The more resistant trachytes have been slowly weathered to leave abundant scree slopes around the bases of the trachyte peaks. However, it is unclear whether arid or humid processes operated at this time (Appendix A; Jensen 1906). The lack of evidence for the mid- and Late Miocene is addressed in this work (Section 6.7), utilising diatom palaeoecology to establish environmental conditions operating at the time of deposition and contemporaneously with volcanism.

Modern landscape alterations occurred when Europeans first arrived in the area (Section 4.2). Rolls (1985) reported that ringbarking and minor clearing occurred in the late 1800s and cropping and clearing increased steadily from this time. After World War II clearing and cropping accelerated through the 1960s and 1970s as larger mechanical-powered tractors became available. At a local scale, the impacts of these activities on geomorphic process has been minor, causing gully erosion and siltation. Impact has been limited to areas outside the Warrumbungle National Park boundaries (Figure 1.2), within which grazing and cropping are not permitted. On a regional scale, hydrological processes have been affected by, particularly infiltration, runoff, erosion and sedimentation. Again, these impacts occur largely outside the National Park. Generally, anthropogenic impacts on the shield as a whole are negligible, except where diatomite mining has taken place (Section 4.4.3.5).

4.4.3.1 Present shield morphology

The outer flanks of the volcano consist of predominantly mafic lavas surrounding a higher central massif of mostly pyroclastic material and felsic lavas (Duggan and Knutson 1993). The central portion of the volcanic shield is characterised by numerous plugs and dykes intruded through poorly bedded and poorly sorted sequences of sediments, tuffs and breccias. These materials were erupted through numerous central and parasitic vents erupted on the flanks of the shield. Well-bedded pyroclastic rocks are evident in the Complex, with some of these deposits frequently reworked and showing evidence of channelisation (for example, Shawns Creek). Major constructional remnants of the original shield are preserved at Mount Exmouth, Siding Spring Mountain (Mount Woorut), Tooraweenah Ridge, Wallumburrawang Ridge and Westons Ridge (Figure

1.2). At these localities stratified lava sequences are exposed although detailed outcrop is poor. Such sequences are useful for interpreting volcanic stratigraphy, determining eruption periodicity based on weathering profiles and erosional unconformities and interpreting shield morphology. Most lava sequences consist of alkali-olivine basalt, olivine basalt, hawaiite and trachyte, together with interbedded pyroclastic breccias and intrusive trachyte elements (Jensen 1907). Some lavas locally overlie and protect lacustrine sediment from erosion. These lacustrine deposits, which are primarily confined to the outer flanks of the volcano, contain fish fossils (Hills 1946), leaf impressions and pollen (Holmes *et al.* 1983), and diatoms (David 1896; Jensen 1907; Thomas and Gould 1981a, b); preserved in, or as, diatomite. These deposits are valuable palaeoclimatic and palaeoecological indicators and their importance will be further described in Section 4.4.3.4.

The following main volcanic formations can be recognised in the Warrumbungle Complex:

1. *lava flows*: individual lava flows may be discerned in the complex, many of which show dissected margins and slope terracing where underlying flows are wider and longer than overlying flows. Such terracing is obvious on aerial photographs. The top of flows are exposed as flat-topped hills (for example, Looking Glass Mountain, Tooraweenah Ridge, Mount Exmouth; Plate 3.3), and are considerably weathered, with thin, rocky soil profiles in places. As such, there is very little evidence of surface flow morphology when compared to the Tweed Volcano where evidence of pressure ridges are preserved (for example, Wyatt and Webb 1970). However, in some locations flow margins may be identified by the presence of brecciated structures (Section 3.4.2.2), and in more basaltic lavas the top of the flow may be vesicular with successive flows separated by a layer of pyroclastic material (for example, Plate 3.3).

2. *plugs/necks*: trachytic plugs form some of the more spectacular features of the Warrumbungle Complex (for example, Crater Bluff, Belougery Spire, Timor Rock; Plate 3.1). All of these features have been reduced in volume by block mass

wasting along jointing fractures. Thus, the bases of these intrusions are characterised by well developed talus slopes.

