CHAPTER 6

SIGNIFICANCE AND SOURCES OF TERTIARY BASALT

6.1 INTRODUCTION

The earliest studies of the Tertiary basalt in the Armidale-Uralla region were carried out more than 100 years ago, following the discovery of deep lead gold in the Uralla-Rocky River area. This Chapter draws on these studies as well as evidence presented earlier in this thesis, to reach conclusions about the Tertiary basalts in the Armidale-Uralla region. An essential part of this process is a critical evaluation of existing ideas about landscape evolution in the Armidale-Uralla region and adjacent areas.

6.2 PREVIOUS THEORIES OF NEW ENGLAND GEOMORPHOLOGY

6.2.1 DAVID

David (1886) referred to the presence in the Uralla-Rocky River area of basalt flows, and laterite 'composed of red volcanic dust and fragments of decomposed erupted basalt'. He claimed that the 'cindery scoriaceous appearance' of the summits of the Sugarloaf (Armidale sheet GR 537106; Plate 57); Doherty's Hill (Armidale sheet GR 527099); and of a hill near Mount Butler (Armidale sheet GR 552198), was clear evidence that they had been points of eruption. From David's (1886) descriptions of 'cindery scoriaceous' hilltops (discussed in Section 6.3), and of glassy 'volcanic bombs of basalt', there is no doubt that he thought the basalt extrusions in the Uralla-Rocky River area had been explosive events, and that they had emanated from localised vents still

<u>Plate 57.</u> The Sugarloaf, 3 km north of Uralla at Armidale sheet GR 535107. The Sugarloaf consists of highly weathered ferricrete (Plate 60; Section 6.3.1). The base of The Sugarloaf (the foreground of this Plate) consists of basalt, underlain to the east (right of Plate) by a continuation of the highly weathered ferricrete, and to the west by deep lead fluvial sediments.

visible in the landscape. David described these 'volcanic bombs' as

> spherical discs, shaped like a doubly convex lens, from the size of a sixpence up to that of a penny. The under surface shows spiral grooves, while the upper is cellular. Many of the bombs have delicate rims curved upwards so as to form tiny saucers, and the edges are translucent.

These spherical discs were almost certainly australites, the name given to tektites found in the Australasian region. Walcott (1898) recorded three finds of australites, or as he called them, obsidianites, in the Uralla-Rocky River area. Even earlier than this, Charles Darwin (1844) had described and drawn an oval button-shaped australite and suggested it was a volcanic bomb (Darwin, 1844). Walcott (1898) was hesitant to ascribe a definite origin to australites, and the same difficulty still exists. Barnes and Barnes (1973) introduced their Benchmark volume on tektites by stating that while most researchers agree that tektites are the result of impact, australites do not fit easily with this explanation, because of their unmistakable aerodynamic ablation features. This view was shared by Sears (1978) who concluded that 'there is probably a consensus view that tektites are a form of terrestrial impact glass, but the details, especially concerning their composition, are far from known'. Because of the uncertainty about the origin of australites, it would be unwise to use their presence as an indicator of volcanic activity.

David (1886) also referred to the frequency with which Tertiary alluvials underlie the Tertiary basalt. Shafts sunk in the Uralla-Rocky River area gave David detailed information about the depth and width of the alluvial deep leads: average thickness of the alluvial leads was found to be about 10 m; widths varied from 100 m to over 800 m (David, 1886).

6.2.2 ANDREWS

E.C. Andrews (1903, 1904) studied an extensive area of the New England tablelands, ranging from the Armidale-Point Lookout area, north to Tenterfield. He considered the tablelands to be a series of stepped erosion surfaces resulting from repeated cycles of peneplanation. Andrews interpreted the Tertiary basalts now present in New England as remnants of an initially almost complete cover. He believed the basalts had been extruded from only a few major sources and had moved long distances.

In a later paper Andrews (1910) reinterpreted most of his original stepped erosion surfaces as a tectonically disrupted single surface. This reinterpretation was not based on field evidence. Young (1978b) has suggested Andrews was influenced by landscape interpretations in other areas. These would have included David's (1902) study of the Blue Mountains west of Sydney, and the work of Taylor (1907) and Süssmilch (1909) in the southern tablelands of New South Wales. Two years later Andrews (1912) reverted to his original interpretation of the New England tablelands as a series of stepped erosion surfaces, when faced with a lack of field evidence to support his earlier theory of block faulting in New England.

6.2.3 TAYLOR

Taylor's (1911) comments on basalt extrusion in New England were made within a wider study of the physiography of eastern Australia. He interpreted the centripetal drainage pattern of the upper Macleay River as the result of major drainage disruption and river capture following basalt extrusion. Taylor (1911) thought that major drainage disruption has occurred throughout New England as a result of basalt extrusion.

6.2.4 CRAFT

Craft (1933) argued that the drainage of the Macleay valley pre-dated the Tertiary basalt extrusions. The basis of his argument was that there is a fall in the elevation of the basalts in the general flow direction of the streams; and that basalts near the present Macleay River overlie river gravels. From a comparison of basalt base elevations on the Macleay drainage divide and on the Macleay valley floor, Craft (1933) claimed that post-basalt uplift cannot have exceeded about 160 m, and that 'this estimate might allow a comparatively low grade for the pre-basalt stream'.

Craft's conclusions were thus at variance with those of both Andrews (1904) who postulated post-basalt tectonism, and Taylor (1911) who suggested major drainage disruption by the Tertiary basalt.

6.2.5 VOISEY

Voisey (1942a, 1942b, 1955, 1957, 1963) interpreted the landscape of the Armidale-Uralla region in terms of cyclic pediplanation. He invoked this theory to explain the survival of landforms he had interpreted as cyclic planation remnants. Voisey (1963) recognised five distinct erosion surfaces.

1. The pre-basalt surface. The extent of this surface was determined 'by noting the level of the base of the gravels which underlie the basalts' (Voisey, 1963). To reconstruct this pre-basalt topography Voisey (1963) should have recorded the elevations of the gravel-basalt contact, rather than the elevations on the base of the gravel. The gravels underlying the basalt are a part of the pre-basalt surface onto which the basalt was extruded. Thus the elevations of the contact between the gravels and the basalt are spot heights on the pre-basalt surface. The elevation of the base of the gravels gives only the elevation of the landscape on which the gravels were deposited. Further, in drawing form lines from sub-basalt spot heights it must be assumed that the basalt extrusions took place over an extremely narrow time period. As the basalts in the Armidale-Uralla region were extruded over a period of at least 11 my, the sub-basalt surface was diachronous, and Voisey's (1963) form line reconstruction of the pre-basalt surface produces results that should be interpreted with caution. Voisey interpreted sediments mapped below the basalt as evidence for a large lake (the Armidale Lake), that he thought had covered much of the pre-basalt Armidale region.

2. The basalt surface. Voisey (1957, 1963) thought this surface was developed on the tops of the highest basalt flows, and argued that as the present streams in the Armidale area cut across the grain of the Palaeozoic basement rocks, they have been superimposed from the basalt surface onto these older rocks. Voisey claimed this superimposition was the result of 'a great change in the drainage patterns' of the Armidale area. He thought this great change involved early basalt flows damming valleys, and subsequent 'deluges of lava' covering even the interfluves and 'burying almost the whole of the Armidale area' (Voisey, 1957).
3. The laterite surface. Voisey (1963) claimed that remnants of this surface rise above other surfaces on many of the flat-topped basalt hills in the Armidale area. Voisey (1963) argued that this now somewhat dissected surface has given rise to the many level skylines in the region at an elevation of about 1000 m. One of the criteria used by Voisey (1957) in recognising the laterite surface was the presence of swamps and lagoons.
4. The post-laterite surface. Voisey (1957, 1963) argued this surface consists now of wide, shallow valleys eroded into basalt, and into which gorges have been incised. The edge of this dissected laterite surface is usually accompanied by 'a sharp break of slope from the flat land on either side of the Main Divide' (Voisey, 1957)
5. The Recent surface. This surface is characterised by 'spotty' geology (by which Voisey presumably meant numerous minor outcrops of differing rock types), terraced plateau landscapes, level skylines and wide valleys.

Recognition by Voisey (1957, 1963) of these five distinct erosion surfaces was based on several assumptions.

1. An assumption that the basalt extrusions in the Armidale area completely obliterated the pre-basalt topography and caused a new drainage network to develop. This assumption is necessary for Voisey's (1957, 1963) reconstructions of the Basalt Surface, but is not substantiated by the evidence presented here. The clear relationship between pre-basalt and

post-basalt streams, and the relief inversion features present in the Armidale-Uralla region (both of which are discussed in Chapter 9), indicate that the landscape was never inundated with basalt. Evidence in this thesis reduces Voisey's (1957, 1963) basalt surface to a network of principally valley-fill basalts, relief-inverted remnants of which now cap interfluves in the Armidale-Uralla region.

2. An assumption that the flat-topped basalt hills still visible in the Armidale landscape are flat-topped because they are capped with a duricrust of ferricrete, and are remnants of a late Miocene surface. I argue (as did Francis and Walker (1978a) that there is no single ferricrete surface, and that ferricrete can be found at all elevations in the Armidale-Uralla landscape. The flat-topped summits that Voisey (1957, 1963) identified as a late Miocene laterite surface are more simply explained as remnants of sub-horizontal basalt flows, on parts of which ferricrete has developed.
3. An assumption that there was only one basalt surface. This assumption is unwarranted for two reasons. First the strong relationship between the present basalt distribution and silicified fluvial sediments in the Armidale-Uralla region, indicates that the Tertiary basalt extrusions modified drainage patterns without completely obliterating them. These valley-fill basalts cannot be called a surface, as in many areas they were low in the landscape until relief-inverted by erosion. Secondly the Tertiary basalts in the Armidale-Uralla region were extruded over a period of at least 11 my, and are not the remnants of a single basalt extrusion, but rather are the remains of at least three phases of extrusion (as discussed in Section 2.3). It is therefore difficult to argue for a single basalt surface, when the basalt extrusions are very likely to have been incomplete in their cover of the landscape, and discontinuous in time.

In studying the basalt flows of the Armidale area, Voisey found little evidence of 'fragmental material characteristic of the explosive types' of volcanic eruption (Voisey, 1955), and concluded that the volcanic eruptions around Armidale were probably fissure eruptions, 'with the lava welling up cracks in the crust' (Voisey, 1955). Voisey thought there were few volcanic plugs in New England. He interpreted basalt hills in the Armidale area as being 'merely residuals resulting from the erosion of the flows and intrusions' (Voisey, 1955). This latter point accords with my conclusions; however I have found no evidence in the Armidale-Uralla region for localised fissure eruptions.

6.2.6 GALLOWAY

Galloway (1967) studied Tertiary basalt distribution in the Hunter Valley adjoining southern New England, and maintained that the entire valley was inundated by basalt flows in the Tertiary, and that 'the scattered [basalt] occurrences of today are survivals of a former continuous sheet'. Galloway argued that this continuous sheet 'buried and preserved the pre-existing surface and presented a relatively featureless surface on which a new drainage system evolved *ab initio*'. He thought these basalts were highly fluid and flooded 15,500 km^2 of the Hunter valley to an original mean depth of 150 m. In Galloway's (1967) view the basalt caps now present on summits in the upper Hunter valley and in southern New England are remnants of this once continuous cover.

Galloway (1967) claimed that the basalt was probably over 600 m thick in the north of the Hunter valley, tens of metres thick in the southwest, and thin in the west, centre and east. He stated that it was possible that twice this quantity had been extruded, but did not provide any evidence to substantiate this claim. The 150 m average depth appears to have been derived from measurement of the present maximum thickness of basalt in the Hunter valley, and is thus a minimum thickness.

6.2.7 WARNER

Warner (1971, 1975), like Voisey, based his account of New England landform evolution on the assumption that Tertiary basalt flows had once covered almost all of New England to considerable depth. In Warner's view the remnants of these flows indicate the level of a once continuous basalt surface in New England. The assumption by Warner (1971, 1975) that Tertiary basalt was continuous over the Armidale landscape was based on two main arguments. First, in the Armidale area, 'apart from the gorges, the landscape before the basaltic floods was very similar to that of the present' (Warner, 1971), because a form-line reconstruction of the sub-basalt landscape suggested similar topography. Secondly, Warner saw little evidence of relief inversion and concluded that basalt had affected most of the landscape. Warner (1971) argued that if the basalt extrusions were localised, 'they would have filled existing valleys only and there would have been more striking differences in the drainage patterns'.

These arguments give contradictory conclusions. If Warner's (1971) form line reconstruction of the pre-basalt landscape in New England is correct in showing the pre-basalt drainage was similar to the present drainage, this is clear evidence that the basalt extrusions were relatively limited in extent: if the extrusions were extensive the pre-basalt drainage would have been obliterated, and a completely new drainage system, would, of necessity, have been initiated. A similarity between pre-basalt and post-basalt drainage lines is only likely if a small volume of lava restricted to existing valleys was extruded; sufficient to cause no more than minor alteration to the pre-basalt valleys into which it flowed. This argument is incompatible with Warner's (1971) claim that the basalts affected most of the landscape. Warner (1971, 1975) was thus suggesting that two mutually incompatible sequences had taken place: that large volumes of basalt had been extruded in the Armidale area; and that the pre-basalt and post-basalt drainage systems are similar. These incompatible claims, as well as a claim countered by evidence presented in this thesis, that there is no evidence of relief inversion in the Armidale area, are crucial to Warner's (1971, 1975) conclusions about landform evolution in New England.

Warner's (1971) map of erosion surfaces between Armidale and Dorrigo (Figure 11) synthesized his arguments for a series of erosion surfaces in southern New England, but it is doubtful that all the surfaces shown are erosional, or that some of the boundaries drawn by Warner actually exist. For example Warner's late Miocene Surface (first post-basalt surface) is not an erosion surface: the boundary shown in Figure 11 between this and Warner's second post-basalt surface, approximates to the modern margins of the Tertiary basalt. Thus Warner's (1971) late Miocene Surface is actually a low relief structural landscape, formed by simultaneous valley incision and basalt extrusions between 33 and 22 my, followed by erosion to the present, and there is no evidence to suggest that Warner (1971) was correct in calling it a pediplain.

