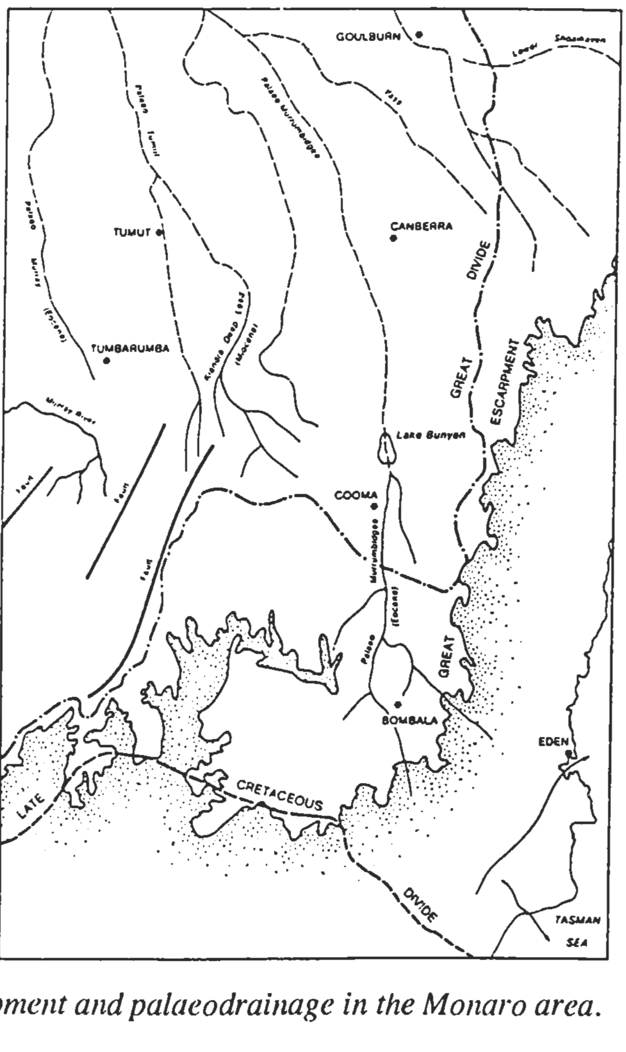

Fig. 6. The Great Escarpment and palaeodrainage in the Monaro area.

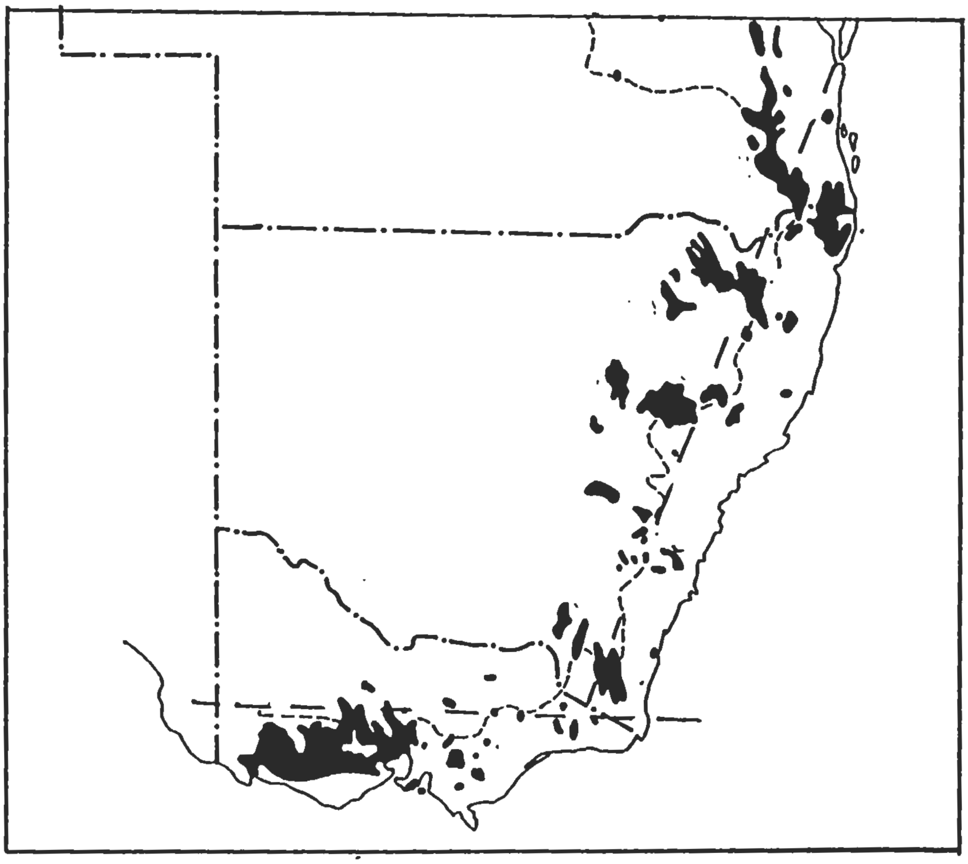

Fig. 7. The Victoria Divide axis and the Great Divide axis (long dash lines), the present position of the Great Divide (short dash lines) and volcanic areas (black).

The regolith of the region is of interest in several quite different ways. The formation of bauxite on early volcanics would be considered normal - like the formation of bauxites in the Tertiary Volcanics of Antrim, Ireland - and fits in with the general idea of world-wide warm and wet climates at the time (Walker and Sloan, 1992). The only complication is that the palaeobotany suggests a cool climate (Taylor, this volume). But the weathering of the basement is of Mesozoic origin, It is particularly significant that the granite, which partly underlies the Monaro Volcano, is of the very weatherable Bega type, which is often eroded into hollows (Kubiniok, 1988). Any former extent of the volcano to the east would have been underlain by rotten, easily eroded granite. Sapping of the granite after uplift of the Great Divide would lead to rapid retreat of the Great Escarpment, and the Monaro Volcano would have been eroded much like the better documented Ebor Volcano in northern New South Wales, where the old volcano was eroded where it lay over soft phyllite, but was preserved on hard rock. The gap between volcanic rocks and the Great Escarpment today suggests more rapid retreat of the volcanic than of the hard basement, a situation that has been described previously from the Barrington Tops region of New South Wales.

Ollier and Taylor (1988) describe an area of radial drainage that covers the Monaro volcanic region and an area to the east, and suggest the latter was superimposed on the sub-volcanic bedrock, just as in the better studied Ebor Volcano (Ollier, 1982b).

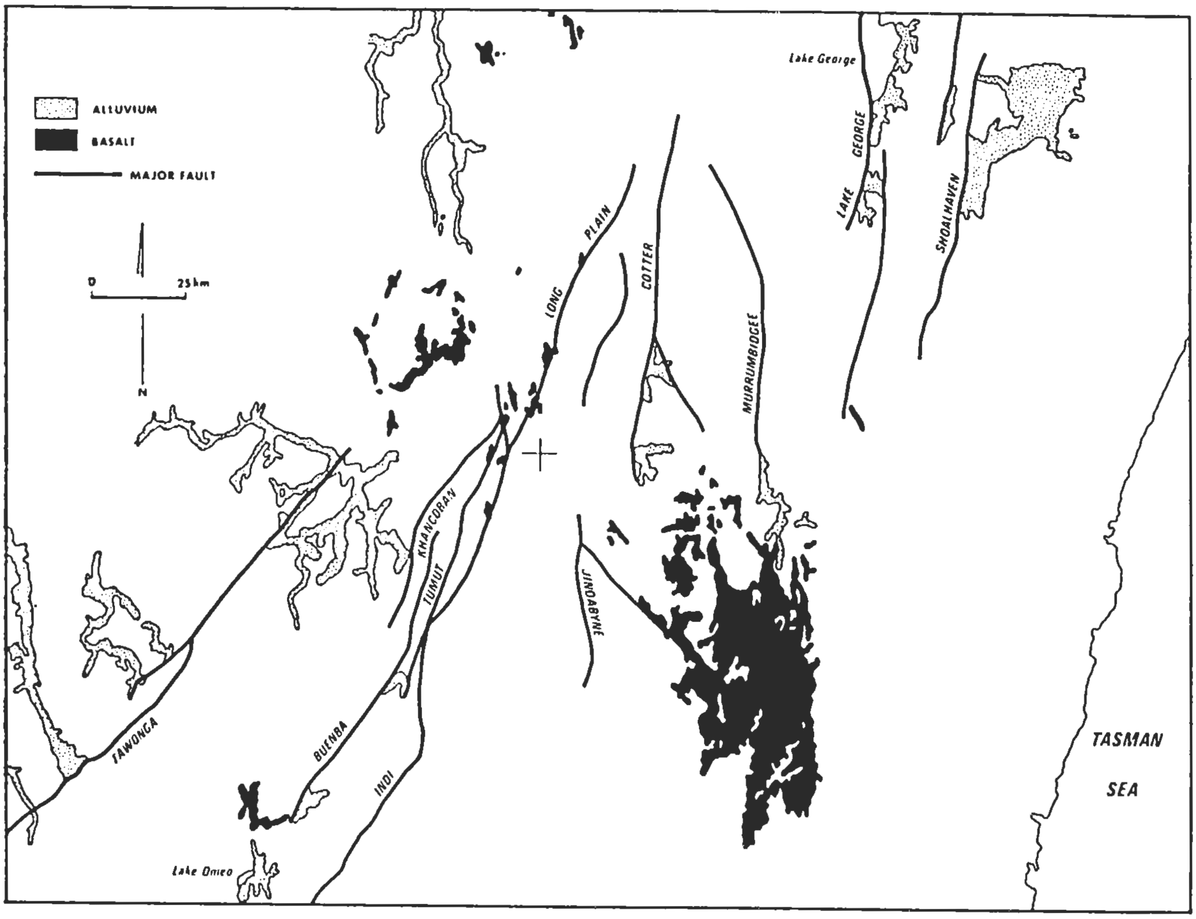

Fig. 8. Faults of the Australian alpine area. The large black patch is the Monaro basalt (after Ollier and Wyborn, 1989).

In summary, the Monaro Volcanic area is a very significant area, at the intersection of the two major tectonic axes (of different age), at the southern limit of the Great Escarpment of eastern Australia and the western limit of the High Plains of eastern Victoria, and in an area modified by late Tertiary block faulting. It is also a region where regolith formation, erosion, and Tertiary sedimentation can all be related, and it offers a great natural laboratory for future studies.