3. *domes*: these are steep sided protrusions of lava that are too viscous to flow away from a vent. It is thought that the development of lava domes in the Warrumbungle Complex marked the close of igneous activity at the vents, with the rigid dome forming a permanent seal to the conduit (Duggan and Knutson 1993). Examples of lava domes in the Warrumbungles include Belougery Split Rock, Bluff Mountain (Plate 3.2), Mount Berrumbuckle and Mount Bingie Grumble. These domes are generally devoid of vegetation and soil and are often cliff-bound. Like the plugs, they also have large talus slopes at their bases.

4. *dykes and sills*: dykes are common in the Warrumbungle Complex and are largely confined to the central shield area. While others may remain to be identified, those listed in Table 6.3 have been exposed by the erosion of softer adjacent material. In the case of the Breadknife (Plate 3.1), the pyroclastic deposits into which the magma intruded were eroded away, leaving the hard trachyte as a spectacular wall some 90 metres tall, 600 metres long and no wider than about 1.5 metres in places. Many of the dykes exhibit bulbous and chilled margins, indicating that they were emplaced through softer or unconsolidated material. While sills may undoubtedly exist in the shield, none are readily identifiable (Duggan and Knutson 1993). Unlike dykes, sills may be difficult to distinguish from lava flows and careful observation may be necessary to identify them.

5. *craters*: three craters have been recognised so far in the Warrumbungle Complex with four more identified in this work (Section 6.4.2). Hockley (undated) recognised distinct rims encircling the Crater Bluff plug (Plate 3.1). Ned Smiths Mountain (Tooraweenah Mountain) has been interpreted by MacKellar (1980) as the remains of a crater complex 2 km wide and 3 km long centered on a roughly circular depression 100 m deep and 800 m. MacKellar (1980) developed the following explanation for its origin: "... *the outer rings are interpreted as being the remains of a volcanic cone that was almost 3 km across the base. Most of the cone was removed by a combination of explosive activity and cauldron subsidence. During this event, pyroclastic materials were blasted out horizontally, and they now form*

the banded ?welded tuffs that occur on the high ground between the central structure and the northern ridge. At a later stage, further volcanic activity produced a smaller cone inside the caldera. The caldera was eventually partly infilled by lava flows. Subsequent erosion has played a part in producing the landform that is observed today ...". MacKellar (1980) also interpreted the morphology of Saddle Mountain in a similar way. The shield-wide investigation of volcanic landforms undertaken in this study has revealed a further four crater-like features and one residual crater-fill lava (Section 6.4.2).

6. *pyroclastic deposits*: tephra occurs in the Warrumbungle Complex as either coarse, poorly bedded deposits in the shield centre, or well-bedded, finer grain deposits on the shield flanks. Flank deposits show evidence of channelisation and lamination, indicating periods of erosion between volcanic activity. Proximal deposits show evidence of soil formation, and dip slightly, preserving shield slope or cone slope angles (for example, Ollier 1981b; Plate 4.2).

7. *lahars*: these deposits are preserved on some intermediate flanks of the shield and appear to have been largely confined to channels scoured in the sides of cones, or water courses on the outer flank. Clast size varies from small pebbles to large boulders more than a metre in width (Plate 4.3).

8. *fluviovolcanic/ lacustrine deposits*: localised lacustrine deposits occur on the flanks of the volcano. These are interbedded with lavas, volcanoclastic and fluvial sediments. These deposits are presumably developed in ephemeral lakes resulting from damming by lava and/or pyroclastic flows. They are generally underlain and capped by lavas, incorporate volcanoclastic sediment and the occasional volcanic bomb. The most significant lacustrine deposit in the shield is diatomite. Outcrop occurs at Chalk Mountain, Paddy McCullochs Mountain and Wandiallabah Creek. These are briefly discussed in Section 4.4.3.4 with a view to using diatomite for palaeoenvironmental interpretation in this study as its formation was coincident with volcanic activity.

Plate 4.3: Soil development (GR903325) in poorly sorted and poorly bedded tephra deposits in the shield centre (a). The gently dipping and unconformable nature of these deposits suggest that the pyroclastic material it developed from was tectonically disturbed or deposited on the side of a cone. (b) A vesicular volcanic bomb is interbedded with a massive trachyte breccia deposit lower in the sequence. (c) Weathering of exposed pyroclastics across the shield has been observed to occur through differential erosion, whereby angular trachyte clasts cap and protect the underlying finer matrix from erosion by rain storms. *Photo*: A. Timmers.