The Pliocene Partial Planation Surface (second post-basalt surface), was thought by Warner (1971) to have been formed following differential uplift of the late Miocene Surface. This 'surface' contains both erosional and depositional elements, and has a relative relief of several hundred metres. Warner's (1971) Pliocene Partial Planation Surface can be explained without postulating differential uplift of the basaltic areas of southern New England, and consists mainly of the areas that were never covered by basalt. Between the Late Miocene Surface and the Pliocene Partial Planation Surface, Warner (1971) mapped a scarp (Figure 11) thought to mark the position of a 'new wave of rejuvenation' resulting from post-basaltic differential uplift. Field investigations during the present study failed to locate this scarp. What Warner (1971) appears to have mapped is the variable but minor break of slope that is common at the margin of the Tertiary basalt. Where this break of slope is present it usually has a relative relief of less than 10 m, with maximum slopes of 5-15o. Despite calling this minor break of slope a scarp, Warner later argued that 'the slope eastwards from Point Lookout is not a scarp but may either be a warped or step-faulted part of the plain' (Warner, 1975). It is unclear what Warner (1975) meant by scarp in this context. The term can refer to 'an escarpment, cliff, or steep slope of some extent along the margin of a plateau, mesa, terrace or bench' (American Geological Institute, 1976). By this non-genetic definition the slope eastwards from Point Lookout is certainly a scarp. Warner's interpretation of the scarp as a faulted or warped extension of the plateau, rather than an erosion scarp, is quite unconvincing. The Tertiary basalt flows that cap the plateau in the Point Lookout area are truncated at the scarp edge. They are not present at the foot of the scarp as would be expected if the scarp was due to faulting.

The presence of gorges along the scarp, and the existence of landslide scars on the scarp face, are further evidence that the scarp is an active erosional landform. The sinuousity of the scarp (Figures 1, 11; Plate 58) also militates against a warping or faulting origin. It is probable that warping has been involved in the uplifting of the eastern highlands, and this may have contributed to the development of the eastern scarp by increasing gradients on the eastern side of the plateau. But even if this is the case the scarp is not itself a warped landsurface, it is the result of increased erosion due to increased gradients.

6.2.8 FRANCIS

Francis (*pers. comm.*) has argued that Tertiary volcanism in southern New England was very limited in volume and extent. On the basis of physiographic appearance and magnetic anomaly data, he concluded that a number of features previously thought to be basalt flow remnants are actually volcanic vents. He argued that the basalt extruded from these vents flowed only short distances, sometimes less than 1 km, and did not obliterate the pre-basalt landscape. The features identified by Francis as volcanic plugs included Bald Knobs, Arthurs Seat, a knoll at the University of New England (Dumaresq sheet GR 695267), and several knolls on and near North Hill and South Hill in the city of Armidale. On North Hill, northwest of Duval High School, he interpreted features as small volcanic plugs 5-10 m in diameter, intruding a basalt flow. The features identified by Francis as volcanic vents are generally located on modern upper slopes or interfluves.

In the same investigation of landform evolution in southern New England, Francis (pers. comm.) measured the long axis orientations of Eocene fluvial pebbles at 7 sites in the Armidale area. From the calculated transport directions he concluded that the pre-basalt drainage was similar to the present drainage. If Francis was correct in arguing that pre-basalt and present drainage patterns in the Armidale area are similar, then the upper slope and interfluve features he identified as volcanic vents, must have been originally formed on pre-basalt upper slopes and interfluves. This requires either much coincidence, or the presence of structural weaknesses along the upper slopes and interfluves containing these features.

Further, if Francis (pers. comm.) was correct in arguing that extrusion was very limited and patchy as a result of vents being minor and localised in influence, little basalt should remain on interfluves. In addition volcanic vents would be expected throughout the whole landscape, unless basalt had been preferentially extruded along lines of structural weakness. If this was the case the lines of structural weakness should coincide with drainage lines, and basalt extruded from localised vents along drainage lines could become relief-inverted to upper slope or interfluve positions. As I have previously noted (Section 5.7.6), there are no recorded faults or lineaments associated with the present basalt distribution in the Armidale-Uralla region. Thus the predominance of basalt remnants on upper slopes and interfluves in the New England region does not support Francis' idea of limited and patchy lava extrusions from localised minor vents.

Francis (pers. comm.) also identified features he called flow benches, associated with several basalt knolls in the Armidale area. If the basalt extrusions in the Armidale area were as limited as he has suggested, the survival in the present landscape of 'flow benches' at the edges of what must, in his interpretation, have been minor flows, implies almost non-existent rates of erosion over the last 20-30 my. The idea of such low rates of erosion may be inconsistent with Francis' own claim that in three of his magnetic traverses, basalt had been 'stripped from the Sandon Beds over areas 100-300 m in extent'.

The difference in rates of erosion required by the views of Francis (pers. comm.) on the one hand, and Voisey (1942a, 1942b, 1957, 1963), Galloway (1967) and Warner (1971, 1975) on the other, is immense. On Galloway's (1967) interpretation, basalts up to 450 m deep were once present in the upper Hunter valley. This requires several hundred metres of erosion since the Tertiary basalt extrusions. Francis' interpretation of the evidence involves, in many areas, only several tens of metres of surface lowering in the same period. Even allowing for local differences in the rate of surface erosion the two views are clearly not compatible.

6.2.9 OLLIER

Basalts to the east of the Armidale-Uralla region have been investigated by Ollier (1982b, 1982c). Topographic profiles in the area around Point Lookout, Bellingen and Dorrigo (Figure 12), and the radial drainage pattern of the upper reaches of the Bellinger River (Figure 13), led Ollier (1982b) to suggest that basalts in the Ebor and Dorrigo regions are remnants of a large shield volcano in the Point Lookout-Ebor area. A gabbro outcrop at The Crescent in rugged terrain at the base of Point Lookout and at the likely site of the volcanic vent, has been dated at 52 my (Appendix D). This is much younger than the Permian age given on the 1:250,000 Dorrigo-Coffs Harbour Geological Sheet, but is 30 my older than the basalts. The physiographic evidence (Figures 12, 13) for a large shield volcano centred east of Point Lookout in the vicinity of The Crescent is persuasive, but the anomaly between

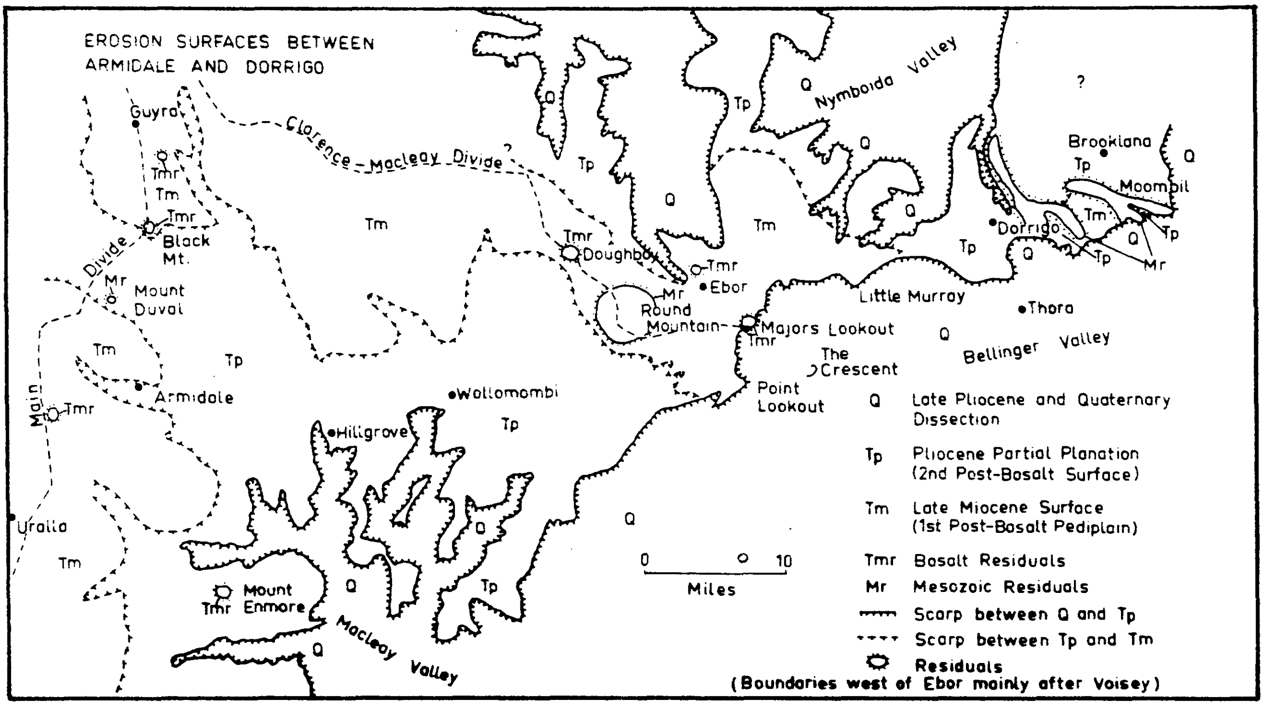

Figure 11. Warner's (1971) map of erosion surfaces in the Armidale-Dorrigo area. This map drew heavily on Voisey's work in the Armidale area. The scarp shown by Warner between the Second Post-Basalt Surface and the Late Miocene Surface is actually the margin of the Tertiary basalt. The Mesozoic residuals such as Mount Duval, are not remnants of a Mesozoic surface. Mount Duval has probably been a topographic high since it was emplaced.

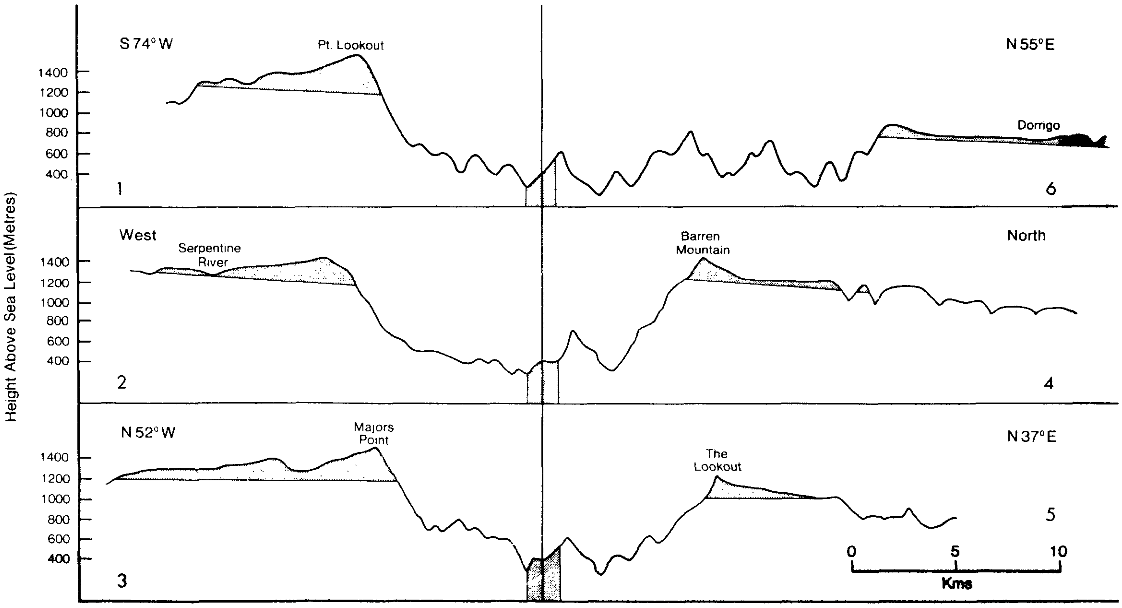

Figure 12. Topographic profiles and inferred sub-basalt topography in the Point Lookout-Dorrigo area (from Ollier, 1982b). The location of the sections is shown in Figure 13. On the basis of these profiles and the radial drainage pattern shown in Figure 13, Ollier interpreted the modern basalt in the area as remnants of a large shield volcano. These basalts are younger than the youngest basalts in the Armidale-Uralla region, and are unlikely to have been a source for these Armidale-Uralla basalts.

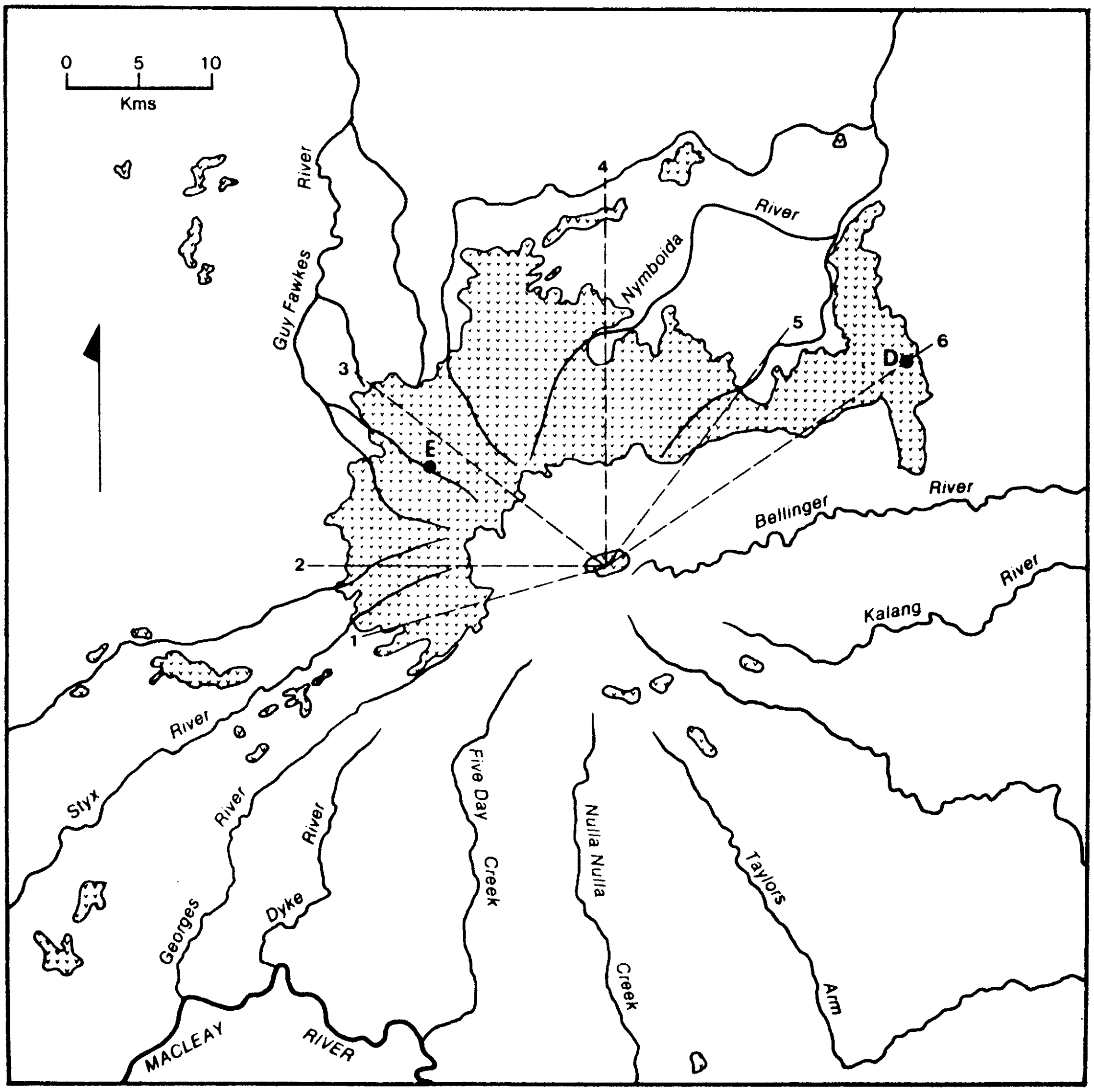

Figure 13. Radial drainage and volcanic rock distribution in the upper Bellinger and Macleay valleys (from Ollier, 1982b). The numbered lines on the map show the location of the profiles in Figure 12. The rivers converge on The Crescent, a gabbro outcrop through which the profiles drawn in Figure 12 all pass. This physiographic evidence for a large shield volcano centred on The Cresent is not upheld by K-Ar dating, which shows that the gabbro is 30 my older than the plateau basalts.

the age of the single gabbro sample so far dated, and the age of the basalts that would comprise the shield of the volcano, has yet to be resolved.