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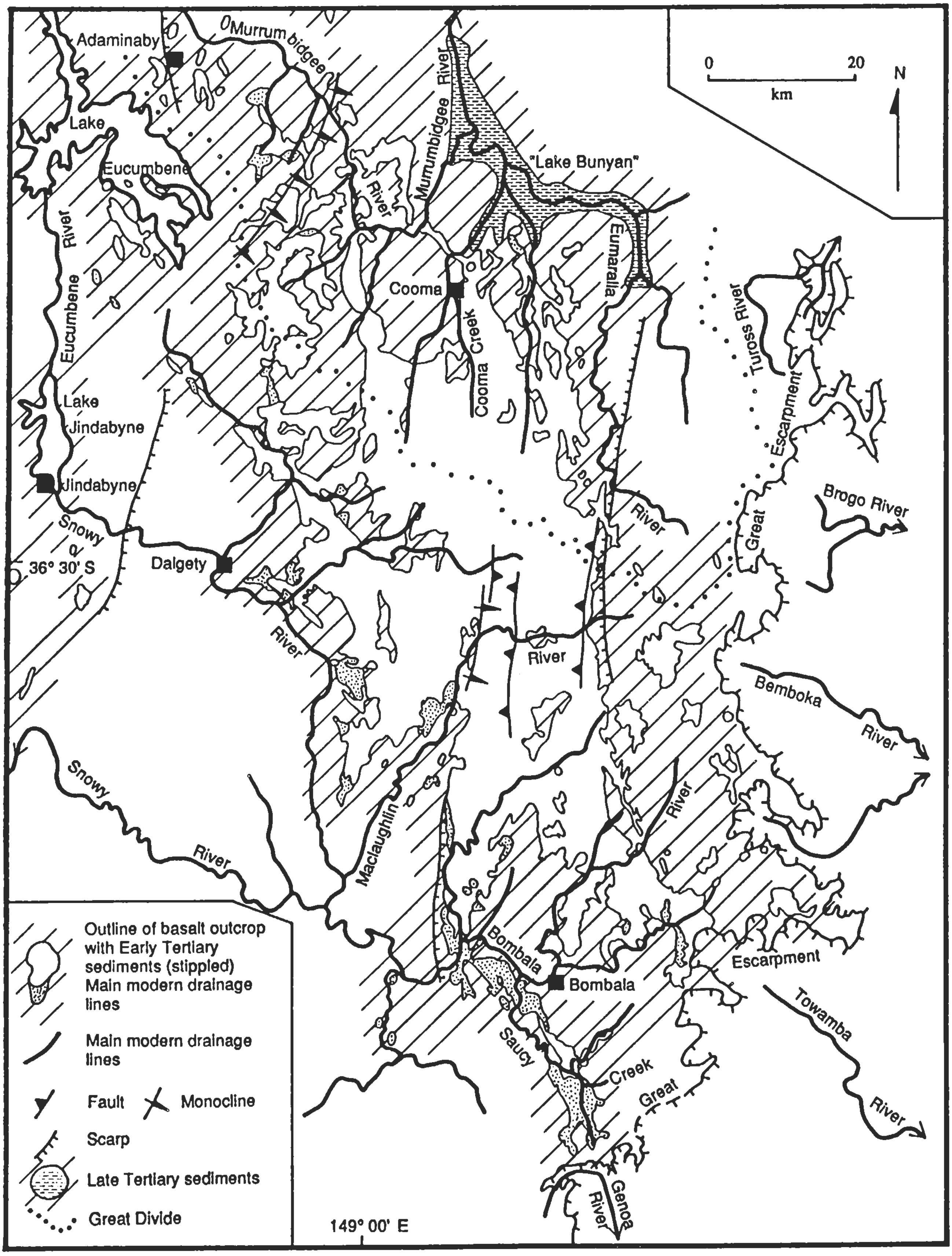

Fig. 1. Main features of the present topography and Tertiary geology of the Monaro Volcanic Province.

An Interpretation of Tertiary Landform Evolution in the area of the Monaro Volcanic Province

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University of Canberra

An old land surface was covered by mafic lavas and interbedded sediments of the Monaro Volcanic Province during the Late Palaeocene and Eocene. The lavas covered an area of at least 4200 km^2 with a thickness up to perhaps 500 m. The lavas and sediments are mostly less resistant to erosion than the underlying, mainly Palaeozoic, bedrock, and parts of the old land surface have been exhumed. Particularly around the margins of the basalt outcrop, much of the pre-basalt drainage network can be reconstructed, in places in considerable detail. Former valleys are now represented by long narrow outcrops or lines of outliers of basalt and old alluvial sediments, with bedrock outcrop higher than their base on either side.

The sub-basalt drainage network was largely controlled by the relative ease of erosion of the bedrock. North-south treading valleys were controlled by the general north-south grain of the folded bedrock, while others developed along NW-SE and NE-SW fractures. Quartz-rich sandstones, hornfelses, and felsic granitoids formed interfluves. There were also some significant fault scarps in the landscape, the most prominent being a 200 m high west-facing scarp immediately to the east of Nimmitabel and Tom Groggin Creek. Many of the valleys were deeply incised, with higher stream gradients than modern streams on the Monaro. Erosional relief was at least 400 m in places.

My interpretation of the overall drainage pattern is that the pre-basalt drainage of much of the region fed into a major river draining to the south-east along a prominent lineament (the Towamba Lineament) now occupied by the Towamba River. This "Palaeo-Towamba" network included the present SSE flowing tract of the Snowy River near Dalgety and the present generally SE tract of the Murrumbidgee River between Adaminaby and Bridle Creek near Cooma. In the north-east around Rock Flat Creek, drainage was to the north, as at present; and in the south-west drainage was towards the north-west into the present north-west tract of the Snowy River.

Build-up of the pile of lavas, probably from vents close to the present Great Divide, progressively blocked southern western, and north-western tributaries of the "Palaeo-Towamba" drainage. Substantial lakes formed in the old valleys and there were major drainage diversions. The upper Murrumbidgee was diverted eastward to join the north-flowing drainage and the Dalgety tract of the Snowy was diverted southward around the margin of the lavas to join its present north-west tract. Some of the sub-basalt valleys appear to record successive stages of drainage diversion.

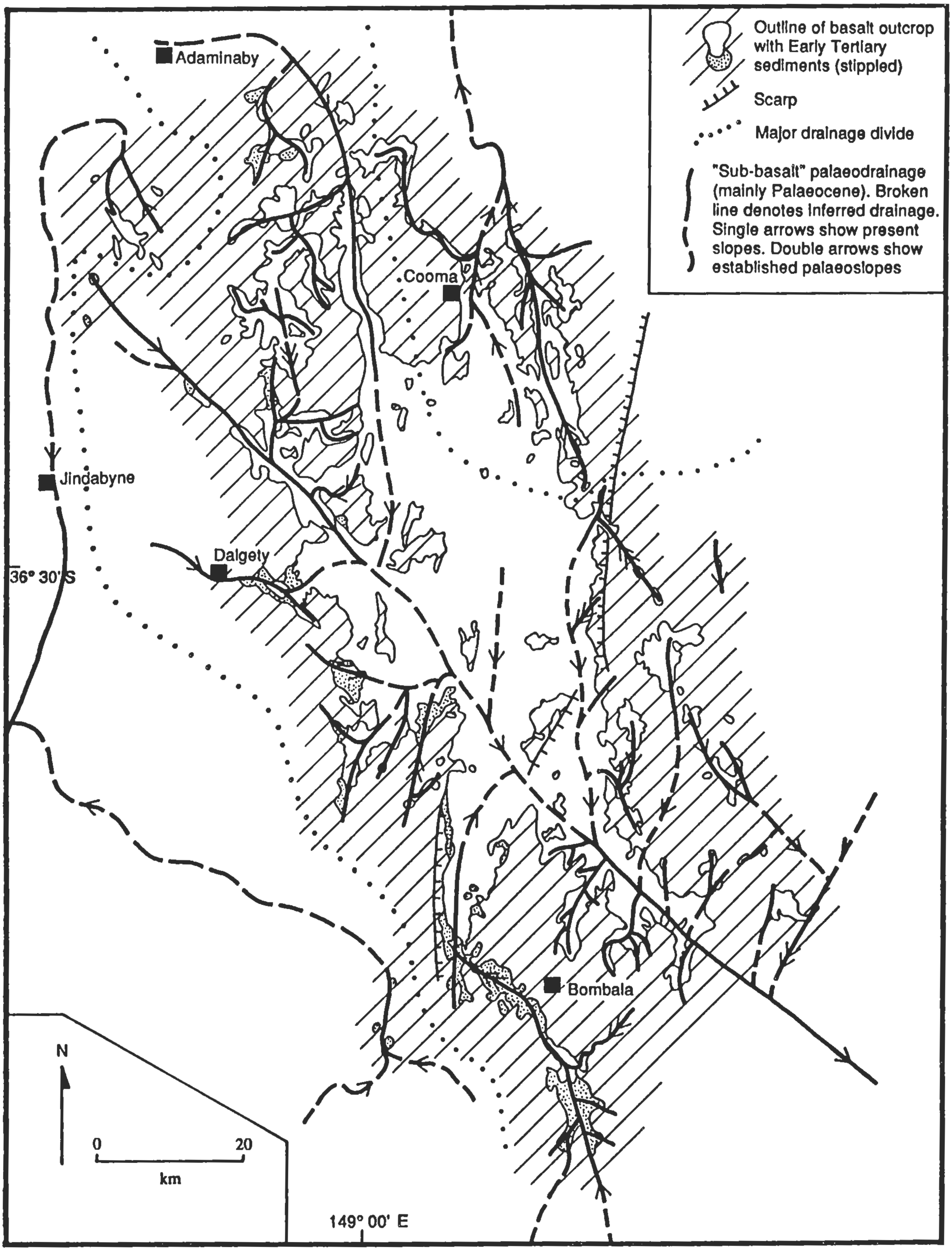

Fig. 2. The sub-basalt palaeodrainage (mainly Palaeocene) and its relationship to present outcrop of early Tertiary basalt and sediments.

The volcanic rocks have been gently warped, with dips mostly less than 2° (and difficult to distinguish from initial dips), but with some steeper dips up to 7° along some well-defined monoclines. There are also locally some folds in basalt with steeper dips up to near-vertical, which appear to be related to loading of dense basalt flows on unconsolidated clay-rich sediments. The lavas and sediments have also been displaced by N-S and NW-SE faults, some of which are reactivated older basement faults. This deformation must mostly post-date the basalts, as it involves all the basalt in the preserved sequence.

The modern drainage, within the present area of the volcanic rocks, is on a broad scale directed away from a concentration of volcanic rocks along the present Great Divide, and appears to have been controlled by a late build-up of the volcanic pile in that area. Some drainage lines appear to be controlled by post-basalt structures. Some follow fractures in the basalt and some flow down plunge along the axis of gentle down-warps. Some of the major drainage lines are, however, clearly antecedent. The MacLaughlin River, flowing west across the basalt, cuts through an east-facing monocline with about 80 m of displacement near Boco. The southerly flowing tract of the Murrumbidgee River upstream from Bridle Creek is deeply-incised into a NE-SW upwarp.

Apart from a long tongue of basalt which must have extended a long way down the Towamba River valley before being removed by westward retreat of the "Great Escarpment", the lavas of the Monaro Volcanic Province are unlikely to have extended much further than their present outcrop. Around much of the present margin of the basalt outcrop there are steams in bedrock valleys parallel to the basalt margin which appear to be lateral streams. These include the Numeralla River, Coolumbooka River, parts of Saucy Creek and the lower Bombala River, and the south-flowing tract of the Snowy downstream from Dalgety. Between the Numeralla River and the Great Escarpment, 20 km to the east, there is about 600 km^2 of country with low relief in which only three very small outliers of basalt have been mapped. It is unlikely that any significant part of the Province formerly extended eastward into this area, as has previously been suggested.