Plate 4.4: Lahar deposit on the John Renshaw Parkway (GR975370). Note the jumbled nature of the deposit and the range of clast sizes. The outcrop has since been removed by roadwork. Photo: C. Duthie.

4.4.3.2 Drainage

The Warrumbungle shield exhibits a typical radial drainage pattern which is made up of intermittent and ephemeral streams (Figure 4.3a) with the circumvolcanic Castlereagh River draining the complex (Figure 4.3b). The Castlereagh rises in the eastern central portion of the Warrumbungle Complex, flows in an easterly direction to Coonabarabran, then takes a southerly and southwesterly circuitous route through Binnaway, Mendooran, then flows northwest towards Gilgandra and Coonamble (Figure 4.3b). There is some controversy as to the original course of the Castlereagh River. One school of thought suggests that the present course is as it has always been. The opposing school suggests that the Castlereagh was diverted by the emplacement and consequent extrusion of the Warrumbungle Complex.

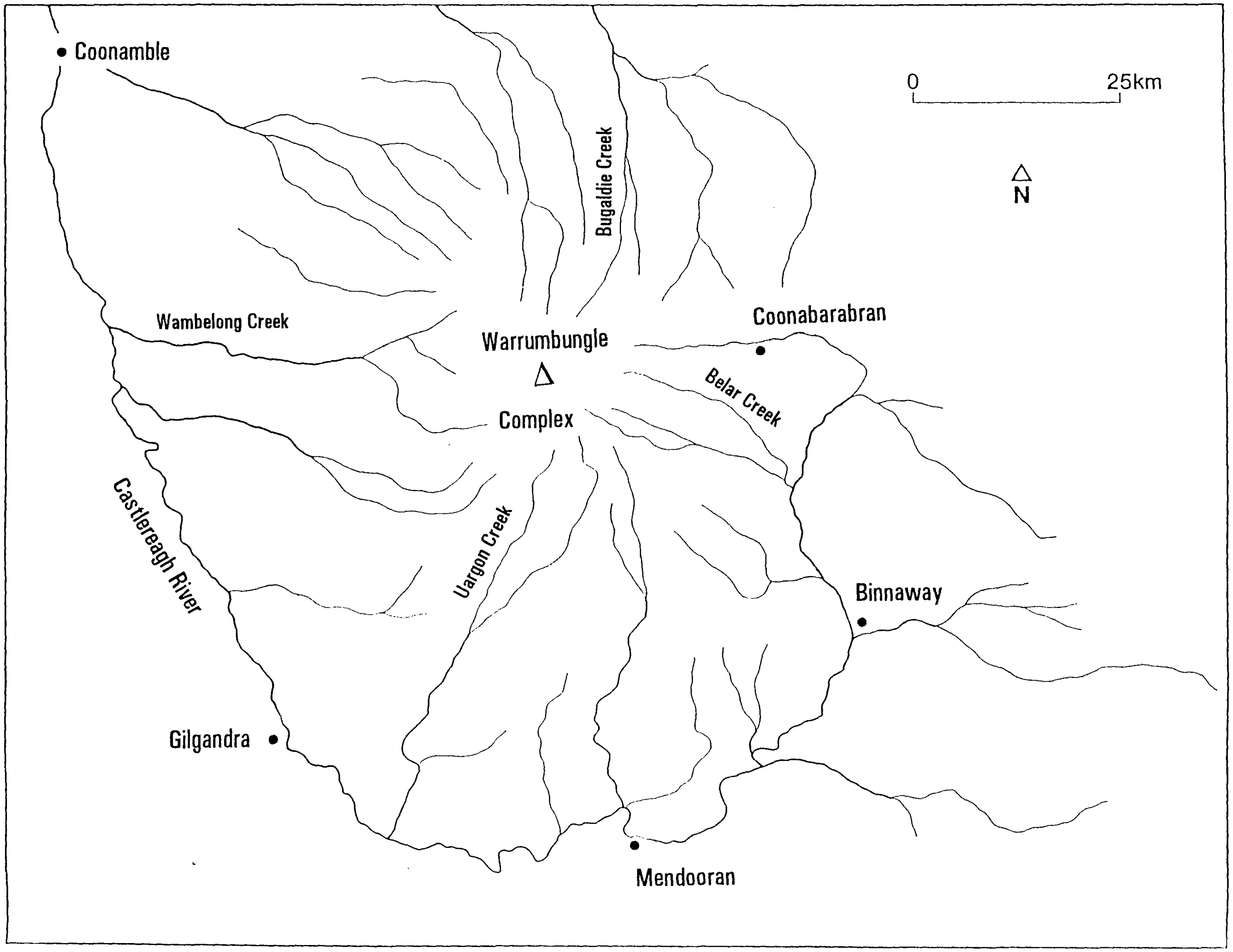

Figure 4.3: (b) The circumvolcanic drainage of the Castlereagh River around the Warrumbungle Complex. The Castlereagh flows northwest beyond Coonamble where it joins the Macquarie River, draining into the Darling Basin.