6.3 CONCLUSIONS FROM THE BASALT DISTRIBUTION

6.3.1 PHASES OF EXTRUSION

Isotopic dating of basalts has established that basalt extrusions in the Armidale area took place over a period of at least 11 my. There appear to have been at least three flow phases, at 33, 25, and 22 my. Isotopic dating thus establishes that there were several flows, but does not immediately indicate their number. One site where there is good field evidence for more than one basalt flow, is 7 km west of Armidale at Armidale sheet GR 633242. At this site ferricrete crops out along contour for a distance of approximately 300 m on the upper slope, separating upper slope basalts from mid-slope and lower slope basalts (Plate 59). The ferricrete outcrop appears clearly interbedded with the basalt, and almost certainly formed in a soil profile during a prolonged pause between basalt extrusions.

At several other sites in the Armidale-Uralla region there is evidence that besides the period of basalt extrusions between 33 and 22 my, there was also an older period of extrusions. At the Sugarloaf (Armidale sheet GR 535107; Plate 57); at Uralla Trig. (Gostwyck sheet GR 555073); near Mount Butler (Armidale sheet GR 551197; at Arthurs Seat (Armidale sheet GR 722153); and at Bald Knobs (Armidale sheet GR 710145), there are deposits of highly weathered massive ferricrete. At Arthurs Seat and Uralla Trig., these deposits have retained traces of their spheroidal weathering pattern (Plate 48).

Thin sections of highly weathered ferricrete from the Sugarloaf, Arthurs Seat, Mount Butler south, and Uralla Trig., all indicate basalt provenance. Ferricrete from the Sugarloaf (Plate 60) contains weathered basalt clasts with olivine and plagioclase visible. Ferricrete from Arthurs Seat contains abundant weathered olivine, some with rims altered to iddingsite. Magnetite or

Plate 58. *The eastern scarp 25 km east of Armidale, showing its sinuous path, and the great difference in relative relief between the plateau and the gorge country.*

Plate 59. *Interbasaltic ferricrete 6 km west of Armidale. The foreground is on basalt, ferricrete crops out along contour on the mid-slope, from the stump and nearest tree to the change of slope. Basalt again crops out from the change of slope to the interfluve (Armidale sheet GR 633242).*

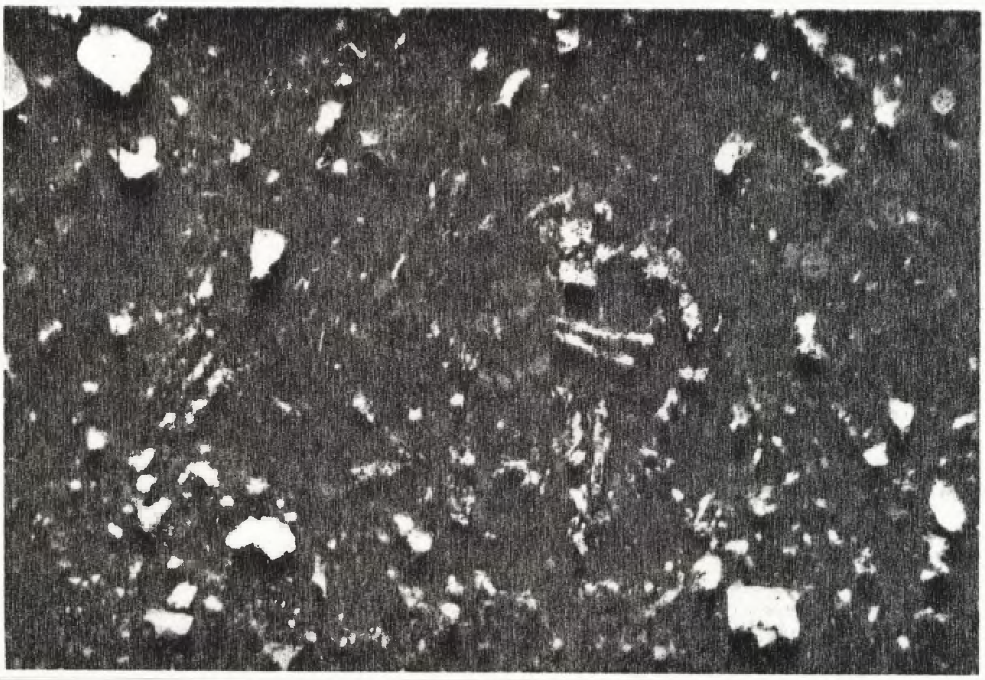

Plate 60. *Photomicrograph of highly weathered ferricrete from the Sugarloaf (Sample 102c, ordinary light). Actual width of field is 2 mm. Nodule in centre of Plate is a highly weathered basalt clast, containing pyroxene, olivine and laths of plagioclase, consistent with olivine basalt provenance. Occasional sub-rounded quartz sand grains (0.1 mm) in the well-weathered material surrounding the nodule (Armidale sheet 535107).*

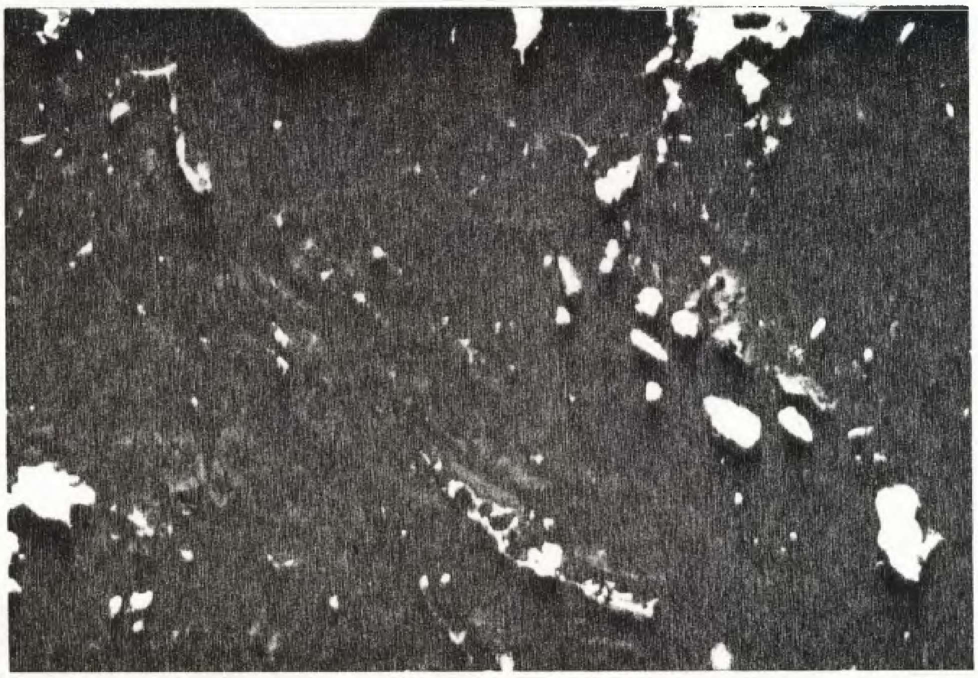

Plate 61. *Photomicrograph of highly weathered ferricrete from Mount Butler south (Sample 099c, ordinary light). Actual width of field is 2.5 mm. Contains weathered olivine, fragments of concentrically laminated iron-rich concretions and sub-rounded quartz sand (0.1-0.2 mm). Another sample from this site is discussed in Section 6.3.1 (Armidale sheet GR 551197).*

ilmenite is also present. Microcrystalline chalcedony fills cracks, and in places appears to form a matrix for the olivine and magnetite/ilmenite. The two sections examined of ferricrete from the Sugarloaf have occasional bright orange-red concentric laminations, indicating that there has been at least some iron mobilisation.

Ferricrete from Mount Butler also contains weathered olivine. This ferricrete also contains microcrystalline silica, as a cement around olivine crystals and as a chalcedonic filling in dilated fractures in the ferricrete. In places the microcrystalline silica abuts fragments of iron-rich, orange-red concentric laminations (Plate 61).This indicates that a phase of iron mobilisation and precipitation preceded the phase of silica mobilisation. Although evident in thin section, the total amount of silica is probably small as the ferricrete lacks cohesion, and in fact had to be impregnated with epoxy resin before thin sectioning. The source of the silcrete is uncertain, but in the apparently minor amounts in which it is present, it could have been liberated during the weathering of siliceous minerals (such as pyroxene, olivine and plagioclase) in the original basic volcanic rock.

At Uralla Trig., the ferricrete contains weathered olivine; some cut by serpentine, some with rims altered to red-brown iddingsite. The thin section examined (cut from Sample 301, Plate 49), contained abundant ilmenite or magnetite, like the ferricrete from the Sugarloaf. Microcrystalline gibbsite, distinguished from chalcedony by twinning, is common as a cavity fill, and indicates bauxitisation.

Olivine, ilmenite and magnetite are indicative of basic volcanic provenance (Kerr, 1977; Moorhouse, 1959; Simpson, 1966; Wilkinson, 1967). The lack of quartz grains in the highly weathered ferricretes suggests much of the weathering has been in situ, with little mixing of the volcanics with fluvial material in the surrounding environment. The presence of some silica in the ferricrete indicates a phase or phases of silica mobility. The presence of gibbsite indicates partial bauxitisation of some of the ferricrete. This in turn suggests a prolonged period of intense weathering; a situation that would also favour silica mobilisation.

At Mount Butler, Arthurs Seat and Bald Knobs these highly weathered deposits are overlain by fresh basalts, which at Bald Knobs have been dated at 22 my. Even though relative degree of weathering can be an uncertain criterion for establishing the relative ages of different materials, the highly weathered appearance of the basic volcanic-derived ferricrete at Arthurs Seat, and its position beneath almost unweathered, 22 my basalts, suggests the ferricrete is substantially older than 22 my.

Initial attempts to date the highly weathered deposits using palaeomagnetic techniques, have been largely unsuccessful. The exception is a sample, collected from the Sugarloaf during this study, that gave a Jurassic age (Appendix E). This age is tentative, and requires replication before it is accepted, but it indicates the possibility that at least some of this highly weathered material is derived from pre-Tertiary volcanism. Certainly the highly weathered ferricrete at the Sugarloaf and near Mount Butler, (the 'cindery scoriaceous' material of David, 1886) contains structures and minerals that are consistent with a volcanic origin (Plates 60, 61). The relationship between the fresh Tertiary basalt and the highly weathered ferricrete at the Sugarloaf and near Mount Butler, is at first sight ambiguous. The Sugarloaf itself consists of ferricrete, with the gently sloping ground at its base comprising little-weathered basalt (Plate 57). Mineshafts through this basalt 200 m southwest of the Sugarloaf, encountered quartz sand and rounded quartz pebbles, indicating the presence of a deep lead. The size of the waste heaps beside the shafts indicates that the basalt was probably about 5-8 m thick. A small dam 200 m south of the Sugarloaf has also been cut through the fresh surface basalt. At this site the fresh basalt is only about 1.5 m thick, and is underlain by the same ferricrete as that comprising the Sugarloaf.

The degree of weathering and the tentative Jurassic age of the ferricrete comprising the Sugarloaf, makes it very unlikely that this material is as young as the relatively unweathered Tertiary basalt that now covers much of the area. The presence of weathered clasts of basic volcanics in this ferricrete (Plate 60), indicate it probably formed from basaltic parent material. The simplest explanation of the field situation of the Sugarloaf, given its probable basic volcanic provenance, is that it formed a pre-Tertiary topographic high of basic volcanic rock, that stood above the subsequent Tertiary lava flows. These same flows also covered gold-bearing alluvial sediments in a valley at the base of the Sugarloaf. The alluvial quartz and gold in the streams that had incised into the ferricrete of the Sugarloaf, must have been transported into the area, possibly from source areas to the northeast (Figure 18).

6.3.2 WEATHERING BETWEEN FLOWS

The inter-basaltic ferricrete at Armidale sheet GR 633242 (Section 6.3.1), indicates that there were periods between basalt extrusions during which weathering, and mobilisation and concentration of iron minerals took place.

The highly weathered profiles discussed in the previous section are evidence that a long period of chemical weathering intervened between an older period of basalt extrusion and the extrusions between 33 and 22 my. The highly weathered profiles at Uralla Trig. and at Arthurs Seat are at least 10 m thick. Although the depth of weathering suggests a prolonged period of exposure to the subaerial environment prior to the profiles being covered by the more recent basalt extrusions, the actual length of time involved is uncertain. Nahon (1977), working in Senegal, found that 6 my was sufficient time for development of ferricrete profiles up to 5 m thick on basic volcanics. These profiles characteristically consisted of an iron crust underlain by a nodular ferruginous horizon, in turn underlain by a complexly weathered profile formed on the basalts. On this basis, weathered profiles similar in depth to those in the Armidale-Uralla region, may take 12 my or more to develop, though as Nahon (1977) noted, the actual time required for ferricrete development will depend on variations in parent rock, topography and hydrologic regime.