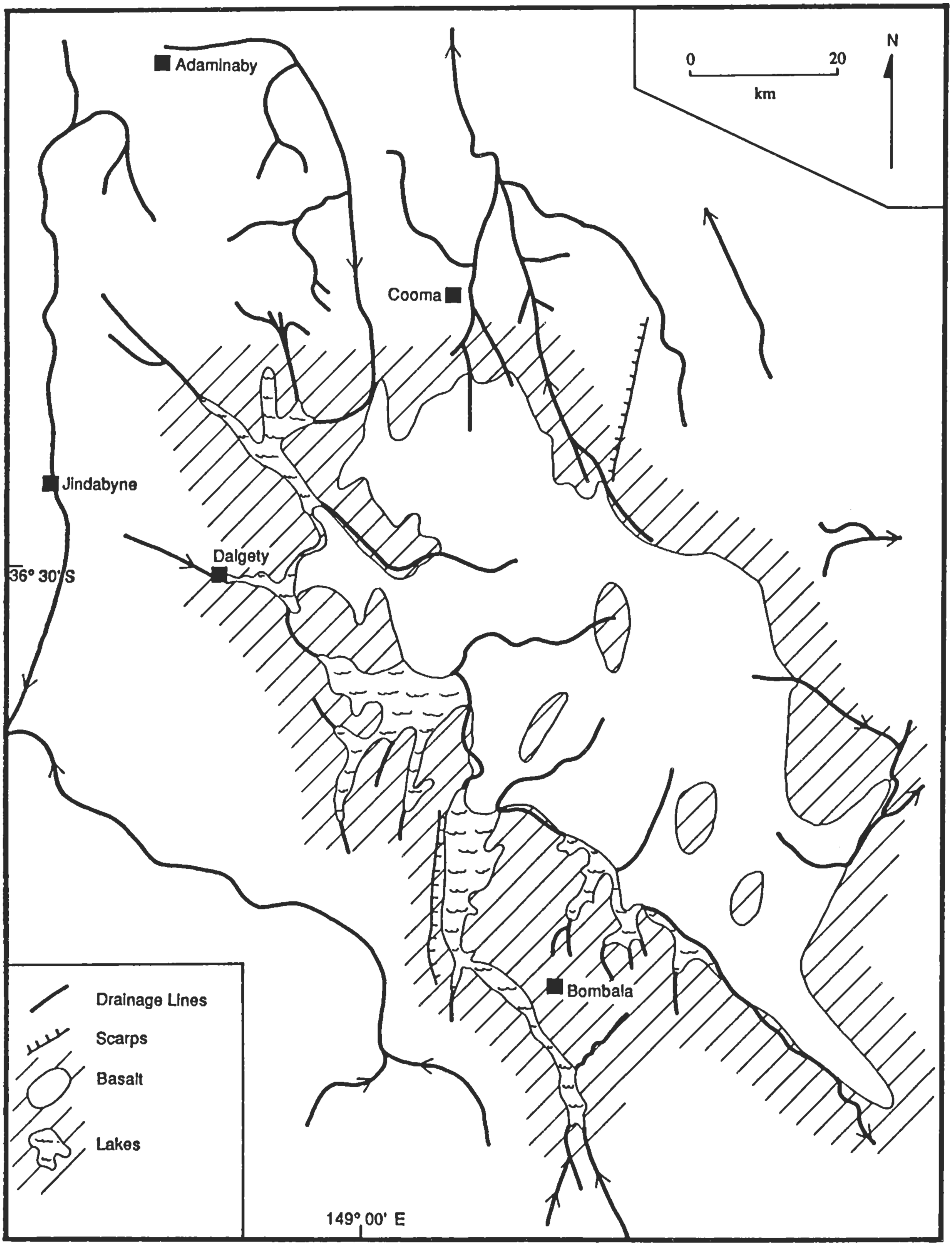

Fig. 3. Interpretation of the drainage pattern at an early stage in the volcanism in the Monaro Volcanic Province (ca. 50 Ma).

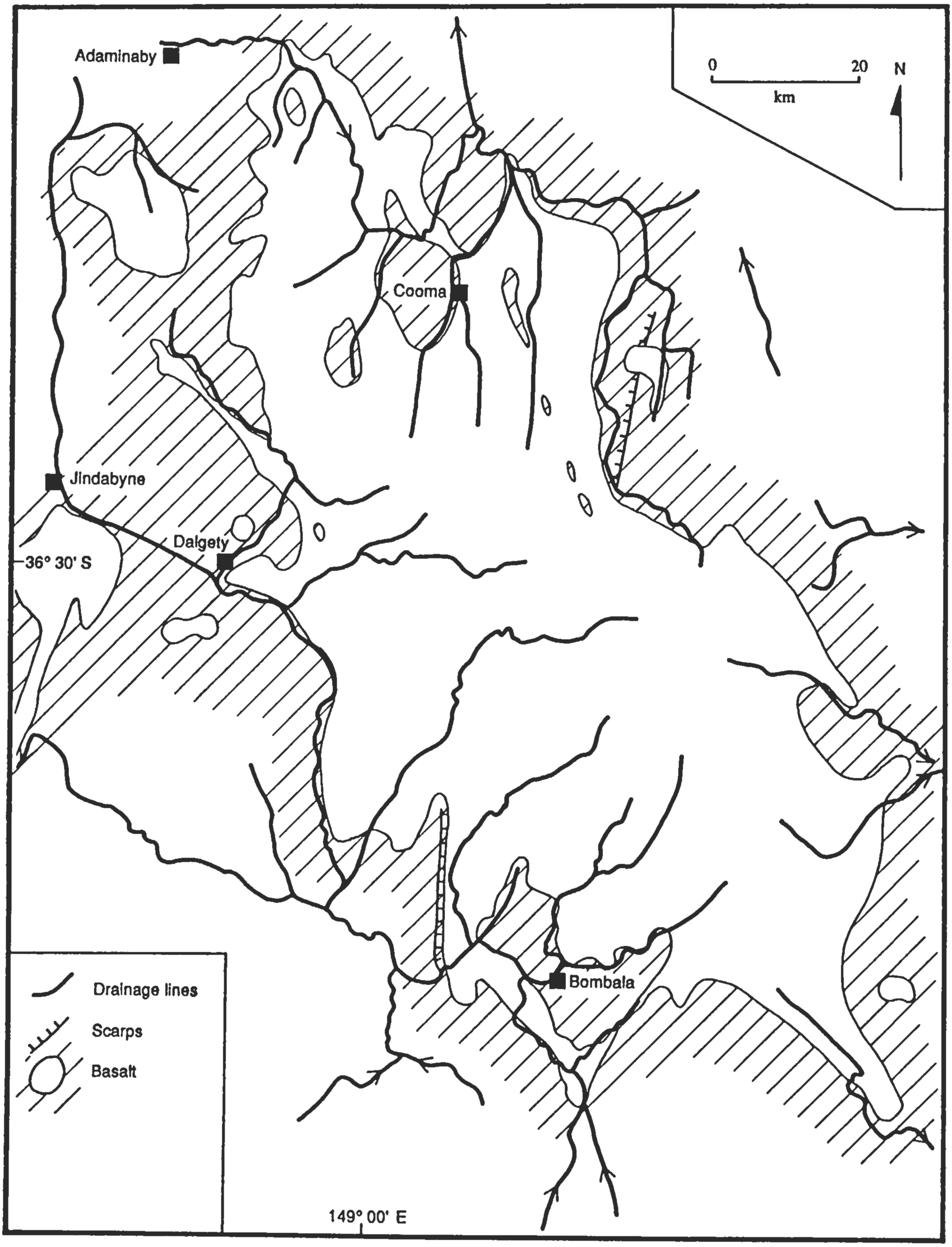

Fig. 4. Interpretation of the drainage pattern at the cessation of volcanism in the Monaro Volcanic Province (ca. 35 Ma). The volcanic rocks south of Jindabyne have not been dated and hence the major drainage diversion at Jindabyne may have occurred earlier or later than shown here.

Geochemistry, Petrology and Structural Control of Eruption Centres in the Monaro Volcanic Province

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The Monaro Volcanic Province is an intraplate volcanic province of lava field style with similarities to the Newer Volcanic Province of Victoria and the Southern Highlands Province of New South Wales. Lavas were issued from at least 65 separate eruption centres (Fig. 1) from a period after 57.5 Ma (Taylor *et al.*, 1990) to about 34.0 Ma (Wellman and McDougall, 1974). At present the Province covers an area of over 4200 km^2 but is estimated to have contained over 630 km^3 of mafic lava and pyroclastic rocks and covered a much larger area during its active period.

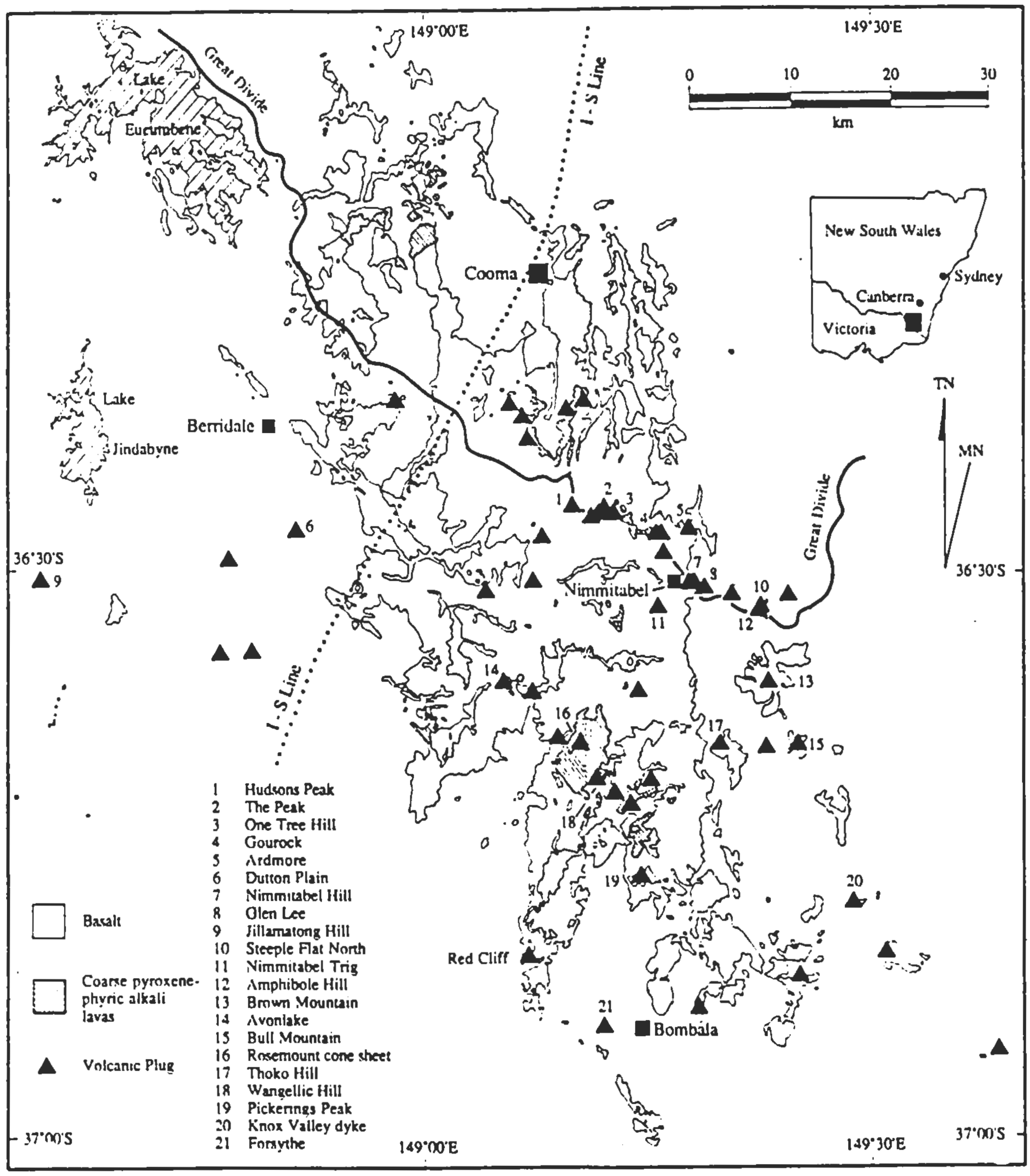

Fig. 1. General map of the Monaro Volcanic Province showing the positions of known volcanic plugs and outcrops of coarse pyroxene-phyric alkali lavas including the Bondo Dolerite (Pratt et al., 1993) which outcrops north of Hudsons Peak. The basalt

outline is from 1:100,000 geological sheet compilations and includes the mapping of the coarse pyroxene-phyric alkali lavas in the NW of the Province by K.R. Sharp.

The volcanic pile consists dominantly of Ne- and Hy-normative lavas including alkali olivine basalt, Ne-basanite and transitional basalt with minor Ol-nephelinite, Ne-hawaiite and Ol-tholeiite (Fig. 2). Ol-nephelinite and Ne-basanite lavas are more prevalent near the top of the pile. At least four flows of a coarse (titanian augite) pyroxene-rich Ne-normative alkali lava (including the Bondo Dolerite) also occur in the lava pile (Fig. 1, 2, 3).