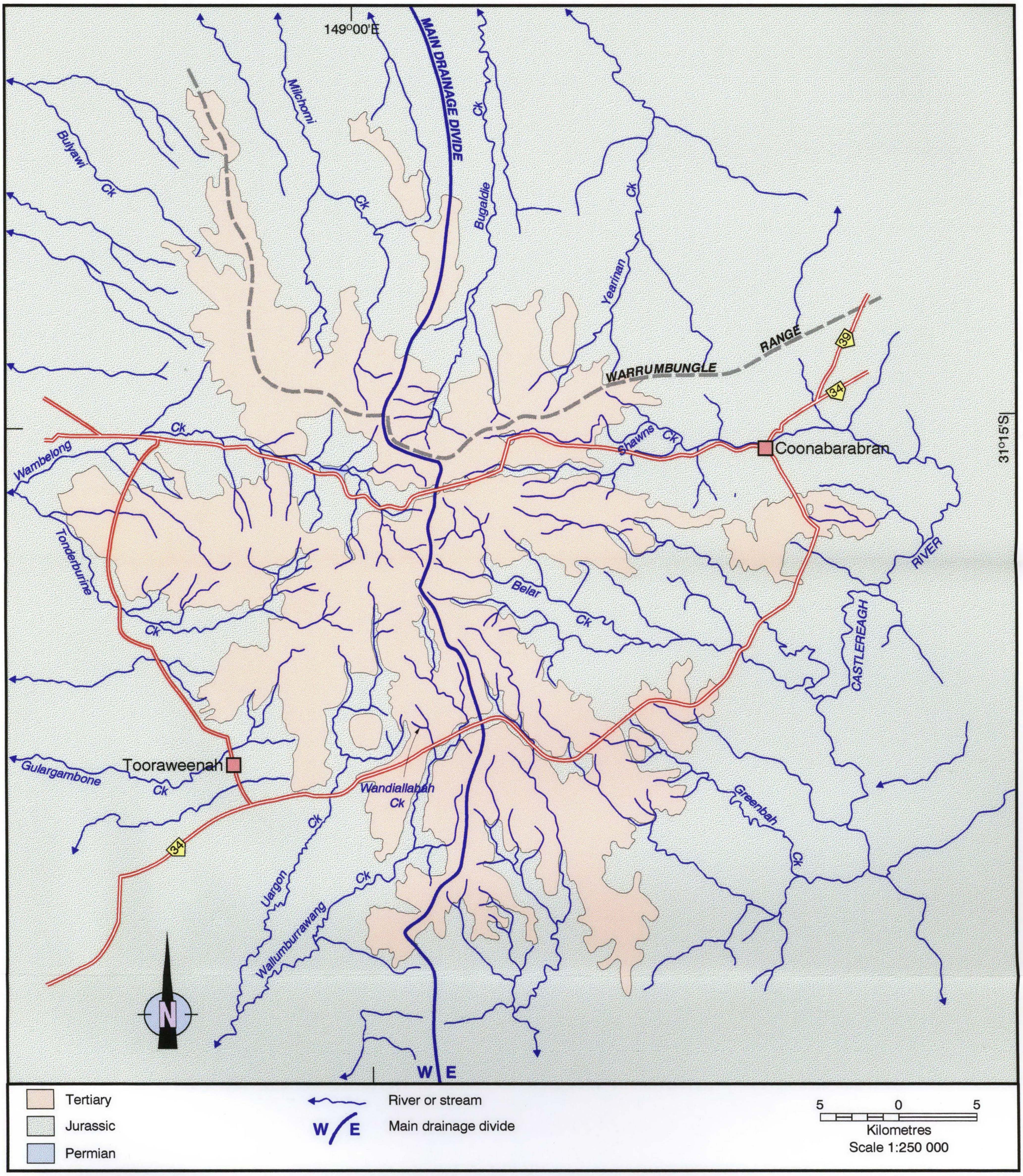

Figure 4.3a: Present drainage of the Warrumbungle Complex. A prominent radial pattern is evident, as is the circum-volcanic nature of its primary stream, the Castlereagh River (Figure 4.3b). The drainage divide is oriented north-south, but has been pushed to the east in the centre of the shield where erosion has stripped the volcanics away to expose the basement material.

Jensen (1906), Kenny (1929) and Fairley (1977) have suggested that there is evidence, both geological and topographical, to imply that the ancestral Castlereagh pursued a course much more direct than its present counterpart. However, these authors have not provided any evidence to support their claims. They suggested that the valley of the Castlereagh was moved successively eastward by the emplacement of the Warrumbungle volcanics, inferring that the flow of lavas erupted from the Complex altered the old drainage pattern by blocking water courses. Prior to these eruptions, the tributaries of the Castlereagh River flowed in a northwest direction. Similarly, Ollier (1985) has suggested that the Warrumbungle Complex was erupted on the course of the ancestral Castlereagh River, which found its way around the volcanic pile as the Namoi and Macquarie Rivers.

By contrast, Dulhunty (1972) has proposed, on the basis of isotopic dating, that the Castlereagh River has demonstrated no appreciable change in course since the pre-mid Miocene (Figure 4.3b). He inferred a close field association between dated basalts on the Oxley-Newell Highway between Coonabarabran and Gilgandra (Figure 4.1) and those of the Castlereagh Valley. The Oxley-Newell Highway basalts dated at 13.9 ± 0.4 and 14.2 ± 0.3 Ma (Table 4.2) are associated with the Warrumbungle Complex and are close in age to that of sample K7 (Table 4.2) in the Castlereagh Valley. Dulhunty (1972) suggested that this was sufficient evidence to indicate that these basalts are co-extrusive. These dates suggest that the southeast of the shield experienced near-continuous volcanic activity for the entire period of eruption. When combined with evidence of Mesozoic volcanics in the river valley upstream near Binnaway, he concluded that a pre-Miocene basalt and pre-Warrumbungle Complex drainage pattern comparable to the present upper Castlereagh system existed with