6.3.3 DRAINAGE MODIFICATION AND RELIEF INVERSION

Landscape modification of areas affected by lava flows usually involves relief inversion and drainage displacement (Ollier, 1968; Green and Short, 1971). When valleys are filled or partly filled by lava flows, the stream previously occupying the valley bottom is displaced. It is common for lava flows to be slightly convex upward in cross-section (Ollier, 1968), and as a result the lowest level in the cross-section of the lava-filled valley is often at the contact with the valley side. It is along this contact that the displaced stream often flows.

As lateral streams continue to incise either side of a valley-fill basalt, lateral valleys develop, and if incision continues the basalt will eventually come to form an interfluve between lateral streams. Relief inversion has now taken place (Figure 14). There are several well documented Victorian examples of lateral streams alongside valley bottom lava flows (Ollier, 1967; Hills, 1975)

The first step in working out the drainage modifications that have resulted from basalt extrusions is to find examples of relief inversion. These mark the location of pre-basalt streams, and if sufficient examples of relief inversion are found, the pre-basalt drainage system can be determined. A well documented area of relief inversion in the Armidale-Uralla region is the Rocky River-Arding area to the west and north of Uralla. In this area Tertiary basalt overlies a deep lead of sand and gravel that has been intensively mined for gold (Gardner, 1854; David, 1886). Map 1 shows the present distribution of these basalts in the Armidale-Uralla region. Bore log data, which will be discussed in detail in later sections, also shows sand and gravel underlying the basalt along the probable paths of the pre-basalt drainage lines. These

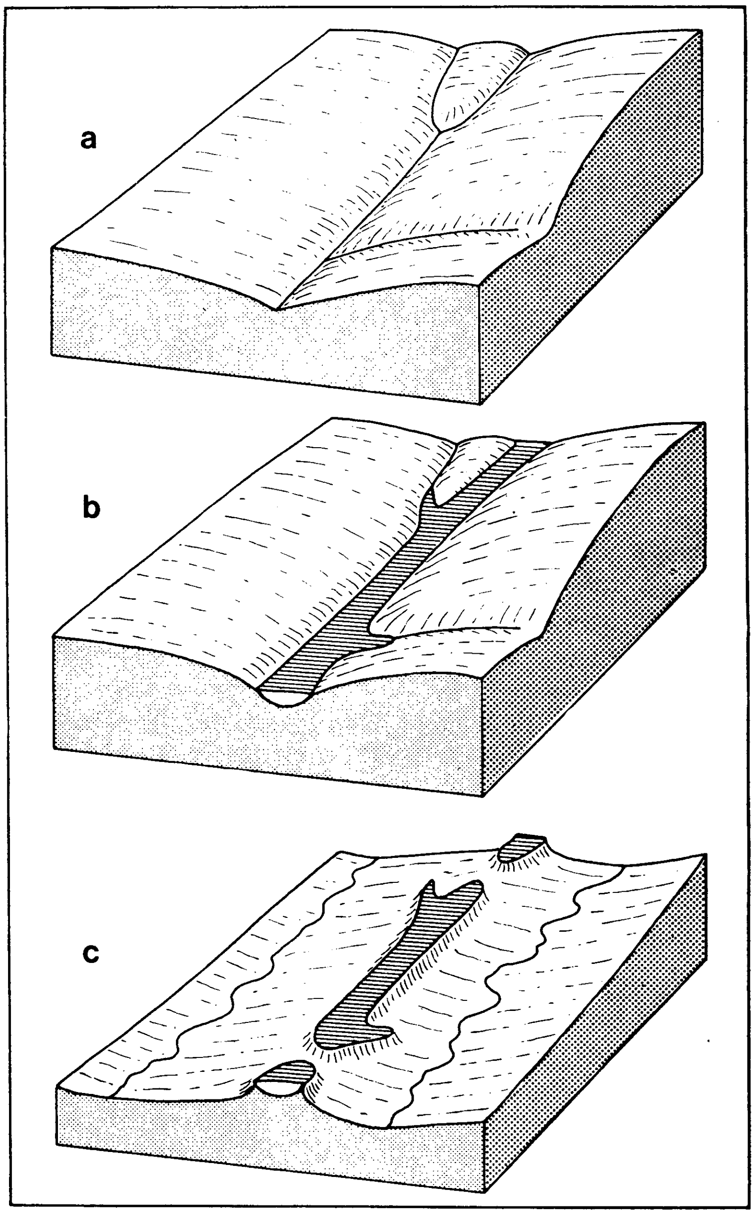

Figure 14. The development of relief inversion. The river valley in (a) is filled by lava (b). Lateral streams develop (c) and incise either side of the flow. This leaves the basalt as a topographic high, inverted from its original position on the valley floor (from Ollier, 1968).

upper slope and interfluve basalts between Uralla and Armidale now mantle much of the Main Divide in this area. This landscape is therefore one of relief inversion.

Two other small but very clear examples of relief inversion are at Gostwyck sheet GR 600040 and Dumaresq sheet GR 565252 (Figures 15, 16). Each of these features consists of an elongate basalt-capped topographic high, about 1000 m long and trending approximately north-south, with deposits of silicified and unsilicified rounded sand and gravel at or near the north and south margins of both.

The feature at Gostwyck (known as the Baumgartner Lead) was mined for gold from about 1912 to 1914. The lead contained gold-bearing sand, averaging 30 cm in depth and 5-6 m in width (N.S.W. Dept Mines, 1912). The thickness of basalt above the lead varied. Three shafts sunk after 1912 bottomed on the alluvial materials at 13, 17 and 31 m. (N.S.W. Dept Mines, 1913, 1914). This final shaft of 31 m encountered 'a seam of water' 14 m from the surface which eventually flooded the shaft and made it unworkable. Prior to this, the lead was followed laterally at the base of the shaft for 80 m, in 'wash dirt' 30-120 cm in depth (N.S.W. Dept Mines, 1914).

The deep lead and relief inversion feature at Dumaresq sheet GR 565252 had not been mined and subsurface information is lacking. I have interpreted it as an example of relief inversion by its margin deposits of silicified quartz sand, and by its dendritic alignment to the relief-inverted basalts of the Main Divide.

Besides these major drainage modifications resulting in relief inversion in the Armidale-Uralla region, there are also examples of minor drainage modification by basalt. Two examples on Saumarez Creek are at Redmans Knob (Dumaresq sheet GR 646257), and at 'Saumarez' (Armidale sheet GR 465193).

At Redmans Knob, Saumarez Creek flows in an arc to the west, around the base of the knob, before resuming its southerly course. At 'Saumarez', Saumarez Creek changes course from south to east around the margin of the

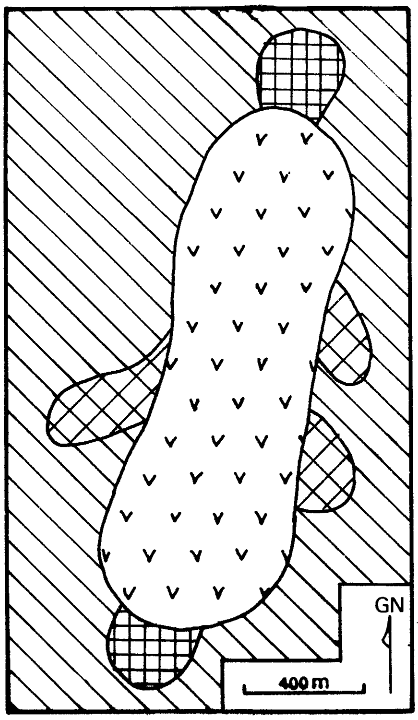

Figure 15. The Baumgartner deep lead at Gostwyck sheet GR 600040. Map symbols are as for Map 1. Gold mine shafts sunk through the basalt between 1912 and 1915 showed that the basalt is underlain by fluvial sediments. I have sampled these sediments from waste heaps near the disused mine shafts.

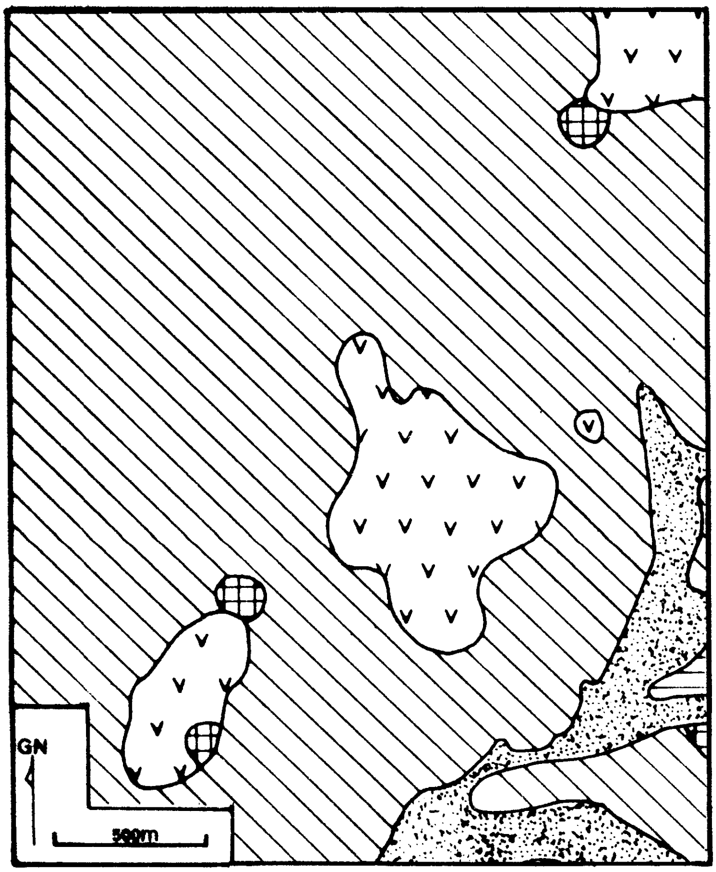

Figure 16. The deep lead at Dumaresq sheet GR 565252 is shown in the southwest corner of the Figure. Map symbols are as for Map 1. The silcrete at the margins of the deep lead consists of silica-cemented rounded sediments and sand. My traverses and mapping at this site show that the palaeodrainage direction suggested by the distribution of the silcrete, is consistent with te deep lead having been a tributary of the larger deep lead underlying much of the Main Divide basalt.

Tertiary basalt (Plate 44). This basalt overlies silcrete containing rounded quartz clasts. It is contiguous with the dated basalts at Armidale Airport 1 km to the north, that overlie gold-bearing fluvial deposits (Section 9.7). At other sites basalt also overlies fluvial sediments, indicating drainage disruption by the basalt. During fieldwork for this thesis, mineshafts through basalt into fluvial sediments were identified at Armidale sheet GR 535008, 535103, 535107, 527107, 529113, 531113, 537120, 531131, 533136, 529129, 640210, and Gostwyck sheet GR 546072. Water bores encountering probable fluvial sediments beneath basalt were identified at Armidale sheet GR 627221 (un-numbered bore near 'Micklegate'), 687200 (bore number 18081; Figure 27), 569169 (bore number 13073; Figure 28), 592163 (bore number 16755; Figure 28), 545199 (bore number 15460; Figure 30).

6.3.4 THE PRE-BASALT SURFACE

There is no general agreement about the amount of basalt that was extruded in the Armidale-Uralla region or in other parts of New England. Working out the landscape modifications due to the basalt extrusions requires an understanding of the pre-basalt surface, but several factors make it difficult to reconstruct this surface in the Armidale-Uralla region. Tertiary basalt extrusions in the area took place over a period of at least 11 my, and possibly substantially longer. The story to be deciphered is therefore one of partial cover and partial stripping of this basalt cover, probably repeated several times. The landscape remnants preserved beneath Tertiary basalts in the Armidale-Uralla region are not remnants of any single landscape that existed in entirety at any one time.

Another factor making it difficult to reconstruct a pre-basalt landscape or landscapes is the discontinuous distribution of the Tertiary basalts. The basalt base can only be determined where the basalt adjoins pre-basalt geological materials such as Palaeozoic Sandon Beds; the granitic rocks of the New England Batholith; and silcrete, which I argue was present in the pre-basalt landscape as sand and gravel.

The usual method of interpreting the pre-basalt surface is to use spot heights on the base of the basalt to construct form lines of the pre-basalt surface (Voisey, 1942b; Galloway, 1967; Warner, 1971). By themselves, form line maps showing the sub-basalt surface cannot resolve the question of how much basalt was extruded in the Armidale-Uralla region. There are at least two reasons for this. First, basalt/pre-basalt contacts are frequently obscured by post-basaltic material such as ferricrete and alluvium (Map 1). Secondly, form line reconstructions are based on the usually unrealistic assumption that all the basalts were extruded within a very short period. Thus the form line map of the sub-basalt landscape in the Armidale-Uralla region (Figure 17) must be interpreted with caution. It shows a sub-basalt landscape that rises to the north of the region, with higher country in the west, along the line of the modern Main Divide. A transverse valley is shown separating the northern and southern sections of the region (Figure 17).

The position of streams in this pre-basalt landscape is uncertain. On the basis of bore log data, mining records, field mapping of fluvial sediments and the form lines in Figure 17, a pre-basalt stream system may have flowed north then west, around the Saumarez-Arding area (Figure 18). In at least the southern half of the Armidale-Uralla region there may have been a drainage divide in about the same position as the present Main Divide. Pre-basalt streams appear to have flowed west from this divide (Figure 18). No pre-basalt drainage is shown in the north of the region. This is due to a lack of subsurface information. The sub-basalt form lines (Figure 18) suggest however, that drainage in this area may have been to the southeast.