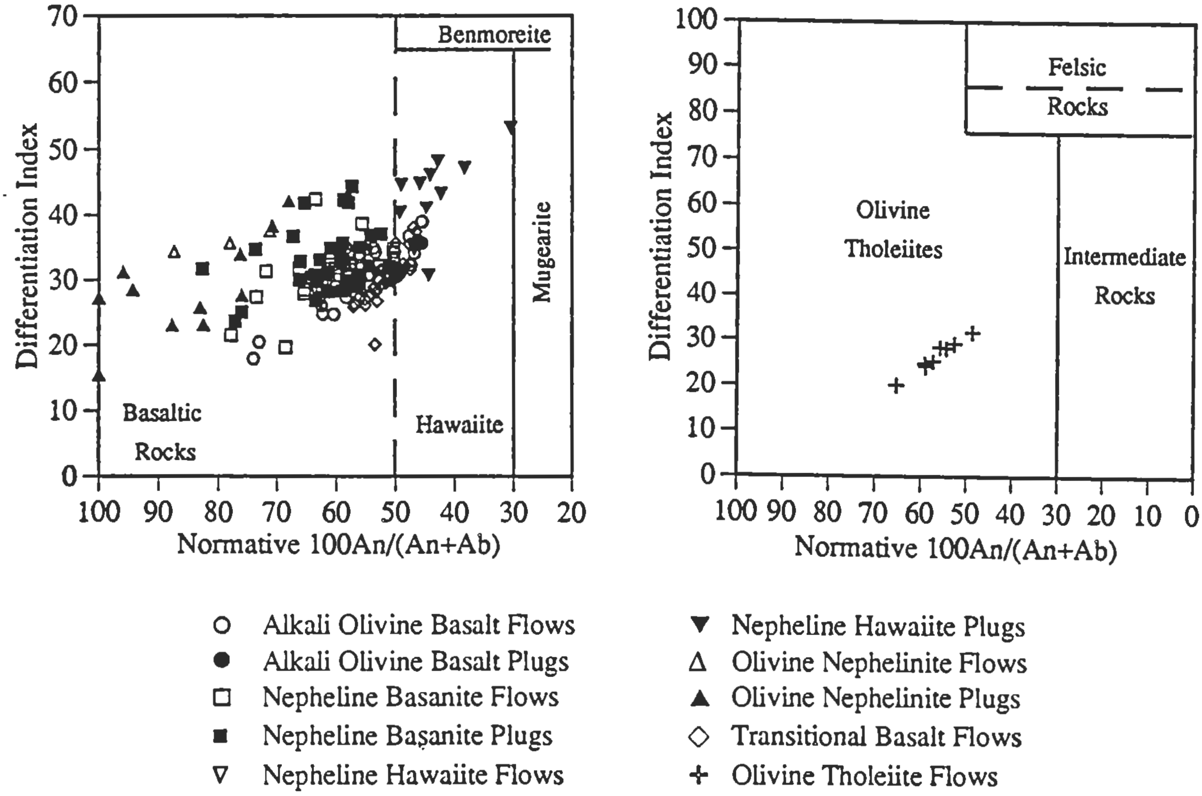

Fig. 2. Normative Anorthite versus Differentiation Index (DI) classification of 165 volcanic rocks from the Monaro Volcanic Province using the method of Johnson and Duggan (1989). CIPW norms were calculated by normalising the major oxides (without LOI) to 100% loss free and recalculating $Fe^{3+}/Fe^{2+} = 0.2$. *DI = Q + Or + Ab + Lc + Ks. Data include those of Kesson (1973).*

Volcanism appears to have commenced with a period of phreato-magmatic activity creating maars in water-logged areas and small cinder cone volcanoes in drier parts. Evidence of maar formation is rare but a partially preserved base surge deposit at Red Cliff (Fig. 1) is covered by later alkali basaltic lavas (Brown *et al.*, 1993). Lavas filled the already well-established valleys and dammed rivers and creeks (Taylor *et al.*, 1990), interbedding with Tertiary sediments and creating lakes in which later transitional, alkali basaltic and basanitic eruptions formed hyaloclastite deposits (Brown *et al.*, 1993). Volcanism progressed sporadically and weathering profiles and bauxite horizons developed on many of the lava flows indicate local cessations of considerable time (Brown *et al.*, 1992). Given the large area of the Province, volcanism probably continued in one part of the Province whilst weathering was occurring in other areas. Later lavas have become more silica-undersaturated, resulting in a prevalence of nephelinitic and basanitic lavas at the top of the lava pile, most of which have been removed by subsequent erosion. An estimated 100-200 m of material has been removed from some parts of the lava pile by erosion.Eruption sites in the Province are represented by plugs, dykes and a cone-sheet at Rosemount (Fig. 1). Volcanic plugs comprise primary to fractionated rocks including 29 Ne-basanites, 11 Ol-nephelinites, 9 Ne-hawaiites and 6 alkali olivine basalts (Fig. 2). Fractionated plug rocks include feldspar-rich Ol-nephelinite, Ne-basanite and alkali olivine basalt and titanian augite-rich Ne-basanite cumulates. The majority of plug rocks consist of aphanitic to fine-grained Ne-basanite and Ol-nephelinite and contain mantle and crustal xenoliths and/or kaersutite amphibole megacrysts. A small number of possible lava lakes have been discovered. These consist of medium- to coarse-grained titanian augite-rich basanite (Bull Mountain, Fig. 1) and medium-grained alkali basalt (Thoko Hill, Fig. 1) and presumably occupy the remains of maars or large eruption craters.

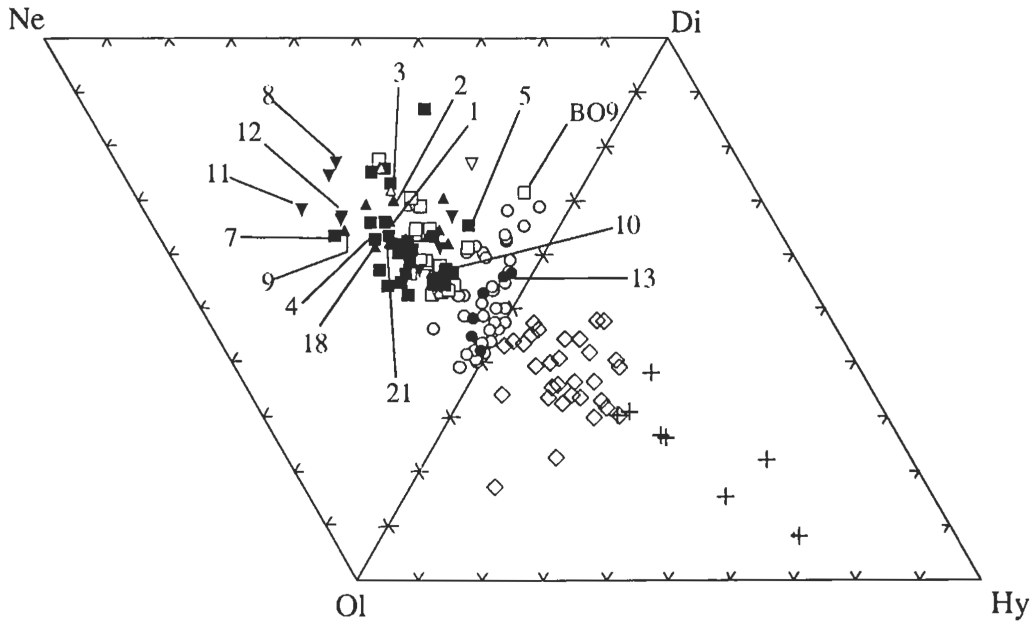

Fig. 3. Triangular plot of normative nepheline, diopside, olivine and hypersthene relationships of 165 samples from the Monaro Volcanic Province calculated using the method of Johnson and Duggan (1989). Data include those of Kesson (1973). Symbols follow the same scheme as in Fig. 2. Numbered symbols refer to locations in Fig. 1. Sample BO9 is of the coarse pyroxene-phyric alkali lava from Mount Cooper, about 3 km NE of Wangellic Hill (Fig. 1).

Mantle xenoliths contained within the volcanic plugs and dykes are mostly spinel-bearing members of the Cr-diopside suite including lherzolite, harzburgite, wehrlite and rare dunite. A small number of amphibole-bearing lherzolite xenoliths have been noted with amphibole (Ti-pargasite) in textural equilibrium with the original phases (Roach, 1991). A small number of phlogopite- and clinopyroxene-veined mantle xenoliths have also been noted (Edgecombe, 1992). Mantle xenoliths from the Monaro Volcanic Province do not exhibit strong foliation or other tectonic fabrics and are not as heavily veined as those described from the Newer Volcanic Province (O'Reilly *et al.*, 1989). Upper mantle/lower crustal xenoliths include two-pyroxene plagioclase granulites and crustal xenoliths include feldspathic quartzite, vein quartz and local granites. Thermobarometric studies of a limited number of spinel-bearing xenoliths by

Edgecombe (1992) indicate derivation from about 45-50 km. No garnet-bearing xenoliths have been located within the Province.

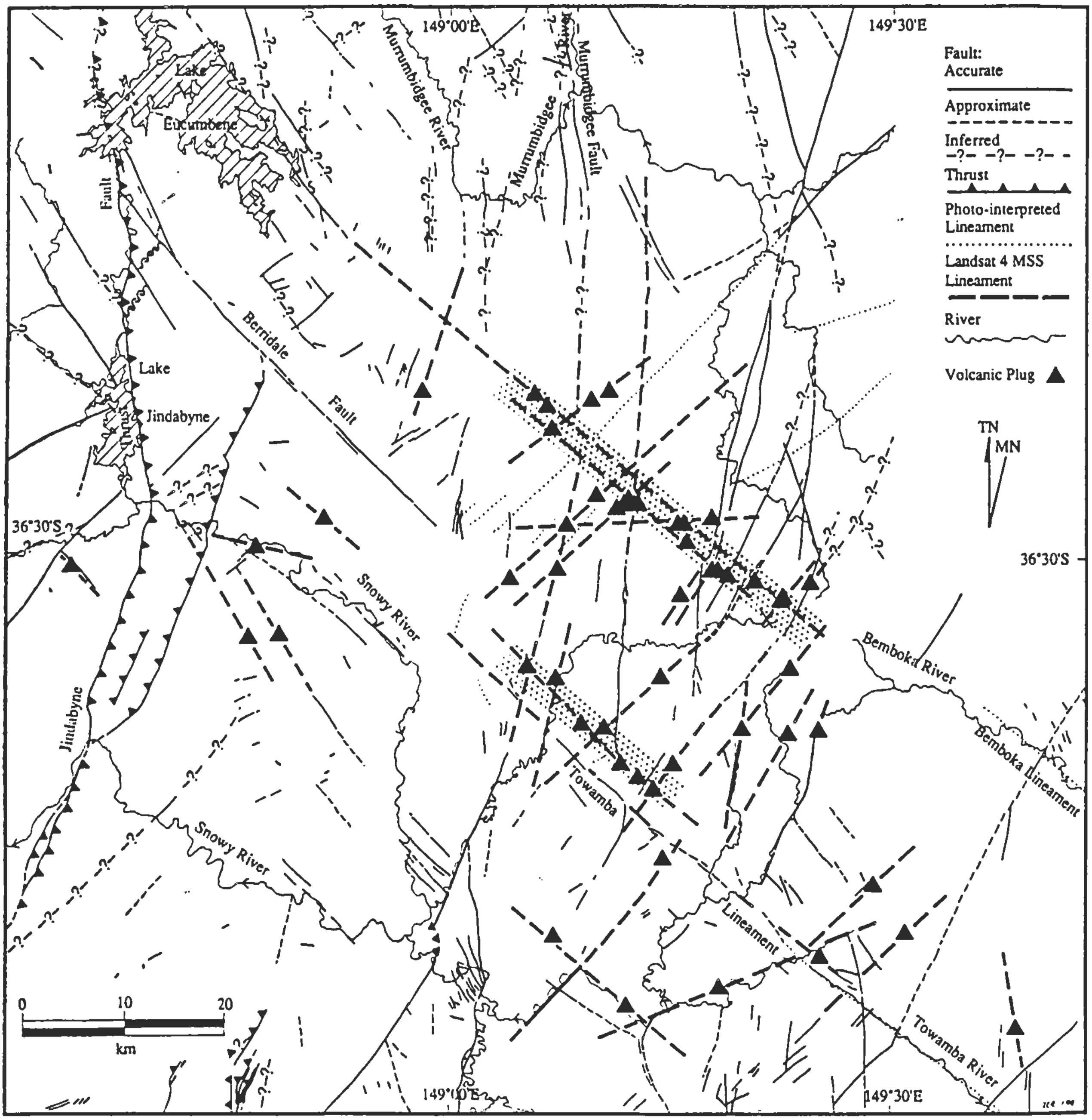

Fig. 4. Relationships between volcanic plugs, known fractures and Landsat 4 MSS lineaments. Known faults and the basalt outline are from 1:100,000 geology sheet compilations. Mapping of the coarse pyroxene-phyric alkali lavas in the NW of the Province is by K.R. Sharp.