a valley of similar profile and even a little deeper than the present river valley. To support this line of thought, Dulhunty (1972) produced geological cross sections that showed broad, synclinal warping with the river channel located in the approximate centre of the syncline. From this evidence it was concluded that the north-south trace of the Castlereagh from Coonabarabran to Mendooran was originally determined by pre-Miocene basalt warping which confined the Miocene ancestor of the present Castlereagh to the syncline. On the balance of evidence, the Castlereagh shows no evidence of having occupied a pre-Warrumbungle shield course that was moved progressively eastward by the emplacement of the shield. However, the effect of emplacement of the Warrumbungle Complex on drainage is pursued in this study in order to establish stages in drainage development and their relationship to broader shield evolution.

4.4.3.3 Diatomite as a palaeoenvironmental indicator

During the Cenozoic, the productivity of diatoms was so great that large deposits formed worldwide, for example, at Lompoc in California, at the Calvert Cliffs on the Patuxent River in Maryland (USA) and in Australia where the most notable deposits occur at the Warrumbungle, Nandewar (Bells Mountain at Barraba) and Tweed volcanic shields, at Bowen Park near Orange and at Lake Bunyan/Middle Flat near Cooma (Figure 4.4).

In Australia, diatomite is almost always associated with volcanic rocks (Figure 4.4). It is found interbedded with lava flows and tuff and in some cases it may be found in depressions in sandstone which occur in association with volcanic areas (Herbert 1968a). The occurrence of diatomite in these situations is thought to be related to the abundance of silica derived from volcanic activity. This contributes to the nutrient status of lacustrine waters from which the diatoms extract silica to form their frustules. Details of diatom occurrence in eastern Australia have been given by David (1896), Jensen (1906, 1907), Skvortzov (1937), Crespin (1947), Gill (1953), Tindale (1953) and Herbert (1968b). Since 1968, several specific analyses on diatom biostratigraphy have been undertaken by Thomas and Gould (1981a, b), Holmes *et al.* (1983) and Taylor *et al.* (1990), with these authors producing limited palaeoecological interpretations.