6.4 SOURCE(S) OF THE TERTIARY BASALT

The lack of good evidence for the existence of Oligocene-Miocene volcanic vents in the Armidale-Uralla region, suggests that the source of the Tertiary basalts could have been outside the area. The region around Glen Innes,

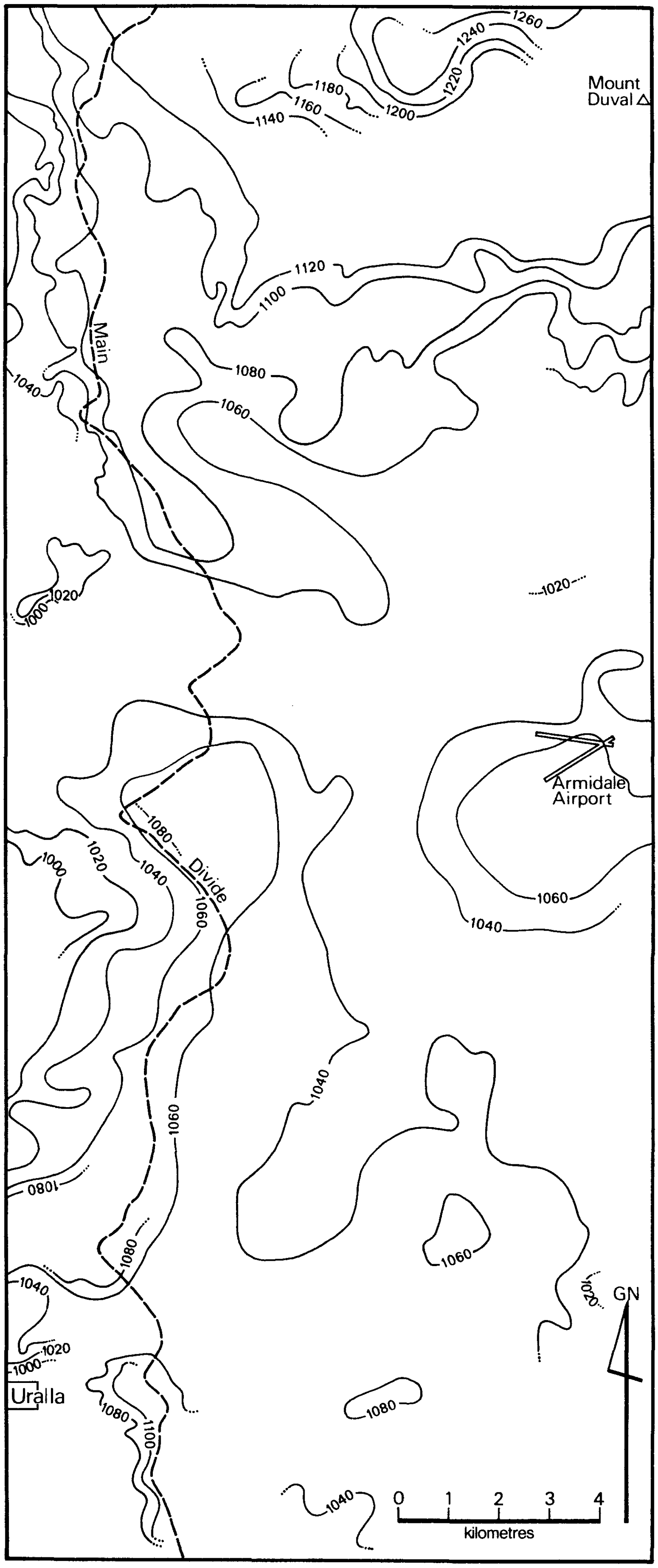

Figure 17. Formline map of the sub-basalt landscape in the Armidale-Uralla region, based on sparse spot height data for the base elevations of basalts extruded over at least 11 my. The sparseness results from the patchy basalt cover, and the lack of contacts with pre-basaltic geological material. The map should therefore be interpreted with caution. The modern Main Divide is shown, and approximates to the location of the main sub-basalt drainage divide in the region. The low country west of Armidale Airport is the site of the modern Saumarez-Arding area (Figure 2), and was possibly a pre-basalt drainage line.

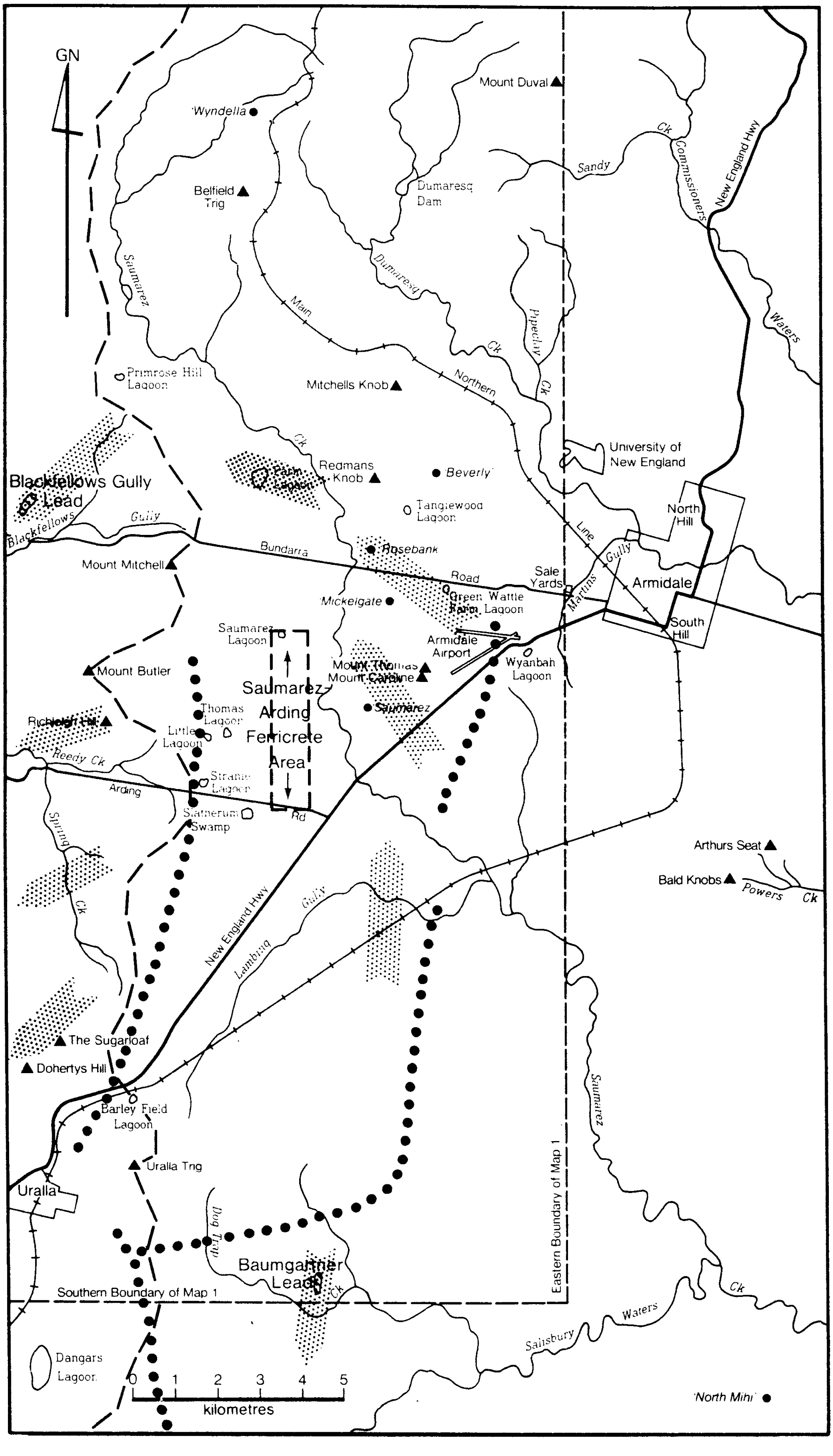

Figure 18. *Possible pre-Oligocene basalt drainage and divides in the Armidale-Uralla region. Stippled arrows show drainage directions; dots show drainage divides. Dashed line shows position of modern Main Divide. Position of pre-basalt drainage and divides has been estimated from bore log data, mining records and field mapping of silcrete containing fluvial clasts. Position of pre-basalt divides has been estimated from the basalt base spot heights used in compiling Figure 17.*

80-100 km north of Armidale is one possible lava source. Flow remnants in this area are still up to 300 m thick (Wilkinson, 1967), indicating that a large volume of lava was extruded

The 34.3-19.0 my age range of basalts dated in the Glen Innes and Inverell areas (Wellman and McDougall, 1974a; McDougall and Wilkinson, 1967) is similar to the age range of dated basalts in the Armidale-Uralla region. The distance these basalts would have had to flow to reach the Armidale-Uralla region is within the range of other basalt flows in Australia, for although alkali olivine lavas are often extruded as flood basalts, inundating large areas (Turner and Verhoogen, 1960), this is not always the case. There are well documented examples of single valley flows over 50 km long in Victoria (Ollier, 1967); and 160 km long in northeast Queensland (Griffin and McDougall, 1975).

A second possibility is that lavas from the postulated Ebor shield volcano flowed as far west as Armidale, but on present information this cannot be verified. The ages so far obtained for basalts in the area (18.2 my for a sample from 6 km northeast of Ebor, and 19.1 my for a sample from Paddys Plain, near Dorrigo) are inconsistent with such a source.

The third possible outside source for the basalt in the Armidale-Uralla region is the Walcha area 70 km south of Armidale (Figures 1, 4). Basalts dated in the Walcha region have ages of 57.5, 48.2 and 45.1 my (Wellman and McDougall, 1974a). The youngest of these is 12 my older than the oldest basalt so far dated in the Armidale-Uralla region, making it unlikely that the Walcha area was the source of basalts extruded in the Armidale-Uralla region.

Of the three regions considered as possible sources for the Tertiary basalt in the Armidale-Uralla region, the area around Glen Innes is the most likely source, as it is the only one of the three areas containing basalts with a similar age range to the basalts in the Armidale-Uralla region. This source is consistent with the approximate north-south orientation of vesicles in the basalt flow remnant at 'Wyndella' 13 km northwest of Armidale, discussed in Chapter 2.

The conclusion that basalt in the Armidale-Uralla region was extruded from regional, rather than minor local sources, does not imply that basalt inundated the landscape in this region. The pre-basalt and post-basalt drainage patterns strongly suggest that this was not the case. It is possible that more sophisticated geophysical measurment and interpretation techniques may show that some features in the Armidale area are volcanic vents, but at present the simplest and best explanation is that the the numerous rocky knolls found on interfluves are flow remnants, not volcanic vents.

In summary, the Tertiary alkali-olivine basalts in the Armidale-Uralla region were extruded from regional vents, possibly in the Glen Innes area, onto a landscape which had significant local relief and a well developed drainage system. The basalt flows modified the drainage pattern but did not completely inundate the landscape. Subsequent erosion has removed much of the basalt and has resulted in widespread relief inversion in the Armidale-Uralla region.

CHAPTER 7

GENESIS AND SIGNIFICANCE OF FERRICRETE

7.1 PREVAILING EXPLANATIONS OF FERRICRETE GENESIS

Explanations of ferricrete development can be grouped into several distinct models.

7.1.1 WATER TABLE FLUCTUATION MODEL

In this model, fluctuations in the water table have been believed to be responsible for the upward movement and subsequent concentration of iron to form ferricrete (Paton and Williams, 1972; McFarlane, 1976). Enriched solutions of iron move upwards with the rising water table in the rainy season, and are precipitated as the water table drops at the end of the rainy season. As iron is moved up through the profile, a pallid zone typically forms in the soil horizons underlying the developing ferricrete horizon. In reality, even where pallid zones are present in the soil profile, it is doubtful that they are always thick enough to have supplied sufficient iron to account for the accumulation of ferricrete in the overlying horizons.

Despite this apparent problem with a water table role in large-scale ferricrete development, in a recent study of ferruginous gravels in north Queensland, Coventry *et al.* (1983) found that the iron oxide mineralogy of glaebules in grey earths indicated periodic saturation of the profile. This saturation was consistent with seasonal water table fluctuations.

7.1.2 RELATIVE AND ABSOLUTE ACCUMULATION MODELS

Douglas (1977) has suggested that ferricrete is a product of the relative accumulation of iron minerals under conditions of intense weathering and good drainage. He argued that under such conditions leaching removes most of the cations and silica from the soil profile, leaving a residue of kaolinitic clays (the pallid horizon) and iron or aluminium oxides (the ferricrete or bauxite horizons). Thus the concentration of iron minerals is the result of removal of non-iron compounds. This contrasts with absolute accumulation, where the total amount of iron minerals in a soil horizon increases as a result of iron minerals moving in from other parts of the soil profile. Absolute accumulation was thought by McFarlane (1983) to be particularly important on lower slopes where there is likely to be a net accumulation of material.

Maignien (1958) suggested that where there is absolute accumulation of iron minerals that have moved downslope and down profile in solution, ferricrete will accumulate and resist erosion, causing relief inversion. In Maignien's model, as erosion continues the ferricrete will come to occupy interfluves. McFarlane (1976) originally also argued that ferricrete now found on interfluves is fossil, having assumed that position by relief inversion. She later modified this view (McFarlane, 1983), to incorporate the realisation that pedogenic ferricrete can form on any surface of low relief, regardless of its topographic position.

7.1.3 PHYSICO-CHEMICAL EVOLUTION MODEL

Ferricrete in Senegal (West Africa) has been shown (Nahon, 1977) to have developed on basic volcanic and sandstone parent rock by a combination of physical and chemical processes. The physical processes involve mechanical weathering of the parent material, and in places incorporation of allogenic material, such as quartz sand, into the developing ferricrete. The chemical processes involve progressive chemical alteration of the minerals and chemical structure of the parent material, until only rare relicts of the original facies remain (Nahon, 1977).

A similar physico-chemical model was suggested by Nahon *et al.* (1980) to explain the development of ferruginous ooids and pisolites in West Africa. The process in this instance was isovolumetric, involving the leaching of potassium, magnesium and silica, and the alteration of glauconite (hydrous potassium iron silicate) to ferruginous and bauxitic compounds.

The physico-chemical evolution of ferricrete is thought to involve leaching, and the subsequent absolute and relative accumulation of iron compounds (Nahon *et al.*, 1977). Thus this model is closely linked to models of relative and absolute accumulation (Section 7.1.2).

7.1.4 IONIC DIFFUSION MODEL

The upward movement of iron by ionic diffusion has also been suggested as a means of ferricrete formation (Thomas, 1974; McFarlane, 1976). In this process ions of iron are removed from well down the weathering profile, diffused upwards and deposited in the zone of ferricrete formation.

7.1.5 CAPILLARITY MODEL

The mechanism of capillarity is yet another suggested means by which iron is mobilised in the soil profile. Capillarity involves the upward movement of iron in solution by capillary action. The iron is subsequently deposited on the ground surface. Capillarity is no longer thought to be instrumental in the development of widespread ferricrete deposits, though it may be of limited local importance (McFarlane, 1976).

7.2 FERRICRETE GENESIS

The development of ferricrete requires the accumulation of iron minerals at a horizon in the soil profile. These iron minerals must come from above, below or adjacent to the zone of iron enrichment. The close field relationship between ferricrete and basalt in the Armidale-Uralla region, and the propensity of basalts to produce hydroxides of aluminium and iron as weathering end products (Simpson, 1966; Nahon, 1977), both suggest that the basalt has been an important source of the iron minerals that were concentrated to form ferricrete. Much previous ferricrete research has been into African ferricrete that is not associated with basalt (for example Goudie, 1973; Thomas, 1974; Ollier, 1976; Young, 1976). Basalt in the Armidale-Uralla region is a weatherable source of iron minerals, and it is reasonable to assume that weathering has released large amounts of iron minerals that have been carried laterally and vertically through the soil horizons as solutes in throughflow and groundwater.