The topographic expression of the volcanic plugs varies depending on rock type and the nature of the surrounding rocks. Plugs within the lava pile are generally elevated above the surrounding basalts. Aphanitic and fine-grained rocks tend to form rounded hills and medium- to coarse-grained plugs form conical hills or elevated, flat-topped deposits on the lava lakes. Plugs are not terraced, as are the surrounding hills which are composed of lava flows. Plugs lying outside the lava field form small rounded or conical stand-alone hills or small circular deposits resembling rock piles with very subdued topographic expression. Plugs range in size from about 10 m diameter to large rounded or conical peaks of over 500 m diameter. Dykes are normally over 10 m wide and over 50 m long, consisting of aphanitic to fine-grained rocks. The Rosemount cone sheet (Fig. 1) is composed of aphanitic Ne-basanite and is approximately 1 km diameter, dipping inwards at about 25° (Brown *et al.*, 1993).

Magmas appear to have been produced in the Low Velocity Zone, defined seismically at between 90 and 190 km beneath eastern Australia (S.Y. O'Reilly pers. comm.). Trace element analysis indicates magmas formed from an enriched garnet lherzolite source leaving garnet in the residue (Fig. 4). Partial melts appear to have been of about 25% percent initially (Frey *et al.*, 1977), indicated by the early dominance of alkali basaltic lavas although a number of partial melts of over 25% are indicated by the presence of transitional and rare Ol-tholeiite lavas. The heat source and amount of partial melting appears to have waned after some time, indicated by the later dominance of basanitic and nephelinitic lavas.

Magmas have been modified by the addition of trace elements from metasomatic volatile- and non volatile-bearing phases including amphibole, phlogopite and clinopyroxene, indicated by variations in Rb, Ba, K, Sr, P, Zr and Ti abundances. Metasomatism within the upper mantle and lower crust beneath the Province is indicated by the presence of texturally equilibrated Ti-pargasite and rare phlogopite and clinopyroxene veins in mantle xenoliths (Roach, 1991; Edgecombe, 1992). Overall enrichment by metasomatic phases is apparently less than in the Newer Volcanic Province, indicated by Sr isotope studies (O'Reilly and Griffin, 1984) and the relative scarcity of metasomatised mantle xenoliths.

Magmas crystallised olivine and clinopyroxene in equal amounts during ascent indicated by the Ni/MgO, Cr/MgO, V/MgO and Sc/MgO partial melting curves of Hart and Allègre (1980) and Ewart and Chappell (1989). The total amount of olivine and clinopyroxene which crystallised during ascent was not large as indicated by the relatively unfractionated nature of the Province as a whole (no trachytic, phonolitic or Q-normative rocks are known). The most serious fractionation appears to have occurred near the surface, either within volcanic plugs or within lava lakes, and the most fractionated rock within the Province is a Ne-hawaiite from Avonlake (Fig. 1, Fig. 3). Entrained mantle and crustal xenoliths and well-preserved amphibole megacrysts in many nephelinitic and basanitic plugs indicate that these magmas passed directly through the upper mantle and crust at extremely high velocities. However, some magmas appear to have been trapped in mid-level magma chambers where they crystallised titanian augite and fractionated feldspar (Wass, 1973). These magmas erupted as the thick, pyroxene crystal-rich flows such as the Bondo Dolerite.

Fractures in the Palaeozoic basement have had a major influence over the location of eruption sites. Volcanic plugs are concentrated along two NW-SE trending zones: the Bemboka Zone in the north; and the Berridale-Towamba Zone in the south (Fig. 4). The Bemboka Zone is a broad zone parallel with the Great Divide, ranging from near the western arm of Lake Eucumbene to the Bemboka River in the east, encompassing the majority of the volcanic plugs in the Province. The Berridale-Towamba Zone consists of 7 aligned volcanic plugs in the south of the Province on what is probably an offset segment of the Berridale Fault which appears to be offset by N-S striking fractures underneath the lava pile and may continue as the Towamba Lineament to the southeast. All of the other volcanic plugs lie between the two major axes or in the west and south of the Province on NE-SW and N-S trending lineaments and known fractures. Evidence of continued activity on many of the faults is seen as warping and offsets on basalt and Tertiary sediment deposits and recent seismic activity in the Snowy Mountains (Lambert and White, 1965). NE-SW opening (Pilger, 1982) during a period of crustal tension (or at least relaxation) during the Early to Middle Tertiary allowed magmas to ascend through the crust and promoted intraplate volcanism in eastern Australia as the Indo-Australian plate moved slowly northwards across sites of magma generation (Duncan and McDougall, 1989).

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The Evolution of the Cooma-Adaminaby area, Northern Monaro District of N.S.W., during the Cainozoic

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Introduction

The Monaro district is a tableland in the Highlands of Southeastern Australia, 100 km to 200 km south of Canberra. The study area lies at the northern end of the Monaro located mostly in the NE corner of the Berridale 1:100 000 geological map but extending onto the Cooma and Tantangara sheets.

A salient feature of the geology of the Monaro is the extensive cover of Cainozoic volcanic rocks. These are basaltic lavas known as the Monaro Volcanics, with ages ranging between 53 Ma and 36 Ma, with some associated sediments. Most of the sediments are minor stream deposits underlying the lavas but there are also lake deposits, where the sediments are more extensive and interbedded with the lavas. The author believes that these larger deposits are mainly, if not entirely, the result of tectonic ponding and not the result of damming by lava flows. This opinion is influenced by studies of similar Miocene deposits in the Kiandra-Cabramurra area (Gill and Sharp, 1957; Moye *et al.*, 1969; and unpublished data) which have cyclic sedimentation indicating three ponding events unrelated to lava flows. Sediments are considered to be valuable tectonic indicators with the inference that the thickness of sediments indicates the minimum displacement produced by a tectonic event whether that event be faulting and/or folding or warping.

The main sediment deposits associated with the Monaro Volcanics are near Bombala, 70 km south of Cooma, and near Adaminaby. The former have been studied by Taylor *et al.* (1990) including Lake Bungarby which has 150 m of sediments and is considered to be 58-60 Ma based on palynology. The sediments near Adaminaby have not been mapped in detail but this study has shown them to be much thicker and more extensive than shown on the Berridale sheet and also that they occur interbedded with the lavas.

Other features of the Adaminaby area (shown on Fig. 1) are the local presence of Miocene (18 Ma) basalt and sediments, not known elsewhere on the Monaro, also extensive deposits of gravel north of Adaminaby at Yaouk which are not associated with basalts.

The Upper Murrumbidgee River flows through the Cooma-Adaminaby area and over the decades there has been controversy about the evolution of this drainage system and in particular whether in pre-basalt time the Murrumbidgee was a tributary of the Snowy. Various versions of the Snowy tributary concept were put forward by Süssmilch (1909), Griffith Taylor (1910) and Browne (1914). However, Craft (1933) and Taylor *et al.* (1985) reject these concepts. Taylor's conclusion that "*...the Murrumbidgee River occupies the same valley as it did before the extrusion of the basalts...*" is not accepted by the author.

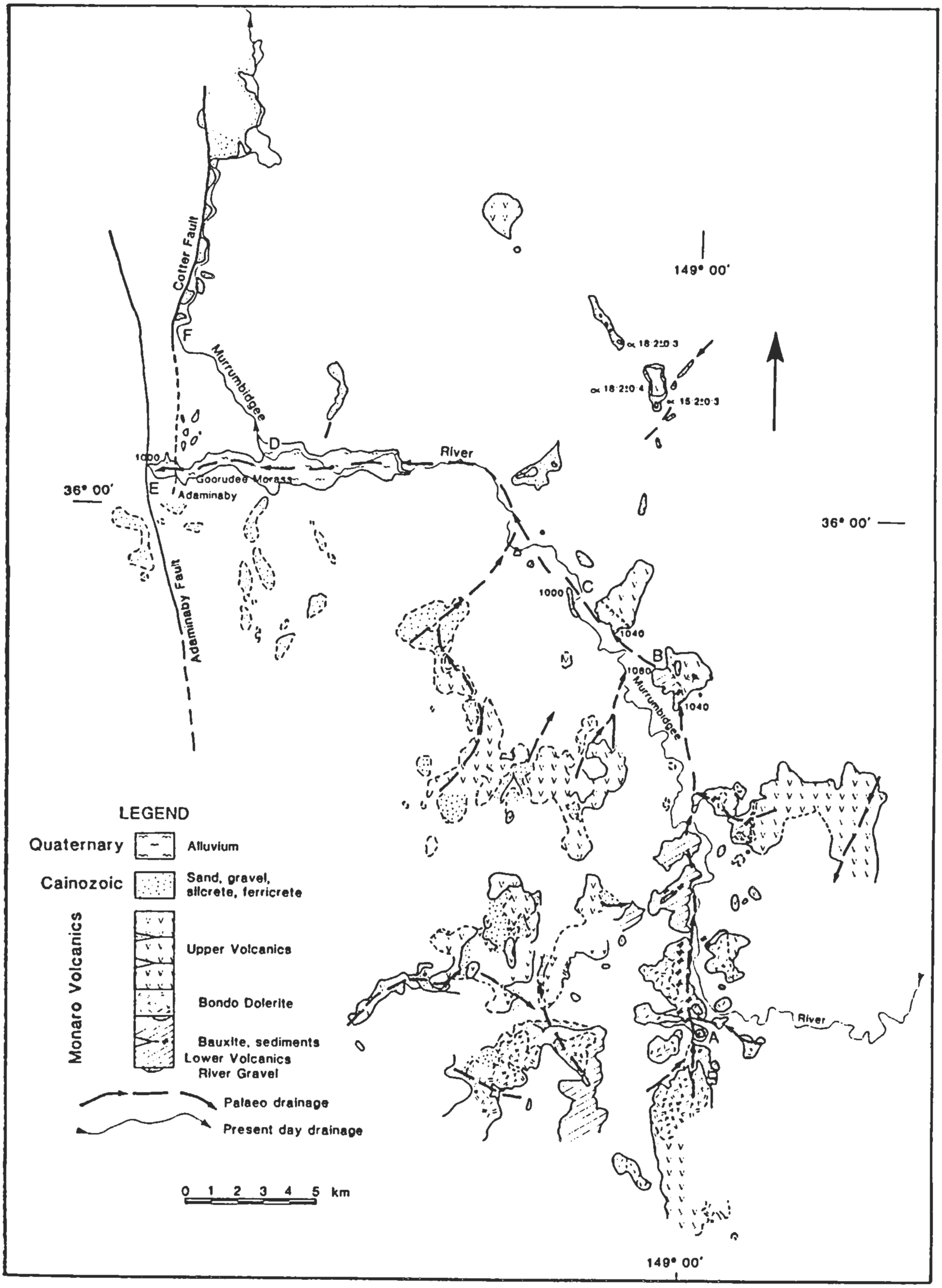

Fig. 1. Map of the Adaminaby-Cooma area showing the areas of outcrop of basalt, inter basalt bauxite horizons, Cainozoic sediments and associated silcretes. Also shown is the present drainage and the interpreted pre-basalt drainage. Letters show localities referred to in the text.