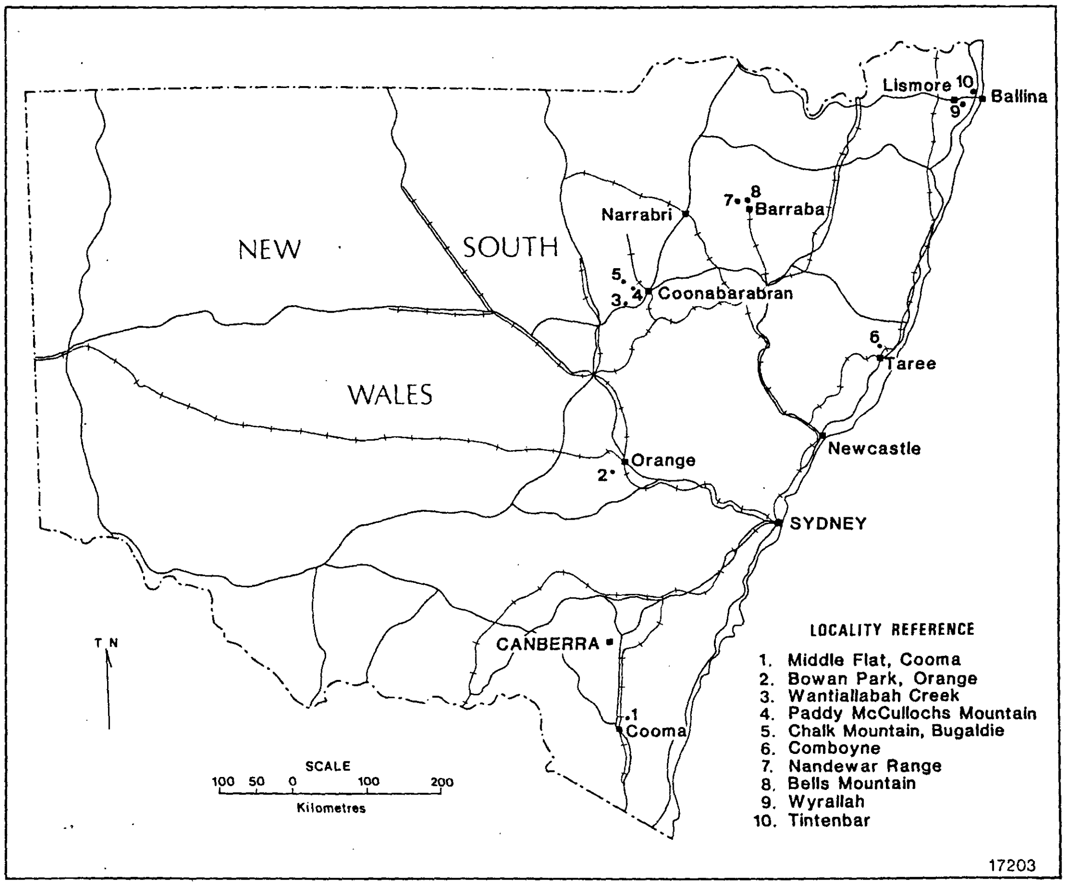

Figure 4.4: The location of diatomite in New South Wales. Note that diatomite deposits are intimately associated with volcanic areas. *Source*: Holmes *et al.* 1982.