The precipitation of iron minerals in the soil profile may have resulted, at least in part, from decreases in groundwater and pore water solubility. These changes could have been caused by temperature variations (solubility decreases as temperature falls), or by ground and pore water evaporating during dry periods. Much of the ferricrete in the local area is manganiferous, and some is bauxitic. It is probable that the mobilisation and precipitation of manganese, aluminium and iron were contemporaneous events.

In the Armidale area ferricrete profiles frequently lack a pallid zone and for this reason cannot be adequately explained in terms of the upward movement and concentration of iron minerals. Thus the process of ionic diffusion is unlikely to have been of major importance in ferricrete development. The recurring lack of a pallid zone also makes it unlikely that capillarity has been of importance in ferricrete development. Because of the presence of basalt as a source of iron, overlying basaltic soil horizons are one source of iron minerals for ferricrete development. As McFarlane (1976) has noted, such a process does not require the large scale upwards movement of iron minerals, and it is far simpler to visualise iron leaching aided by, rather than against, gravity.

Thus the water table in the Armidale-Uralla region has probably not been the major influence in the development of ferricrete horizons. Besides this, in the Armidale-Uralla region ferricrete has frequently developed above unleached soil or solid bedrock (Plates 50, 51). In neither of these situations can ferricrete have its origin in water table fluctuations and the upward movement of iron. For this reason it is necessary to look at lateral and downwards transport of iron as possible mechanisms of ferricrete formation.

It is likely that ferricrete in the Armidale-Uralla region has not developed solely by the vertical movement of iron minerals. Lateral movement of iron-rich groundwater and pore water have probably been important, as shown by Nahon et al. (1977) for ferricrete in West Africa. Several workers (such as Young, 1976) have pointed out that the thickness of the overlying rock needed to provide the iron present in many thick ferricrete horizons, usually far exceeds the depth of the soil immediately overlying the ferricrete. If this is so, and as basalt soils and ferricrete deposits in the Armidale-Uralla region have frequently developed downslope of basalt outcrops, mobilisation of iron downslope is likely. The operation of this process in the modern Armidale-Uralla region has been verified in studies of solute and suspension transport on and through slopes in the area (Bevan, 1970; Zakaria, 1977; Lam, 1979; Hutchings, 1981; Field, 1983). In his study of runoff, solutes and sediments in a small catchment on the southern slopes of Mount Duval, Lam (1979) found that Hortonian type overland flow was rare, and subsurface flow moved most sediments and solutes. The study catchment was on granitic rocks, and the results may be only partly applicable to less permeable basaltic soils, but Lam (1979) established the efficacy of throughflow in transporting solutes and sediments in the Armidale-Uralla region. Unfortunately this is not evidence for the operation of the model proposed by Maignien (1958), in which ferricrete is thought to form by the absolute accumulation of iron minerals that have moved downslope and down profile in solution. But if Maignien (1958) is correct, much of the ferricrete in low topographic positions in the Armidale-Uralla region may have formed in this way. Work in West Africa (Nahon et al., 1977) has established a clear relationship between slope position and stage of ferricrete development, with the best developed ferricrete on lower slopes. Even ferricrete now on interfluves in the Armidale-Uralla region may have undergone this sequence of downslope accumulation of iron. It would have involved iron minerals in solution moving downslope and down profile before precipitating, undergoing denudation, and being stranded as cappings on basalt interfluves. The close field relationship between ferricrete and basalt, and the examples of basalt relief inversion in the local area (discussed in Chapter 6) add to this likelihood.

The widespread absence of pallid zones in exposed ferricrete horizons in the Armidale area militates against relative accumulation being the sole cause of ferricrete development, and suggests that absolute accumulation is also operating. Relative accumulation may be most important at sites where drainage and weathering conditions cause localised leaching of non-iron minerals. This would result in fairly narrow bands of ferricrete forming from the residual iron-rich material.

Much of the ferricrete in the Armidale-Uralla region is consistent petrographically and stratigraphically with development by physico-chemical processes involving absolute accumulation of iron compounds, as discussed by Nahon et al. (1977). In many cases, ferricrete has developed in soil profiles overlying basaltic parent rock. The parent rock grades upwards into weathered subsoil which in its upper horizons often incorporates ferruginous nodules. This horizon is characteristically overlain by a horizon of nodular ferricrete, which either forms the ground surface, or is itself overlain by up to 45 cm of iron-depleted, light-coloured soil. The characteristic texture and colour of this soil is consistent with prolonged leaching. The variable thickness of the overlying soil suggests it is probably in the later stages of removal by erosion. At the time of time of maximum ferricrete development the soil cover (and hence the amount of leachable iron) may have been considerably greater.

It is likely that where ferricrete boulders and cobbles contain sand fractions, but the soil associated with the ferricrete does not, the ferricrete was formed from different parent material than the soil with which it is now associated. The soil originally associated with the ferricrete has eroded, leaving the remnants of the ferricrete as lag deposits on underlying material.

It has been suggested (McFarlane, 1971; Young, 1976) that the ferricrete profile is lowered along with the ground surface as slopes evolve. If ferricrete profiles do maintain their depth during slope lowering, exposures of ferricrete would only be expected where the sub-surface ferricrete has been indurated. Once ferricrete is indurated it should be largely unmoved during continued slope lowering, and will eventually be exposed by erosion. This is probably the case in the Armidale area where the degree of induration, and the presence of ferricrete as relief-inverted features, suggests much of the ferricrete is relict.

7.3 SOURCES OF QUARTZ GRAINS IN FERRICRETE

The shape, extinction patterns and abundance of fluid inclusions in quartz can help in working out likely quartz grain provenance. Angular quartz clasts are unlikely to have been transported far, while rounded clasts have almost certainly been transported a considerable distance. The angularity of sand-sized quartz grains is probably a poor indicator of transport distance however, as their rate of rounding in rivers is extremely slow (Folk, 1968). This is partly due to the low coefficient of abrasion of quartz (Douglas, 1977), and partly due to the small mass, and hence low momentum of sand-sized grains.

The extinction pattern of quartz grains under crossed nicols has been linked to provenance. On the basis of his own work and that of others, Folk (1968) suggested that straight to slightly undulose extinction is characteristic of igneous provenance. In this view, increasing undulosity is an indicator of progressively greater strain, indicating increasing metamorphism.

This view is opposed by Blatt (cited by Folk, 1968), who argued that there is no real difference between the extinction patterns of quartz grains in igneous and metamorphic rocks. I have attempted to at least partly overcome this conflict by also considering fluid inclusion abundance and the type of quartz grains present. There is at least some agreement (Folk, 1968) that polycrystalline quartz grains indicate probable metamorphic provenance, while medium sized grains comprising few crystals are commonly of granitic origin.

Examination of fluid inclusions in rock samples is recognised as one means of identifying possible source areas (Craig and Vaughan, 1981; Folk, 1968; Roedder, 1977, 1979). An abundance of fluid inclusions in quartz grains suggests vein origin, while the presence of few fluid inclusions, especially if linked with straight or slightly undulose extinction, is typical of granitic origin (Folk, 1968).

Any study of quartz grain provenance must consider what materials are actually available as possible quartz sources. In the Armidale-Uralla region the main possible sources are granitic rocks (mainly adamellite and granodiorite) of the New England Batholith, and quartz veins in the Sandon Beds.

Variations in the size, shape, extinction patterns and fluid inclusion abundance of quartz grains (Section 3.2.3; Appendix F), suggest the quartz in ferricrete in the Armidale-Uralla region has been derived from both granitic and vein sources, as illustrated by the following examples.

The main source appears to be granitic,with most quartz consisting of single grains with few fluid inclusions and straight to slightly undulose extinction. Samples 135 and 286 (Section 3.2.3; Plates 8-11; Appendix F) are representative of this group.

Despite the overall strong suggestion of a common granitic provenance for both the matrix and glaebule quartz in Samples 135 and 286, there are important differences in the extinction patterns of quartz grains in Sample 135. The matrix quartz in this sample of nodular vesicular ferricrete is mainly composed (83%) of grains with straight extinction and few fluid inclusions. In contrast, only 55% of the glaebule quartz has straight extinction and few fluid inclusions. This difference is significant at the 0.001 level (X^2=17.71; 2 degrees of freedom).

Sample 135 is from a ferricrete exposure adjacent to Saumarez Creek at Armidale sheet GR 600191 (Map 1), within several metres of the modern creek level. It is likely that the matrix and glaebule quartz was derived from sources within the Mount Duval Adamellite and/or Tilbuster Granodiorite that outcrop extensively 11 km to the north. Given the difference in extinction/inclusion characteristics of the matrix and glaebule quartz, they may have been derived from quite different sites within the granitic rocks, and transported to GR 600191 by Saumarez Creek. This is consistent with the evidence for an inherited (transported) origin for the glaebules in Sample 135, set out in the caption to Plate 8.

There are not always such differences between matrix and glaebule quartz grains within samples. For example Sample 286 (Plates 10,11), a massive nodular ferricrete, has almost identical extinction/inclusion characteristics for matrix and glaebule quartz (appendix F). The minor differences are not significant at the 0.2 level ($X2$=1.32; 1 degree of freedom). Despite this similarity in extinction/inclusion characteristics, quartz grains in the matrix are generally much larger than those in glaebules (up to 0.5 mm, compared with less than 0.1 mm for glaebule quartz). This size difference is consistent with the evidence for an inherited (transported) origin for the glaebules, set out in the caption to Plate 11.

Even with these differences it is probable, on basis of the very similar extinction/inclusion characteristics of matrix and glaebule quartz grains, that they have similar granitic provenance. Sample 286 is from an exposure at Armidale sheet GR 577230, 1 km east of Mount Mitchell (Figure 2), and the closest granitic outcrops are 8 km to the north, where there are extensive outcrops of Mount Duval Adamellite and Tilbuster Granodiorite (Map 1). No modern drainage runs from the Mount Duval area to GR 577230, but neither are there granitic exposures elsewhere that drain through this site. Therefore the quartz grains in Sample 286 are probably relict; either from an ancestral Dumaresq Creek draining the Mount Duval area, or from a pre-basalt stream in the Mount Mitchell area. If the latter is the case, the quartz grains could be derived from the Uralla Granodiorite in the vicinity of Uralla. This source would be consistent with the possible pre-basalt drainage system in the Armidale-Uralla region (Figure 18).

Some ferricrete, such as Sample 145 discussed in Section 3.2.3, contain quartz grains that appear to be derived from at least two different sources. The petrography of both matrix and glaebule quartz grains in Sample 145 suggests that about 75% of the quartz grains are of granitic provenance, with most of the remainder derived from quartz veins. The sample was collected at Dumaresq sheet GR 602281, on the floodplain of Dumaresq Creek, 1.5 km east of Primrose Hill Lagoon (Figure 2; Map 2). Rocks of the Sandon Beds, containing numerous quartz veins, outcrop throughout this area (Map 1), and are a possible source of the fluid inclusion-rich quartz component of this sample. The Sandon Beds in the area are also the likely source of the chert clasts in the sample. The quartz grains with few fluid inclusions may have weathered from Mount Duval Adamellite and Tilbuster Granodiorite, which outcrop extensively 6 km to the north (Map 1). Both vein and granitic quartz grains could have been transported to GR 602281 by Saumarez Creek. The angularity of the chert clasts in Sample 145 suggests transport over a fairly short distance.

As with Sample 135 above, there are some subtle but important differences between matrix and glaebule quartz in Sample 145. Straight extinction is charactistic of 56% of glaebule quartz, but was a feature of only 24% of matrix quartz (Appendix F). The differences in extinction/inclusion characteristics in matrix and glaebule quartz in Sample 145 are significant at the 0.001 level (X2=33.69; 2 degrees of freedom). This suggests that glaebule and matrix quartz were probably derived from different sites within the vein and granitic parent material.

7.4 AGE OF FERRICRETE

The presence of scattered surface concretions and sub-surface ferricrete horizons in close proximity to each other but at different elevations in the Armidale-Uralla region, suggests that ferricrete in the area was not formed as a single ferricrete horizon related to a particular phase of climate or stage of landscape evolution. For this reason ferricrete in the Armidale area cannot be used as an indicator of a marked change in climate or style of landscape evolution. Despite multiple horizons of ferricrete now visible in the Armidale area, the existence of a single ferricrete surface was an important postulate in the landscape reconstructions of earlier workers such as Voisey (1942a, 1942b 1957, 1963) and Warner (1971, 1975). Francis and Walker (1978a) described what they called multiple laterite surfaces around Armidale, but their interpretation of ferricrete surfaces in the Armidale area should be viewed with caution as the degree of extrapolation involved is high. From incomplete subsurface data thay have drawn ferricrete outcrops as being continuous beneath basalt residuals and other features in the Armidale region. On this basis they concluded that ferricrete deposits at different elevations in the Armidale area are the remnants of multiple ferricrete surfaces.

Topographic position does not necessarily indicate the relative age of ferricrete, because ferricrete develops in soil horizons, and these form sub-parallel to the surface. Thus ferricrete at different elevations on a slope may be of the same age.

The periods of silcrete and ferricrete development in the Armidale-Uralla region overlap. At a site 8 km southwest of Armidale at 'Saumarez' (Armidale sheet GR 605192; Plate 52), ferricrete cements cobbles of silcrete. The silcrete cobbles are almost certainly older than the ferricrete cementing them. On a smaller scale, 4 km west of Armidale, silcrete hand specimens contain ferricrete pisoliths (Plate 35), indicating the silcrete in them is younger than the ferricrete.

There is no reasonable doubt that much of the iron that has accumulated to form ferricrete in the Armidale-Uralla region has weathered from ferromagnesian minerals in the Tertiary basalt of the area. This means the ferricrete probably post-dates at least the oldest basalt. Some ferricrete is almost certainly much younger, having formed in soil profiles on contemporary flood plains and lower slopes. For example there are good outcrops of nodular ferricrete in the banks of Martins Gully near the Armidale Saleyards (Armidale sheet GR 668223).

Midslope and upper slope ferricrete that may have been relief-inverted cannot have formed until the basalt had weathered to form a soil profile in which mobilisation and concentration of iron minerals could take place. The oldest possible age for this oldest ferricrete is probably early Miocene. Deposits in low topographic positions could be substantially younger.