Some distance after passing Adaminaby the Murrumbidgee turns and flows south as if it were a tributary of the Snowy and for 20 km exhumes an ancient basalt-filled valley until it reaches Bridle Creek. (Fig. 1, point A). Although the basalt-filled valley continues to the south the present day river forsakes this and suddenly turns east. The valley is then deeply incised for the next 15 km and there is no basalt except where it crosses the basalt filled valley of the ancient Pilot Creek. This section of river cannot be part of the valley of the pre-basalt river.

The objectives of the study were to resolve the controversy over the evolution of the drainage system, pursue the concept that the sediments associated with the basalts were deposited as a consequence of tectonic activity and perhaps find a connection between the two.

The following is a condensed version of the findings about the evolution of the area.

Monaro Volcanics Stratigraphy

Most of the lavas are very similar, making it difficult to resolve the stratigraphy. To the south of Cooma, Pratt *et al.* (1993) have locally divided the Monaro Volcanics into a lower basalt unit, the Bondo Dolerite Member and an upper basalt unit. The Bondo Dolerite Member is widespread in the Murrumbidgee Valley, so the same divisions can be made over much of this area. However on the basis of local geology a difference stratigraphic nomenclature is used. The lower volcanics have been restricted to the lavas up to and including a prominent but intermittent red bauxite horizon. These lavas are sediment free apart from gravel in an ancient river channel. The bauxite has been partly eroded and sediments make their first appearance in the sequence as thin intermittent deposits at the same general level as the bauxite, signifying changes in the geological environment. From here on extensive sediments occur beneath and interbedded with the lavas, but they are not uniformly distributed, being more prolific in the NW of the area. (Fig. 1). There is at least one and in places definitely two flows beneath the Bondo Dolerite. On the east bank of the Murrumbidgee there are at least two flows above the Dolerite, and on the west bank where the flows have interbedded sediments there are at least three and probably four. Total thickness of all the volcanics is probably less then 200 m.

The sediments are mostly poorly exposed but appear to be non-cyclic, consisting dominantly of fined-grained silty sand with sand and gravel near the base of some deposits. Clay with organic remains is only known from one farm bore. Silcrete is widely developed in the western part of the area both associated with and remote from the basalts.

Geological Structure

Most of the lavas are gently dipping but although some were relatively steep, 4° to 5°, it was some time before it was realised that this was the result of folding. The geometry of this folding was subsequently fairly reliably determined by structure contouring the top of the Bondo Dolerite. The main structure is a basin with a maximum displacement of about 300 m on the NW limb (Fig. 2). The adjacent areas have also been deformed but information is piecemeal because there are no suitable marker horizons. Northwest of the basin is an anticlinal axis beyond which the lavas dip gently NW, while the silcretes near Adaminaby dip to the NE.

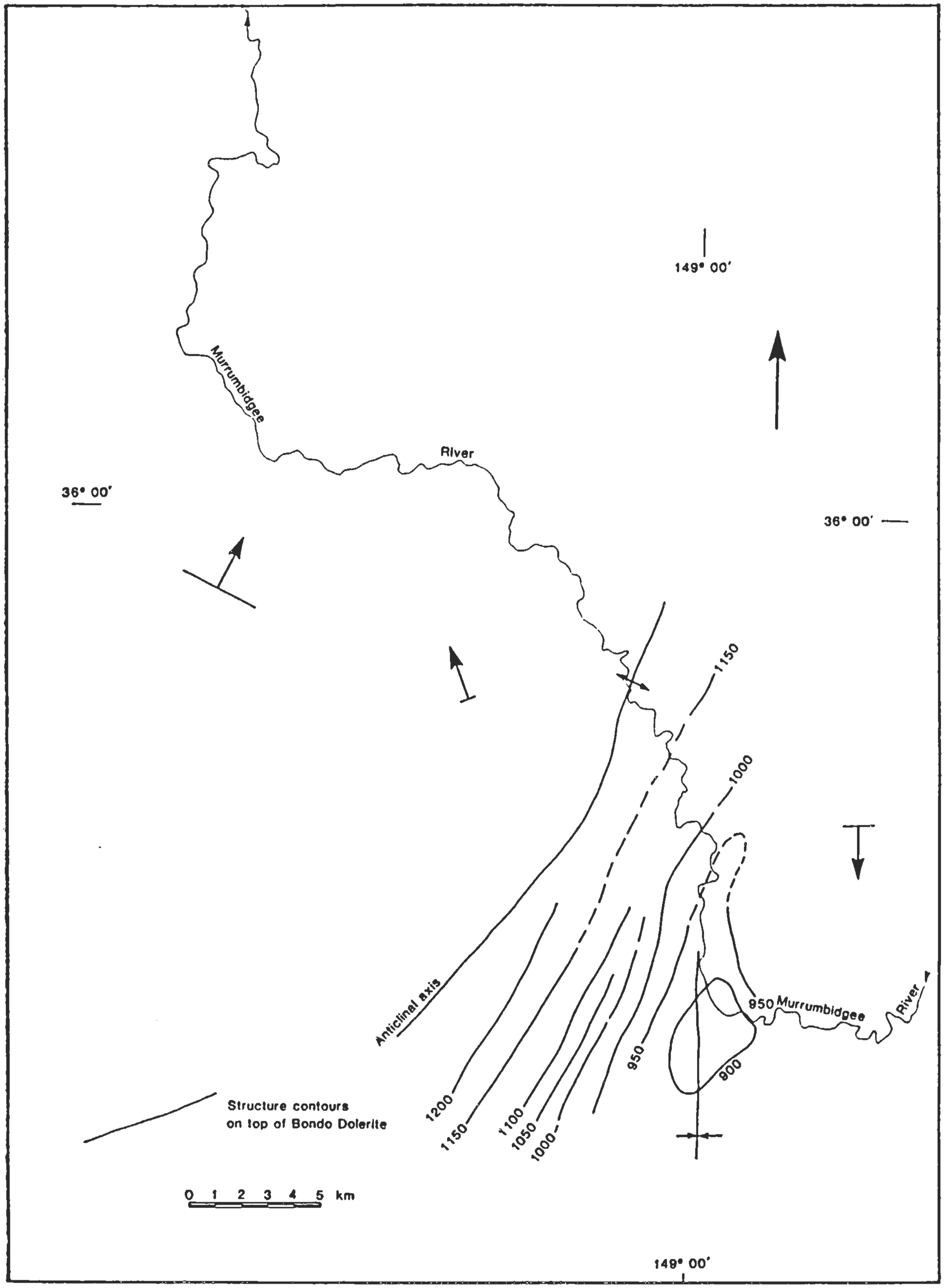

Fig. 2. Map showing structure contours for the top of the Bondo Dolerite unit and interpreted fold structures.

The Pre-basalt Drainage

Reconstruction of the ancient course of the Murrumbidgee presented an enigma. The ancient river could not have continued south from Bridle Creek (Point A, Fig. 1) because bedrock beneath the basalt rises in this direction as indicated by Taylor *et al.* (1985). This cannot be explained as being due to tilting as the older volcanics also wedge out in this direction. The ancient river bed apparently rose up to the north and there seemed to be no possible routes to the east or west. However, as mapping proceeded it was found that the levels to the north rose from about 800 m at point A, to 1080 m at point B, but then fell to 1000 m at point C. This together with the discovery that the basalts were folded finally resolved the enigma. Reversing the deformation indicated by the structure contours on the Bondo Dolerite flattened out this hump in the stream profile showing that the ancient river could have flowed north. Following the Murrumbidgee "upstream" instead of downstream reveals some interesting features. The country firstly widens to a broad mature valley. At point D (Fig. 1) a striking physiographic feature appears where the present day Murrumbidgee enters from the NW in a V shaped valley while the broad ancient valley (the ancient river) continues on as the Goorudee Morass for another 4 km to point E. Here it stops abruptly against the Adaminaby fault. High level gravels on the western or upthrown side of the fault provide evidence that the river once crossed the fault. It apparently headed south crossing the present day main dividing range where Cooloowyne Embankment (a saddle dam of Lake Eucumbene) is located. This was the ancient river and it flowed in the reverse direction to the present day Murrumbidgee until it was cut off by the Adaminaby fault.

The stream reversal appears to have been a complex process which took place in stages. The section of river between points B and A (Fig. 1) presumably reversed its direction of flow in the early stages of formation of the basin structure. The reversed river obviously broke out to the east at point A because this was the lowest point in the basin rim adjacent to the lowest point in the basin. The section of river between points B and E reversed at a later date being controlled by the uplift of the block to the west of the Adaminaby Fault.

Displacement on the Cotter Fault similar to that on the Adaminaby Fault (and possibly concurrent with it) dammed the Murrumbidgee at point F interrupting its course to the SW from Yaouk. This resulted in a major accumulation of gravel, and caused it to cut a new course between points F and D, and forming the present day river system.

Discussion and Conclusions

The evolution of the Cooma-Adaminaby area was influenced by three main tectonic events. The first commenced after the lateritisation at the end of lower volcanic time (Middle Eocene?) which resulted in tectonic ponding and the deposition of sediments along with the upper volcanics.

The second event which took place after the volcanism (Mid Oligocene?), was the folding of the basalts and surrounding terrain.

The third episode of tectonism involved movements on the Adaminaby and Cotter faults which caused major modification of the drainage (Miocene?).

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Palaeoweathering and Bauxites

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Introduction

Basic volcanic rocks of the Tertiary Monaro Volcanic Province predominantly overlie Palaeozoic rocks or earlier Tertiary sediments. Numerous early authors writing on the Monaro commented on weathered rocks beneath the basalts, although none made anything of it. Pillans (1977) was the first to publish specifically on the weathered Palaeozoic or Tertiary rocks of the Monaro, although Taylor and Smith (1975) had attributed the formation of sub-basaltic silcrete to weathering of 'lead' sediments below and interbedded with the basalts.

To my knowledge no work had been published before the 1980's on the weathering of basalt, with the possible exception of Lambert and White (1964) who recognised a metamorphosed soil at the 'Hazeldean Plug', although they did not go on to further develop the significance of this discovery.

The work of Taylor and Walker (1986a and b) on Lake Bunyan began the first detailed studies on weathered Palaeozoic rocks beneath the Miocene lake sediments of the northern Monaro. The University of Canberra Departmental mapping project on the Bombala 1:100:000 Sheet began the first detailed work on both bed-rock and inter-flow weathering on the Monaro.

Sub-Tertiary weathering

There is no doubt that sub-Tertiary rocks on the Monaro are deeply to moderately weathered where they have been protected from erosion by overlying rocks and sediments. Schmidt and Ollier (1987) reported similar late Mesozoic weathering from beneath basalts in New England. Some (e.g. Daly *et al.*, 1974.) have argued that sub-basaltic weathering is the result of post-basalt processes. Throughout the Monaro there are examples of pre-basaltic weathering profiles which appear to be truncated lateritic or ferruginous deep-weathering profiles, (e.g. Cambalong Creek at Cambalong and a location 2 km north of Mafra). Additionally there are numerous sub-basaltic colluvial deposits in which highly weathered fragments of bed-rock, as well as very near fresh fragments are preserved (e.g. 3 km east of Mt Cooper). These clearly indicate that the bed-rocks were weathered prior to the extrusion of the basalt. Bird *et al.* (1990), working on some of the same localities, clearly showed that the kaolinite in many of these weathering profiles predates the basalt and indicates cooler climates and higher latitudes than at present.