As well as this post-basalt ferricrete development, there was also ferricrete development during the long period of basalt extrusions between 33-22 my, as shown by the presence of inter-basaltic ferricrete in the Armidale-Uralla region (Plate 59; Francis and Walker, 1978a). Elsewhere in New England, Bayliss and Loughnan (1963) have argued that there was penecontemporaneous ferruginisation of basalts at Inverell, citing as evidence the concentrations of bauxite minerals at various depths below the surface in mine shafts and open-cut mines excavated in basalt in the area.

7.5 LANDSCAPE SIGNIFICANCE OF FERRICRETE

The main landscape significance of ferricrete in the Armidale-Uralla region is that it acts as an erosion resistant horizon or surface capping, and changes of slope on valley sides often coincide with the outcropping of a ferricrete horizon. The landscape significance of ferricrete in the Armidale area is not unique. Pallister's (1956) work in Buganda showed that slopes on ferricrete tended to develop through parallel retreat, with the protective caprock of ferricrete on the interfluves resulting in relief inversion. Pallister (1956) thought that after the protective ferricrete caprock was removed by erosion, slopes become subject to decline and gradual lowering. Thomas (1974) argued on the basis of African experience that surfaces unprotected by ferricrete duricrust are lowered more rapidly than ferricrete capped surfaces.

A similar conclusion was drawn by Ollier and Tuddenham (1962) about duricrust-capped hills in northern South Australia. The duricrust in the region is siliceous, in bands 0.6-4.6 m thick. Siliceous duricrust has a landscape effect similar to that of ferricrete duricrust, and Ollier and Tuddenham (1962) found that where slopes were capped with duricrust the softer rock beneath the duricrust was protected from erosion. As a result duricrust-capped slopes were steeper than slopes without duricrust. They concluded that 'the hard band acts as a datum for slope development just as certainly as base level'. Development of the duricrust-capped slopes was thought to take place by gradual undercutting of the duricrust cap with resulting periodic collapse of the unsupported duricrust. Ollier and Tuddenham (1962) argued that the rate of retreat of the slope as a whole was governed by the rate of retreat of the duricrust cap. Many interfluves in the Armidale-Uralla region contain ferricrete, more usually as discrete outcrops than as extensive surfaces. On this basis it is probable that the ferricrete caprock which originally caused relief inversion of these ferricrete deposits was once much more extensive, but is now in the later stages of erosion.

The clustering of ferricrete base elevations at 1025-1085 m (Figure 6), does not mean that there is an extensive, erosion-resistant ferricrete surface developed at this elevation. Ferricrete does not form a new topography when it develops. Unlike basalt for example, which can infill valleys either wholly or partly, ferricrete develops within the existing topography. Only when it has been exposed by erosion can it affect the topography of the landscape. The modal distribution of ferricrete base elevations in the Armidale area appears to be the result of a modal distribution of elevations in the pre-ferricrete landscape.

Ferricrete develops sub-parallel to the existing topography, and a pre-ferricrete landscape could be expected to have the same morphology as the ferricrete covered landscape that has developed from it. Paton and Williams (1972) recognised the difficulties involved in correlating landscapes capped by ferricrete. Such correlations usually involve 'the unproven assumption that the laterite is about the same age as the surface it overlies', and attempts at correlation 'can lead to circular reasoning whereby a surface is identified on the basis of laterite morphology, and the laterite is dated by reference to the surface on which it occurs' (Paton and Williams, 1972).

Voisey, (1957) recognised a 'laterite surface' in the Armidale area. The criteria he used to map it were level topography, the presence of 'laterite soil profiles in some places and much broken laterite in others', and the presence of swamps and lagoons. Others, such as Francis and Walker (1978a), have also referred to ferricrete surfaces in the Armidale area and other parts of New England. These references appear erroneous. A landscape containing ferricrete is not a ferricrete erosion surface. Nowhere in the Armidale-Uralla region does ferricrete appear to exist as a surface in the sense of it being an erosion surface or an indicator of a once more extensive ferricrete surface.

In the African context this was recognised by McFarlane (1971) who concluded that the Buganda surface in Uganda 'is neither a planation surface nor a single surface of high relief'. McFarlane's (1971) use of the term 'surface' referred only to the material comprising the ground surface and involved no connotation that there was a pre-ferricrete or post-ferricrete surface after the fashion of pre-basalt and post-basalt surfaces. Moss (1965) was also aware of the problems involved in drawing conclusions about the significance of surfaces of ferricrete. He wrote that in ferricrete of pedological origin in Africa, 'clearly the present occurrence represents a level which corresponds fairly closely to the original surface on which it was formed'. If ferricrete is formed as a result of water table fluctuations not closely related to surface topography this correspondence does not apply. In this case 'the present occurrence of hard laterite is then not the fossilised remnant of an old surface, but the relic of a certain level more or less deep in the regolith' (Moss, 1965).

I have argued in this Chapter that it is unlikely that much of the ferricrete in the Armidale-Uralla region developed solely as a result of water table fluctuations. It is more likely that iron minerals have been moved downslope and down profile in solution, before accumulating to form ferricrete. In this case ferricrete has probably developed in bands approximately parallel to the land surface. Thus the present ferricrete topography (Plates 46, 47, 59) probably approximates to the topography at the time of ferricrete development.

CHAPTER 8

GENESIS AND SIGNIFICANCE OF SILCRETE IN THE ARMIDALE-URALLA REGION

8.1 GEOCHEMISTRY OF SILICA

The element silicon combines with oxygen to form silica (SiO_2) minerals such as quartz, opal, cristobalite, tridymite and chalcedony. Silicon also combines with oxygen to form silicates; compounds consisting of arrangements of SiO_4 tetrahedra (Krauskopf, 1967), and with metallic elements such as aluminium, iron, calcium and magnesium.

Quartz has a very low solubility of about 10 ppm of Si02 at ordinary temperatures. Silica gel has a higher solubility of about 120 ppm. When silica does dissolve in water it forms silicic acid (H_4SiO_4), which when supersaturated, slowly becomes a sol, with the silica in colloidal suspension. If sufficient excess silica is available, the sol either forms a gelatinous precipitate or a uniform gel. Only colloidal silica coagulates; silica in true solution does not (Krauskopf, 1967).

8.2 THEORIES OF SILCRETE DEVELOPMENT

Australian silcrete frequently forms an erosion-resistant caprock, which is often underlain by bleached or mottled country rock (Hutton, Twidale and Milnes, 1978; Milnes and Twidale, 1983). Beds of silcrete in Australia are commonly 1-2 m thick, sometimes up to 5 m, and almost always display vertical jointing (Langford-Smith, 1978). Hutton, Twidale and Milnes (1978) reviewed a number of theories of silcrete development and concluded that the microcrystals of quartz in silcrete may have grown directly from solution, or from 'some form of silica gel such as is readily obtained by the precipitation of silica'. Ollier (1978b) argued that silica is released by the weathering of silicates, and is then transported in either surface water or groundwater. This silica was thought to precipitate around clean quartz sand nucleii to form silcrete.

In the Walgett-Cumborah area of central northern New South Wales, silcrete consists mainly of well silicified coarse to medium grained sand (Taylor, 1978a). Taylor suggested a local source for the silica in the silcretes outcropping in the Barwon River, as 'the fluvial sediments in the area are quartz-rich'. Given the ability of silica to be transported in solution in surface or groundwater, it is not necessary to argue for an in situ source for the silica in these silcretes. The same argument applies in other areas where a local source is suggested for the silica cement in silcrete. The possibility of contributions of silica from elsewhere should always be considered.

Silcrete has sometimes been explained as the remains of a ferricrete profile from which the iron-rich zone has been removed by erosion (Mohr, 1933; David, 1950, Vol.1). This idea envisaged silica being leached from upper soil horizons and precipitating beneath the ferricrete horizon formed by relative accumulation of iron minerals. Langford-Smith and Dury (1965) disputed this explanation on the basis of field evidence in northwestern New South Wales. They argued that such explanations 'raise grave geomorphic difficulties' due to the assumptions of peneplanation that are often involved in hypotheses of ferricrete formation, and the difficulty of correlating largely unfossiliferous strata.

Langford-Smith and Dury (1965) concluded that the hypothesis that surface silcrete has been exposed by the erosion of overlying ferricrete 'can be disposed of by recognising that silcrete, as opposed to laterite, is characteristic of dry inland areas'. The situation is less simple than this. As Langford-Smith and Watts (1978) made clear, silcrete is found in close association with ferruginous weathering products at numerous sites throughout Australia, and ferruginous weathering products are usually taken to be indicative of humid conditions. Silcrete has formed in a humid environment in coastal southeastern New South Wales. Silcrete deposits in this region cover a wide topographic range, from just below sea level to an elevation of 700 m (Young, 1978a). In contrast extensive silcrete is found low in the topography in regions of Australia that are now arid to semi-arid. An example is the silcrete of the Yuleba hardpan in southeast Queensland (Van Dijk and Beckmann, 1978). Silcrete in such low topographic positions may have formed more recently than other silcretes, in climatic conditions conducive to rapid evaporation of silica-rich surface and near-surface waters. In Western Australia, silcrete forms topographic highs in low-relief landscapes, and grades laterally into ferricrete. Van de Graaff (1983) suggested such catenas formed in a hot, humid and strongly seasonal climate, with rainfall over 1,000 mm/yr. In contrast, Wopfner (1983) argued that silcrete in the Cologne Embayment, West Germany formed in an arid-alkaline environment. He further suggested this silcrete formed similarly to the Group I and II silcretes derived earlier from studies of Australian examples (Wopfner, 1978; Chapter 4 this thesis).

Silcrete from both inland and coastal areas in Australia appears to be petrographically similar, but the development of these silcretes may differ. Coastal and highland silcretes appear to have developed as silica-rich groundwater has been channeled into sub-basalt sand and gravel, very often in deep leads. The genesis of silcrete in inland areas appears to more often involve the broad-scale mobilisation and precipitation of silica in sediments covering wider areas than coastal and highland examples. Evaporation of silica-rich surface and near-surface water is possibly a major cause of silica precipitation in hot, low relief inland locations.

A major field relationship of much Australian silcrete is its frequent close association with Tertiary basalt. Although this association has been frequently described (Raggatt, 1938; Süssmilch, 1940; Galloway, 1967; Browne, 1972; Taylor and Smith, 1976; Ollier, 1978b), no firm genetic relationship has been demonstrated. Despite the lack of proof, theories about the development of silcrete have often suggested a causal link between silcrete and Tertiary basalt. For example Browne (1972) thought that sub-basalt sands and gravels were silicified by silica released during the weathering of overlying basalt. He claimed 'there can be little doubt that the solutions responsible for the changes in the original deposits were somehow connected with the basalts'.

Francis and Walker (1978b) argued that silcrete in the Armidale area is of subaerial origin and that it pre-dates the Tertiary basalt extrusions. The bases of their arguments were that there is no close relationship between the distribution of basalt and silcrete, and that silcrete not now near basalt cannot have been exhumed from beneath an eroded basalt cover, because little basalt was extruded from the minor local vents they claim existed in the Armidale area. Other theories for the development of silcrete have included development of the rock directly from basalt; heating of interstitial water in underlying sediments by molten basalt, resulting in the solution, then re-precipitation of silica; and the leaching of silica from basalt by late deuteric activity (Taylor and Smith, 1975).

Taylor and Smith (1975) disputed the view of workers such as Ollier (1978b) that silica in silcrete is derived from weathering basalt. They argued that if this were the case, trace elements (such as Cr, Ni, V) in the basalt would also be released, and should be present in the silcrete. These elements are not present in silcrete, and Taylor and Smith (1975) thought that the basalt does no more than act as a protective caprock over fluvial sand and gravel while groundwater percolates through the sand and gravel dissolving and re-precipitating silica. Ollier (1978b) suggested that the reason for the absence of trace elements from silcrete, may be that there are 'no suitable mineral sites in a silcrete for these elements to find a hold'. This suggestion is unproven.

Hutton, Twidale and Milnes (1978) have suggested that despite silica often being present in groundwater, silcrete is not forming at present. They gave no supporting evidence for this claim, but concluded that geologic and geomorphic evidence shows that silcrete 'is associated with entropic surfaces of low relief that have developed through long periods undisturbed by diastrophism': silcrete is thus the 'result of prolonged pedogenic activity under stable environmental conditions'. These claims are not substantiated by field evidence.

8.3 GENESIS OF SILCRETE

Most of the silcrete in the Armidale area is composed of variably sorted silica-cemented sediments of fluvial origin (Plates 22-36). It is possible that the silica cement moved as a solute in groundwater, as suggested by Milnes and Twidale (1983), but with the added protection of a caprock of Tertiary valley-fill basalts. The silica in solution in the groundwater was most likely derived from the upstream weathering of basalt and siliceous rocks of the Sandon Beds, as shown in the schematic section in Figure 23.

Francis and Walker (1978b) argued that silcrete in southern New England formed subaerially in pre-basalt times. They cited four strands of evidence in reaching this conclusion. Some of this evidence is contentious and is discussed below.

1. Francis and Walker (1978b) reported that a disconformable contact between silcrete and overlying basalt, in a road cutting 19 km south of Armidale, shows that the silcrete formed before the basalt was extruded. The evidence in this road cutting is now ambiguous because of slumping and erosion, but this deterioration has taken place since Francis and Walker's inspection (G.T. Walker, Univ. New England, pers. comm.). While the cutting does contain silcrete clasts and basalt, and some silcrete that is

topographically lower than basalt, there are also good outcrops of silcrete on the ground surface, higher in the topography than some of the basalt. Because of this it is difficult to draw any conclusions about stratigraphic relationships or the relative ages of the basalt and the silcrete at this site.

2. Francis and Walker (1978b) found fluvial sediments containing silcrete clasts, underlying basalt in the Armidale area. They concluded from this that 'the silcrete must pre-date the basalts, and be Eocene or older'. I suggest that the only conclusion that can be drawn is that some of the silcrete in southern New England is older than some of the basalt. No regional conclusion can be drawn from this evidence about the age relationship between silcrete and Tertiary basalt.
3. Francis and Walker (1978b) claimed that 'no close relationship exists between the distribution of basalt and silcrete'. My mapping in the Armidale-Uralla region (Map 1) shows this is not the case. At most sites where the relationship is clear, silcrete is contiguous with basalt, either underlying it, or being topographichally lower than it. For nearly all the silcrete in the Armidale-Uralla region, a sub-basaltic origin is therefore possible, and Francis and Walker (1978b) were not justified in ruling out this possibility.
4. Francis and Walker (1978b) argued that it is difficult to link basalt with the development of what they call breccia silcretes (silica-cemented brecciated chert). This argument is solid, and there is no evidence that most of this silcrete, such as that at North Mihi 20 km south of Armidale (Figure 2), was ever covered by basalt. It is likely though, that silica-cemented brecciated chert is of a similar age to some of the other silicified sediments in the Armidale-Uralla region. This is so because the silicification of brecciated chert would have been enhanced by the same environmental conditions that enabled silicification of fluvial sediments.