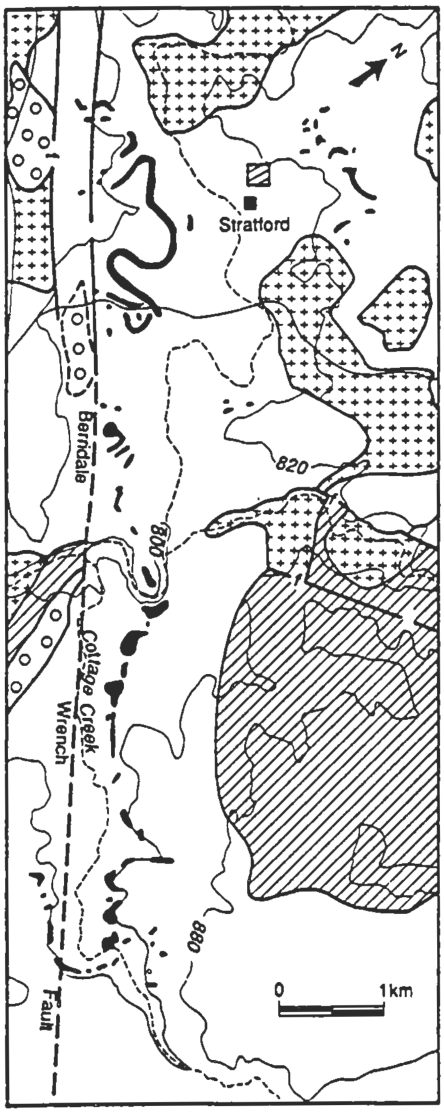
Pre-basalt Tertiary sedimentation

Palaeocene lake and fluvial sediments up 200 m thick occur below the Monaro Volcanics (Taylor *et al.*, 1990) and these cover the deep-weathered profiles at a number of localities (e.g. Cambalong Creek at Cambalong, McLaughlan River along the Nimmitabel/Berridale road, at Bungarby). Similarly in the Bega no.7 borehole at Lake Myalla the hole bottoms in lacustrine sediments over deeply-weathered metamorphic rocks of the Cooma Metamorphic Complex (Brown *et al.*, 1992). These lake and fluvial sediments reflect a provenance of weathered Palaeozoic rocks, and the large volumes of sediment suggest a landscape with deep regoliths from which the sediment was provided.

The lake-and fluvial sediments contain predominantly kaolinite, quartz and organic matter, suggesting the pre-Tertiary regolith was deeply-weathered prior to the formation of the sediments and basalt outpourings.

Intra-basaltic weathering

Taylor *et al.* (1990) mapped and described numerous inter-flow weathering profiles developed on basalt and perhaps on tuffaceous material at some sites. These profiles are up to 7 m thick, but, most are 1-3 m thick. Fig. 1 illustrates the distribution of some inter-flow profiles and Fig. 2 shows the characteristics of such profiles at Coal Pit Creek, a tributary of the McLaughlan River at 'Boco' and at Bridle Creek, a southerly tributary of the Murrumbidgee River. The majority of profiles for which the mineralogy has been examined contain gibbsite, kaolinite and goethite/hematite in their upper parts, with or without minor amounts of smectite and quartz . The lower parts contain kaolinite, smectite, goethite/hematite with minor quartz, although these parts of the profile crop out much less frequently than the upper parts.



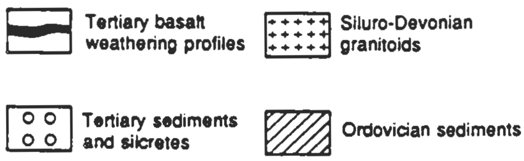


Fig. 1. Map showing the distribution of inter-flow bauxitic weathering profiles in the Bobundra Creek area.

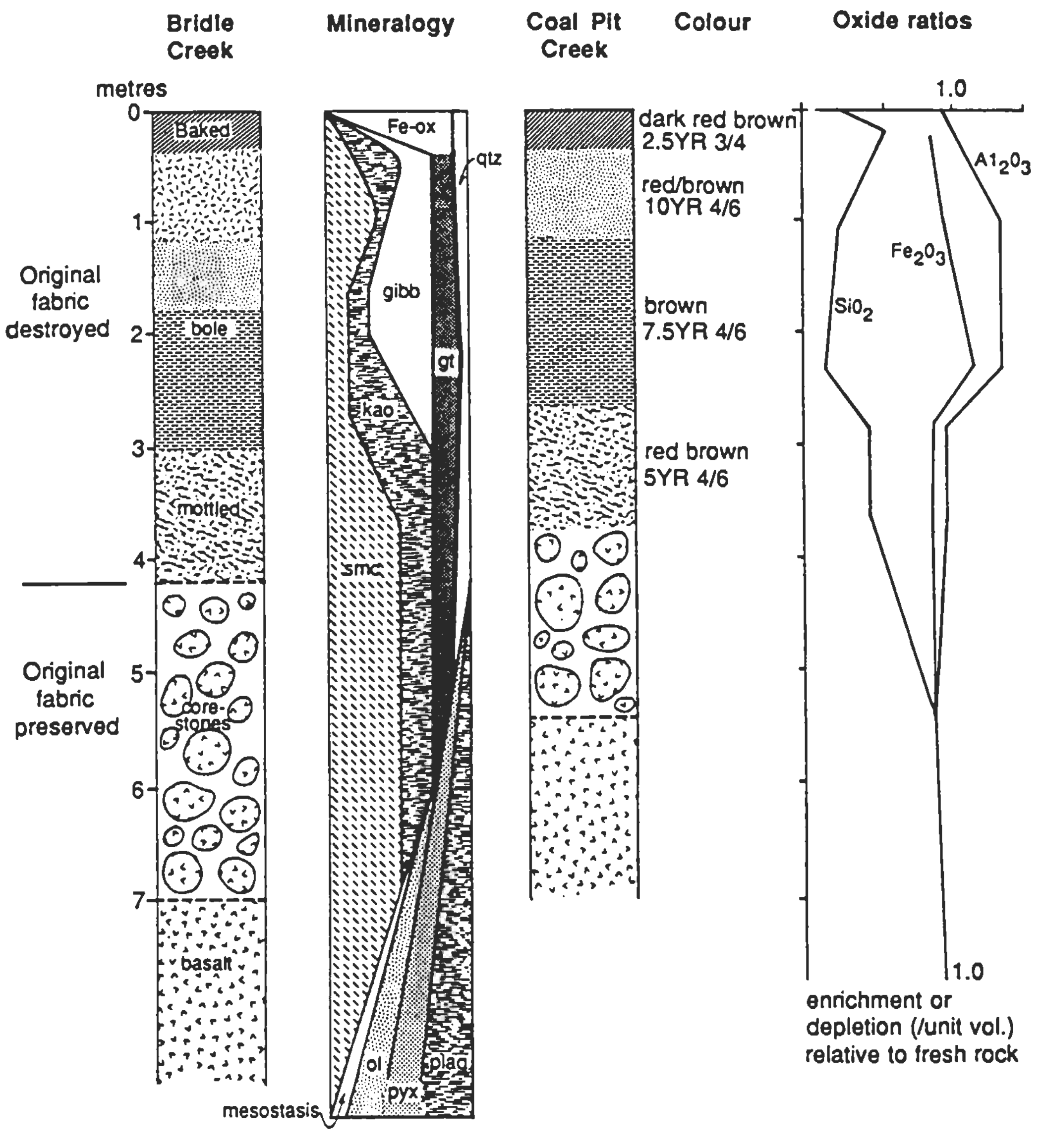


Fig. 2. Mineralogical and chemical features of inter-flow weathering profiles from Coal Pit Creek and Bridle Creek (from Holzhauer, 1983 and Taylor et al., 1992).

In the region of the McLaughlan River outcrops of bauxite occur predominantly near the bottom of the basalt pile. In core from borehole Bega (BMR) no. 7 bauxite profiles are found mainly within the upper part of the pile. (Fig. 3, Brown *et al.*, 1992). A total of nine lateritic bauxite profiles were cored at positions between basalt flows. Table 1 provides a partial chemical analysis of the lateritic bauxites from the borehole.

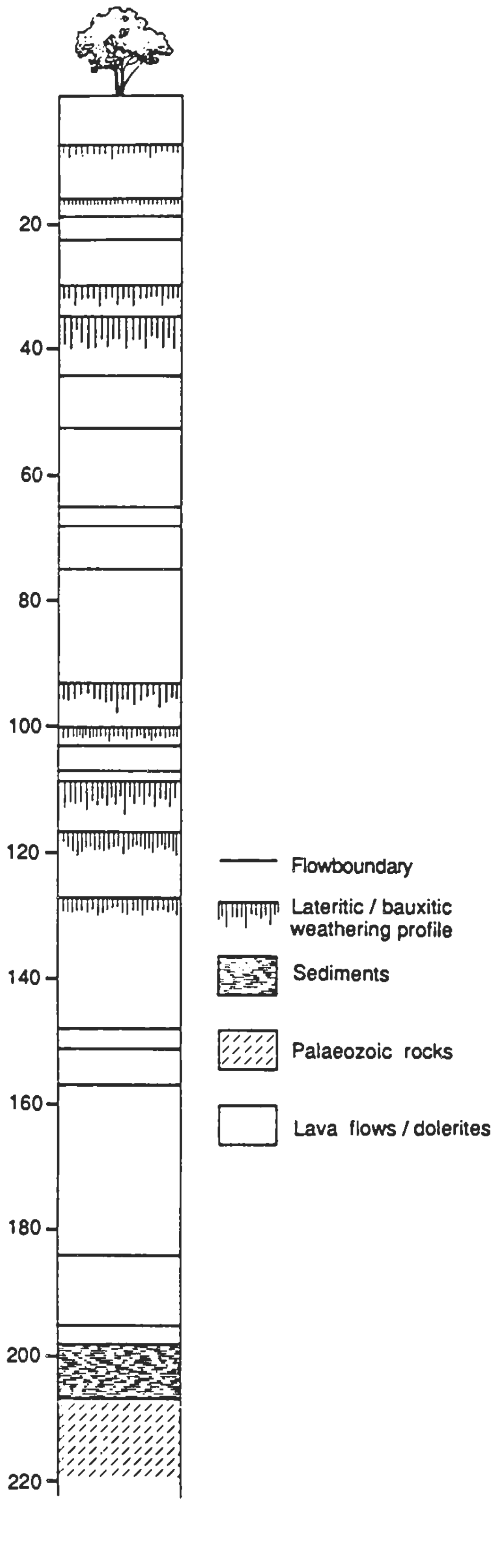


Fig. 3. Summary log of core from borehole BMR Bega no. 7 from near Myalla Lake.

Table 1: Selected major element analyses of weathering profiles from the Bega (BMR) no. 7 borehole (unpublished data) and Bridle Creek (Eggleton *et al.*, 1987). Also shown are data for typical Monaro basalt (Kesson, 1973). Alumina/silica ratios can be interpreted as indicators of the degree weathering as weathering generally reduces silica at the expense of alumina. Since kaolinite generally has a alumina/silica ratios of about 1, those values >1 (bold) probably indicate the presence of alumina rich minerals in the profile (bauxite minerals).

Depth, top profile (m)	%Al2O3	%SiO2	%TiO2	%Fe2O3	Al2O3/ SiO2	Weathering index[2]
8.7	19.2	34.3	2.1	16.0	0.56	1.57
30.4	30.3	18.0	4.5	20.6	**1.68**	**2.20**
36.1	24.1	34.7	3.4	16.1	0.69	1.20
38.9	20.5	32.9	2.9	24.4	0.62	1.26
94.0	46.1	9.6	5.1	11.2	**4.80**	**5.54**
100.3	23.7	31.4	2.6	20.9	0.75	1.71
109.9	28.5	37.1	2.9	12.5	0.77	1.56
110.4	43.5	25.9	2.3	3.6	**1.68**	**4.30**
119.1	34.4	19.2	4.2	19.0	**1.79**	**2.51**
128.0	24.4	33.6	3.1	17.4	0.73	1.38
159.2	12.5	34.7	1.3	10.7	0.36	1.63
Bridle Creek 1[3]	24.3	36.5	3.0	15.2	0.67	1.31
Bridle Creek 2[4]	24.8	34.1	2.9	19.9	0.73	1.48
Bridle Creek 3[5]	35.2	16.5	4.0	19.0	**2.13**	**3.14**
Average basalt[6]	14.6	46.5	1.8	10.6[7]	0.31	1.00

Discussion

The sub-basaltic weathering profiles are truncated and rich in kaolinite and goethite/hematite, indicating that they almost certainly existed prior to the deposition of the overlying Tertiary sediments and basalt extrusions. All the interflow weathering profiles which crop out contain gibbsite, and although mineralogical profiles are not available for Bega no. 7, Table 1 shows there has been considerable weathering and that the samples in bold in the right hand columns probably contain significant bauxite minerals.