Much of the clastic component of silcrete in the Armidale-Uralla region originated as sand and gravel in pre-basalt stream channels. The cause of the variable but characteristic cementation of sediments on the margin of deep leads while sediments in the centre of the deep lead often remain unsilicified, is unclear. The preferential silicification of the margin sediments may have been related to slower flow of subsurface water along the margins of the deep lead and a resulting increase in the rate of silica precipitation in these areas. It may also have been related to temperature variations in the deep lead groundwater, resulting in lower silica solubility at the margins of the deep lead, and subsequent precipitation of silica. On the available evidence these can be no more than suppositions.

As the sand and gravel clasts of the local silica-cemented fluvial sediments were in or near creek beds at the time of cementation these materials occupied low parts of the pre-basalt landscape. Thus they were well situated for saturation by the silica-rich groundwater from which the silcrete cement was precipitated. Thin sections indicate that the clasts in some silcretes are etched by weathering (Plates 29, 35), but this is not ubiquitous (Plates 25, 37). Thus it is almost certain the silica cementing of the clasts involved at least some absolute accumulation of silica transported in solution.

The silica cement in silica-cemented brecciated chert probably originated as silica transported in solution. Though its precise origin is unclear, some of it, as suggested by Francis and Walker (1978b), may have been released from argillites associated with the Sandon Beds, as they weathered to form kaolinitic clays. Once fractured by weathering, the bedrock would have been susceptible to recementation by silica precipitated from percolating groundwater. As the chert clasts in silica-cemented brecciated chert show no evidence of fluvial transport (Plates 38, 39), they may never have been on or near valley floors. It is possible that the disintegration and silica cementation of the chert could have preceded the silicification of fluvial sediments in the Armidale-Uralla region, and may have even taken place before the chert was exposed at the surface by erosion.

8.4 SOURCES OF QUARTZ

Examination of the extinction/inclusion characteristics of quartz grains (Section 4.2.1; Appendix F) showed that most grains have straight to slightly undulose extinction, with a variable abundance of fluid inclusions. Most grains consist of single crystals, though overgrowths are common in some samples. The significance of extinction/inclusion characteristics is reviewed in Section 7.3.

Much of the silcrete in the Armidale-Uralla region contains quartz grains that appear to be derived from both granitic and vein sources. Sample 289 (Plates 36,37) for example, contains a wide variety of grain types. Quartz grains with few fluid inclusions comprise 55% of the sample, while grain with abundant fluid inclusions comprise 39%. This suggests significant contributions of both granitic and vein quartz. The sample was collected from an outcrop at Armidale sheet GR 581185, on the western edge of Thomas Lagoon (Maps 1, 2; Figure 18).

I have argued (Section 8.3) that the sand and gravel now cemented in silcrete was originally fluvial sediments in pre-basalt streams. If this is the case, possible source areas for quartz grains should be consistent with suggested pre-basalt drainage lines (Figure 18). The closest outcrops of Sandon Beds, the probable source of most vein quartz in the Armidale-Uralla region, are 8 km to the southeast, and 10 km to the south (Map 1). The closest outcrop of granitic rocks consistent with suggested pre-basalt drainage directions, is 9 km to the south, where Uralla Granodiorite outcrops near Uralla township.

The abundance in Sample 289, of quartz grains suggestive of vein provenance, could be due to the smaller outcrop area of granitic rocks compared with Sandon Beds, in the possible quartz source areas. This would partly overcome the more plentiful supply of quartz grains from granitic rocks than from quartz veins within the Sandon Beds.

Sample 056 (Plates 34, 35) is from a silcrete outcrop at Armidale GR 656227, within a larger area of sand and gravel, cemented to varying hardnesses by siliceous and ferruginous cements. The inherited (transported) ferruginous glaebules in the sample reflect this mixed heritage. Quartz grains with abundant fluid inclusions account for 67% of grains in the matrix of Sample 056, while 17% of grains contain few fluid inclusions. This suggests vein quartz was the major source of quartz in the matrix of Sample 056, with a minor contribution from granitic sources.

The location of pre-basalt streams is uncertain in the area where Sample 056 was collected (Figure 18), but there are numerous outcrops of Sandon Beds as close as 1 km to the east and north, forming much of the eastern margin of the variably cemented sediments (Map 1). The closest outcrops of granitic rocks are the Mount Duval Adamellite and Tilbuster Granodiorite 8 km to the north (Map 1). The extent and close proximity of rocks of the Sandon Beds is consistent with the abundance in Sample 056, of quartz grains with many fluid inclusions.

The ferruginous glaebules in Sample 056 also contain numerous quartz grains, and these have quite different extinction/inclusion characteristics to the matrix quartz grains in the silcrete (Appendix F). These differences were significant at the 0.001 level (X2=75.41; 4 degrees of freedom). In comparison with the matrix quartz, the quartz in the glaebules is far more likely to have slightly undulose rather than straight extinction. More importantly, over half the glaebule quartz has few fluid inclusions compared with less than one-quarter of the matrix quartz.

The minor variations in undulosity can perhaps be explained in terms of different source areas within the same parent rock. The difference in fluid inclusion abundance suggests that in comparison with the matrix quartz, a larger proportion of glaebule quart has granitic provenance.

Three factors suggest an inherited (transported) origin for the glaebules and their included quartz. First, there is a wide variation in the amount of quartz in glaebules:some glaebules contain almost no quartz grains; others are rich in quartz., suggesting the glaebules have formed in different environments to one another. Secondly, glaebule quartz grains are generally smaller than those in the matrix, making a common quartz source again unlikely. Thirdly, many glaebules are broken and/or abraded, with fragments of resistant quartz grains protruding from their surfaces.

Given the likelihood that the glaebules have been formed elsewhere and transported to the site of Sample 056, their formation in an area containing granite-derived quartz grains is likely. Under these circumstances the predominantly angular quartz grains would have protected within the glabule, from physical abrasion during transport.

Sample 280 (Plates 24, 25) was collected at Dumaresq sheet GR 674266, 2 km west of the University of New England (Map 1; Figure 18). In this sample, 87% of the quartz grains have straight extinction with few fluid inclusions. These characteristics are consistent with a granitic origin (Folk, 1968), and the outcrop from which Sample 280 was collected is only 4 km south of extensive exposures of Mount Duval Adamellite and Tilbuster Granodiorite. However, between the granites and the silcrete there are exposures of Sandon Beds, and a higher representation of quartz grains suggesting vein origin could reasonably have been expected. It is possible that some of the larger clasts in Sample 280 originated in veins, particularly such clasts as the zoned example in Plate 24, but the full reason for the apparent under-representation of vein-derived quartz in the sample is unknown.

8.5 AGE OF SILCRETE

Absolute ages are not known for silcrete in the Armidale area. Relative dating of silcrete is complicated by the fact (discussed in Section 7.3) that at some sites silcrete is formed as inclusions in ferricrete (Plate 52), while at other sites ferricrete is found cemented by silcrete (Plate 34). It is further complicated by the fact that although silicified sediments in the Armidale-Uralla region often underlie basalt, it is probable that silicification of these sediments took place at some time after the basalt was extruded. These sites indicate the close field relationship between silcrete and ferricrete in the Armidale area, and are evidence that the periods of development of the two materials in the area overlapped at least partly.

Thus, field evidence indicating that some silcrete is older than adjacent ferricrete and that other silcrete is younger than adjacent or included ferricrete, does not necessarily mean that there were multiple phases of silcrete development. The field evidence can be explained by there having been either repeated phases of ferricrete development, repeated phases of silcrete development, or repeated phases of both silcrete and ferricrete development.

The presence of interbedded basalt and ferricrete in the Armidale-Uralla region (discussed in Section 6.3.1; Plate 59) indicates that there were repeated phases of ferricrete development, but there is no field evidence suggesting distinct multiple phases of silcrete development. Further, despite the fact that silcrete is widespread in the region there is no need to assume multiple silcrete surfaces in interpreting the geological relationships. Although there is no field evidence for multiple phases of silcrete development in the Armidale-Uralla region, it is likely that silicification of sediments took place over an extended period, during and probably after the Tertiary basalt extrusions. This is the case because much of the silcrete in the Armidale-Uralla region appears to have developed on fluvial sediments in or near streams that were active until disrupted by the Tertiary basalt extrusions. Silicification may have followed each episode of basalt extrusion, when valley floor sediments became confined and subject to groundwater percolation beneath valley-fill basalt.

The above arguments suggest that the silcrete in the Armidale area, with the possible exception of silica-cemented brecciated chert, is younger than the basalt with which it is associated. On this basis the silcrete is possibly early to mid-Miocene in age, much of it having formed beneath basalts extruded between the late Oligocene and early Miocene. This age is within the range postulated for other Australian silcretes. Near Cumborah in western N.S.W. Taylor (1978a) found silcrete separated by ?lower Miocene Cumborah gravels. Other silcretes outcropping in the Barwon River channel were thought by Taylor (1978a) to be Pleistocene or even younger. Hutton, Twidale and Milnes (1978) assigned an early Tertiary age to quartzose silcretes in the Lake Eyre region of South Australia. They thought that period of maximum development of these silcretes was probably in the Miocene.

From investigations in northern South Australia, Wopfner (1978) concluded that there had been three main periods of silcrete formation in Australia: late Jurassic; early Cainozoic (late Eocene to Oligocene) and late Cainozoic (Pliocene to Pleistocene). Senior (1978) has argued that silcretes in southwest Queensland are of mid-Tertiary age, and were silicified during a period of active chemical weathering. During this time 'silica was mobilised in surface water and in groundwater, and was precipitated, forming beds of silcrete'.

This work was taken further by Senior and Mabbutt (1979), who fixed the age of several deeply weathered silcrete and other profiles in southwest Queensland at late Cretaceous to Miocene. The Curalle silcrete profile was assigned an Oligocene to Miocene age, as basalt filling valleys incised in the profile have been dated at 23 my. The Haddon silcrete is laterally continuous with the Curalle silcrete profile and was therefore assigned the same age of Oligocene to Miocene. The Morney profile, which has a siliceous upper zone (0-6 m), kaolinitic middle zone (6-60 m) and ferruginous base zone (60-100 m), was dated using four methods. First, the maximum age from the age of the host rocks, is mid-Cretaceous. Secondly, the minimum age is 23 my, the age of isotopically dated basalts filling valleys cut in the profile. Thirdly, palynological studies of unconformably overlying strata suggested a minimum

Palaeocene to Eocene age. Finally, palaeomagnetic measurements of ferricrete from the base of the Morney profile indicated that weathering of the profile took place between the late Cretaceous and early Eocene.

The early to mid-Miocene age I have suggested for the silcrete deposits in the Armidale-Uralla region is at the young end of the age range suggested by Senior and Mabbutt (1979) for deeply weathered profiles containing silcrete in southwest Queensland, but is well within the age range of other Australian silcretes for which ages have been calculated or estimated.

The conclusion that silcrete in the Armidale-Uralla region is probably pre- basaltic, is at odds with the findings of Young and McDougall (1982) on the south coast of New South Wales. Young and McDougall (1982) suggested a pre-basalt age for silcrete underlying mid-Oligocene basalt, on the basis of a disconformity between the silcrete and the overlying basalt. The silcrete appears to have been partly eroded, and has remnants of a fossil soil in its upper layers, indicating development well before the basalt extrusions. On the basis of this evidence the conclusion that the silcrete is post-basaltic appears completely justified.

The silcrete studied by Young and McDougall (1982), having formed prior to the mid-Oligocene, may be substantially older than the silcrete in the Armidale-Uralla region, for which I have suggested an early to mid-Miocene age. If silcrete development depends on purely local geomorphic and hydrologic factors, such an age difference is interesting but of no real significance. However silcrete development is intimately linked to ground and surface water availability, both of which are governed ultimately by climate. Thus it could be expected that in areas of fairly similar climate such as New England and the south coast of New South Wales, where climatic variations are also likely to be similar, silcrete would form during about the same period.

On present evidence this appears not to be the case, and further investigation (Section 10.3.3.) will be necessary before this apparent anomaly in silcrete ages can be resolved.

8.6 LANDSCAPE SIGNIFICANCE OF SILCRETE

Where silcrete is exposed at the surface its resistance to weathering severely impedes the rate of erosion and slows the rate of landscape development. In the Armidale-Uralla region this effect is lessened because much of the silcrete is in small outcrops. These outcrops are too small and scattered to control slope development to the extent found for example by Ollier and Tuddenham (1962), on duricrust-capped slopes in the Coober Pedy area of northern South Australia. The result of this localised duricrust control of slope development in the Armidale-Uralla region, is that small-scale relief inversion is common (Armidale sheet GR 600182; Plates 31, 33), with relative relief from several metres to more than thirty metres.

Relief inversion is not necessarily the sole result of the relative resistance of silcrete to erosion. There is frequently too little silcrete for this to be the case. Where there is interfluve silcrete, it is usually closely associated with Tertiary basalt (Map 1), and relief inversion of the silcrete has probably taken place in conjunction with relief inversion of the basalt. Not all upper slope and interfluve silcrete is necessarily valley floor silcrete that has assumed its present position by relief inversion. As discussed in Section 8.3, replacement silcrete may have formed in higher topographic positions than some of the silicified fluvial sediments.

The fact that pebbley silcrete is found at some sites (Plates 24, 26, 30, 32), while other silcretes contain only sand sized clasts (Plates 22, 23, 36), suggests that increasing clast size is related to a drop in fluvial energy in the stream that originally carried the sediments, causing pebble-sized clasts to be deposited at that site. Thus modern sites of pebbly silcrete possibly indicate reaches of lower gradient in pre-basalt streams. These sites are concentrated in an area between 2 km and 10 km north and northwest of Armidale Airport (for example at Dumaresq sheet GR 674266, 682254, 671251), an area of pre-basalt low relative relief that was flanked to the north by steeper country (Figure 17).

There can be little doubt that the main landscape significance of silcrete in the Armidale-Uralla region is that many exposures mark relict water courses, and enable deep leads beneath the Tertiary basalt to be traced. This in turn enables assessment of the effect of the Tertiary basalt extrusions on the drainage system of the region.