Taylor *et al.* (1990) have clearly shown that, at least during the late Palaeocene climates were cool to cold, very wet and thermally seasonal. This implies that at least those bauxites low in the sequence formed under climatic conditions very different to those normally associated with intense weathering. The development and preservation of bauxites under such conditions is thought to be mainly the result of long periods of weathering, very low erosion rates and a high preservation potential due to covering of profiles by subsequent flows.

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[2] Alumina/Silica normalised to titania in sample and to titania in basalt, assuming Ti remains immobile (Holzhauer 1983).
[3] Kaolinite-rich zone from base of weathering profile (Eggleton *et al.*, 1987).
[4] From the lower bole (Holzhauer 1983, Eggleton *et al.*, 1987).
[5] From the upper part of the bole in the gibbsite rich (40%) zone (Eggleton *et al.*, 1987).
[6] From Kesson (1973) for alkali basalts only.
[7] FeO + Fe_2O_3 expressed as Fe_2O_3.

It is likely that many of the pre-basaltic weathering profiles are of late Cretaceous age or older. There is also good evidence that much of the late Cretaceous was cool to cold and wet in southern Australia, (Francis and Frakes, 1990; Bird *et al.*, 1990).

To summarise, there was extensive and widespread weathering across the Monaro from the Cretaceous to the late Oligocene, much of this under cool wet conditions and most of it preserved because of its covering of sediments and/or basalt.

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Consensus on the Monaro? Directions for Future Research

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Introduction

A major objective of the Monaro workshop was to establish the degree of consensus on the interpretation of the Tertiary history and evolution of the Monaro region of southeastern New South Wales. It was also planned to determine some directions and goals for future research. This contribution outlines the consensus achieved in discussions of the various presentations, points to areas of continuing disagreement, and suggests directions for future research, needed to progress our understanding of the geomorphic and geological history of the Monaro.

What is Known and Agreed

It was generally agreed by all participants in the workshop that the Monaro holds important clues to the tectonic and geomporphic history of southeastern Australia. These clues include:

1) an Early to Middle Tertiary basaltic volcanic province with implications for understanding upper mantle and lower crustal processes during this period;
2) a preserved pre-basalt land surface indicating the degree of relief developed in the region by the end of the Mesozoic;
3) Early Tertiary lake and river sediments and a contained fossil flora with implications for understanding Early Tertiary climatic conditions;
4) pre-basalt and inter-flow weathering profiles which also provide information on weathering and hydrological conditions from the Late Cretaceous to Middle Tertiary;
5) structures preserved in the basalt pile that indicate post basalt deformation.

It was agreed that sediment packages preserved beneath, within and around the basalt pile are important as a record of erosional events, as tectonic indicators and as possible indicators of basalt damming.

There was majority acceptance of the following interpretations:

1) much of the pre- and post-basalt landscape in the Monaro owes its fundamental character to inheritance from the Palaeozoic lithologies and structural grain,
2) major drainage patterns in the Monaro were changed at about the Early Tertiary;
3) volcanism had a significant impact on the geomorphic evolution of the region;
4) volcanic eruptions were from numerous vents, probably controlled by reactivated basement fractures;
5) bauxites and deep weathering profiles indicate extensive leaching consistent with wet climatic conditions during the Early Tertiary;
6) regional erosion rates during much of the Tertiary were low, possibly between 1 and 10 mm per 10^3 years.
7) there has been some post-basalt tectonism, but the extent of this is still to be agreed upon.

A Basic History

There is sufficient agreement about the various features of the Monaro to construct a simple model for the geological history and landscape evolution of the region This still needs much refinement but it represents a significant step forward in our understanding (refer to abstracts in this volume and also Süssmilch, 1909; Browne, 1914; Craft, 1933; Costin, 1954; Wellman and McDougall, 1974; Bishop, 1985; Taylor *et al.*, 1985; Bishop, 1986; Ollier and Taylor, 1988; Taylor *et al.*, 1989; Taylor *et al.*, 1990; Taylor *et al.*, 1992; Brown *et al*, 1992; Taylor *et al.*, Brown *et al.*, 1993; McQueen *et al.*, 1993; Pratt *et al.*, 1993; Roach *et al.*, 1993; 1994).

By the late Palaeocene (58 Ma) a well dissected land surface had developed in the Monaro region, with relief certainly in the order of 400 m, and possibly up to 800 m. This suggests the existence of highlands at this time. The extent of the highlands and possible location of an eastern escarpment is not clear. However, the drainage divide passed through the Monaro region, probably not too far from its present position. Evidence from the palaeoflora indicates that the climate was cool temperate and very wet (Taylor *et al.*, 1990). Deep weathering profiles were developed on this landscape. The area was covered by rainforest and associated swamps with podocarpacean and araucarian conifers, *Nothofagus* and ferns as the dominant vegetation types (Taylor *et al.*, 1990).

Mafic volcanism commenced about 55 Ma ago. Eruptions were sporadic and appear to have been from scattered vents. There is some evidence of early pyroclastic eruptions but the main volcanic products were alkali basalt lava flows. This early volcanism had a dramatic effect on the landscape, progressively infilling many of the existing valleys and damming the drainage to produce lakes. Accompanying tectonism may also have had a role in damming some streams (cf. Sharp this volume). Deposits of lake sediments up to 150 m thick were preserved beneath subsequent lava flows and numerous exposures of these sediments have been found near the margins of the basalt in the central western and southern parts of the volcanic province. Hyaloclastite deposits and minor pillow basalts formed in a number of localities where lava flows entered lakes. Alluvial, colluvial, lacustrine and lignite deposits are preserved within the basalt sequence, generally near the base.

As volcanism progressed a number of coarse-grained pyroxene phenocryst-bearing lavas were extruded, possibly by climactic eruptions which emptied the lower parts of crustal level magma chambers. These covered extensive areas particularly in the north and central parts of the province close to the main concentrations of volcanic vents. There is also some evidence that basanitic and nephelinitic magmas became more important in the later stages of volcanism. Preserved volcanic plugs (many basanitic) are clustered along two northwest trending linear zones which appear to overly two major crustal-scale structures. The volcanic sequence developed to a thickness greater than 250 m and eventually covered an area exceeding 4,200 km^2. During breaks in volcanism at particular sites deep weathering profiles, some bauxitic, were developed on many of the basalt lava flows. This is consistent with continuing wet climatic conditions (probably at least into the Eocene). The preservation and generally limited reworking of many weathering profiles suggests low erosion rates. Formation of the mafic volcanic pile, possibly combined with associated fault movements, disrupted the pre-existing drainage pattern and shifted the divide so that it now follows the main northwest trending zone of volcanic vents and the highest part of the volcanic terrain. There is some evidence for synvolcanic faulting, for example along the Berridale fault where basalt appears to have dammed against an active fault scarp (cf. Lambert and White, 1965).

Volcanic activity ceased in the main part of the Monaro volcanic province by about 34 Ma but apparently continued further to the northwest, near Yaouk, until about 20 Ma (Wellman and McDougall, 1974, Taylor *et al.*, 1990). There is evidence of post-basalt deformation in the form of tilting, warping and gentle folding of basalt flows. This deformation was possibly due to reactivation of underlying basement faults. Post-basalt erosion has significantly dissected the lava pile leaving a landscape of terraced hills, small buttes and remnant volcanic plugs and lava lakes. Erosion has also exhumed areas of the pre-basalt landscape, particularly around the margins of the lava field. Areas of silcrete have protected some of the softer sub-basaltic sediements from erosion. There are also extensive post-basalt alluvial, colluvial and some lacustrine deposits. Numerous small lakes, probably formed by deflation and solution removal of soluble components, are common on the basalt terrain today.

Topics of Disagreement

There is still disagreement on the interpretation and significance of a number of the features discovered in the Monaro region. Contentious issues include:

1) the existence and location of the great escarpment in the Early Tertiary;
2) the degree of dissection and relief of the pre-basalt surface;
3) the main direction of flow in the palaeo drainage, i.e. predominantly to the north or to the southeast;
4) the nature and original shape of the basaltic volcanic pile; was it a single circular volcanic complex or an irregular lava field?
5) the climatic regime that led to the formation of the bauxites; was it cool or warm?
6) the regional significance of the post-basalt deformation.

One of the most interesting outcomes from the workshop, at least from the author's point of view, was the realisation that many of the disagreements over interpretation of the landscape evolution of the Monaro result from confusions of scale. The significance of features and the correlations between them are different at different scales. Information was presented at the workshop for three different scales. Ollier presented a model of landscape evolution which encompassed the whole of Eastern Australia. Taylor, Brown and Roach presented models that pertained to the whole of the Monaro region. Sharp presented observations restricted to the northern Monaro. While features at all of these scales provide evidence for, and place constraints on, the geological and geomorphic history of the Monaro, the perceived importance of some features is affected by the field of view of the observer and the scope of the conceived models.

For example, the relative importance of post-basalt deformation in the region clearly depends on the scale for which these structures are viewed. Are the warps and gentle folds in the basalt stratigraphy the result of loading and sag over unconsolidated Tertiary lake sediments, the result of localised block faulting due to reactivation along existing basement structures or do they indicate a Middle Tertiary orogeny which extended over the whole southeastern part of the continent?

Interpretation of the nature of the pre-basaltic surface is also affected by the scale considered. Ollier has argued for a plain, whereas Brown and others present evidence for a deeply dissected surface. The two interpretations are not necessarily mutually exclusive if the sizes of the areas being considered are different. Ollier shows a large area of uplifted terrain which on a regional scale resembles a plateau with an eastern escarpment. Erosion to form the escarpment could extend deep valleys some distance back into the uplifted block and the irregular dissected surface beneath the Monaro Volcanic Province could represent such an area.

Understanding the original form of the Monaro volcanic province has implications for estimating the extent of post-basalt erosion and determining the location and time of formation of the eastern escarpment to the southern highlands (cf. Ollier and Taylor, 1988). If the province formed as a central volcano with a circular shape then there would need to have been considerable erosion of the edifice, particularly of the eastern half to account for the present irregular shape of the basalt distribution. If the province formed as a lava field with an irregular shape to begin with, as appears to be the case (Roach *et al.*, 1994), there is no requirement for such extensive erosion.

Future Research Priorities

It was clear from the workshop that there are a number of important problems that still need to be resolved by further research on the Monaro.

Research is needed to understand the reasons for uplift of the eastern highlands and the subsidence of the Tertiary basins, including the Murray Basin. Is there a mantle connection?

Further research is needed to understand the controls on the mafic volcanism which formed the Monaro Volcanic Province. A number of enigmatic features such as the thick phenocryst-bearing units also need to be more conclusively explained.

The stratigraphy of the volcanic sequence has still not been established. This is critical for a proper understanding of the nature of the volcanism and the timing of weathering and depositional events preserved in the pile.

We need much better controls on the timing of development of the different drainage patterns and of the basalt eruptions. We need more accurate information on the duration of the weathering events. This will involve more and better constrained dating.

The formation of the bauxites and their relationship to other weathering profiles is not fully understood and requires further research. The distribution of the bauxitic horizons throughout the volcanic pile also needs to be established

More detailed information is needed on the flow directions of the palaeodrainage for different times.

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