4.4.3.4 Diatomite in the Warrumbungle Complex

Diatomite deposits have been widely documented in the Warrumbungle Complex. The larger diatomite deposits in the shield are of lacustrine origin. These diatomites are characterised by a particulate structure, high porosity, low density and chemical stability. The diatomite has largely been deposited in water bodies formed on the irregular surface of the Pilliga Sandstone, on basaltic or trachytic lava flows that failed to completely infill or level the original surface, or have formed in areas dammed by lava flows. As early as 1896, David reported evidence of *Melosira* in association with fresh water sponges

(*Spongilla*). Both Jensen (1907) and Herbert (1968b) reported significant diatomite deposits at Chalk Mountain, Paddy McCullochs Mountain and Wandiallabah Creek. While other diatomite deposits were mapped by myself and others in the shield, (for example, David 1896; Herbert 1968a, b) landowners do not wish their locations to be divulged, however, these deposits are largely confined to elevations of 600-650 m ASL. Jensen (1907) described diatomite in association with tuffs containing *Cinnamomum leichhardtii*, *Endiandra praepubens* and other, undescribed, leaf remains at Gowang near Parramatta Mountain. Reports of diatomite interbedded with basic tuffs (below which lies a sheet of phonolytic trachyte and above which lies a sheet of vesicular basalt) at Chalk Mountain were interpreted by Jensen (1907) as indicating that this deposit extends under the entire summit of the mountain and outcrops on all sides. Indeed, it is now possible to trace the deposit around the mountain in open cut mine workings, shafts and trenches (Herbert 1968b). Jensen (1907) noted that both the Chalk Mountain and Paddy McCullochs Mountain deposits occur at a similar altitude (about 610 m ASL) in similar geological associations. Thomas and Gould (1981a, b) reported seven diatom species in association with the Warrumbungle Complex (Table 4.3), the ecological preferences of which are outlined in Appendix B.

Table 4.3: Diatom species found in association with the Warrumbungle Complex.

	Location		
Taxa	Chalk Mountain	Paddy McCullochs Mountain	Wandiallabah Creek
Melosira granulata	*	*	*
Gomphenema intricatum	*		*
Fragilaria construens var. *venter*	*		*
Pinnularia sp. af. *major*	*	*	*
Stauroneis frauenfeldiana	*		
Eunotia pectinalis	*		*
Cymbella ventricosa	*		
Navicula amphibola	*		*
Total taxa	7	2	6
Total genera	7	2	6
Estimated age (Ma)	15-16	15-16	14-16

Source: Thomas and Gould 1981a, b.

4.4.3.5 Chalk Mountain diatomite

Chalk Mountain (GR972546; Figure 1.2) is located on the northern edge of the Bugaldie Range, a northern extension of the Warrumbungle Mountains some 26 km northwest of Coonabarabran and four kilometres west of the Bugaldie railway station. The 38 hectare outcrop of diatomite at this site is capped and underlain by basalt associated with the Warrumbungle Complex to the south (Holmes *et al.* 1983). It is likely that the original lake in which the diatomite formed was much larger than this, but the extent of erosion around the outcrop is unknown. It is known, however, that the extent of the deposit prior to mining in 1959 was 85 ha. This represents a lake of significant size.

The Chalk Mountain sequence is capped by olivine basalt. Directly under the basalt is a flat lying sequence of Tertiary silts, tuffs, mudstones and brecciated diatomite. Underlying this is pure diatomite which rests on a series of basaltic, trachytic and andesitic flows (Herbert 1968b). These flows lie on the Jurassic sandstones of the Pilliga Beds. Diatomite at Chalk Mountain consists largely of *Melosira* with rare *Synedra* and *Neidium*. Fossil leaves of dicotyledonous plants and the fossil fish *Maccullochella macquariensis* are well preserved (Herbert 1968a). Thomas and Gould (1981b; Table 4.3) recorded the presence of seven diatom taxa at this site with *Melosira granulata* dominating the assemblage.

Oakes (1979) reported gentle warping of the Chalk Mountain sequence and at least one significant fault (normal, with a throw of about 15.5 m) which post-dates the diatomite sequence and probably pre-dates the overlying olivine basalts. The presence of an unconformity between the basalt and sediments indicates that at least some erosion occurred before the basalt was erupted.

4.4.3.6 Paddy McCullochs Mountain diatomite

The diatomite at Paddy McCullochs mountain (GR035453; Figure 1.2) lies about 17 km northwest of Coonabarabran and three kilometres west-northwest of Yearinan and appears to directly overlie the Pilliga Sandstone. Thomas and Gould (1981b) considered that the diatomite formed in a depression at least 30 m deep in the Jurassic Sandstone basement. The top of the deposit is overlain by 6 m of trachyte which caps the mountain. Four to six metres of tuff containing vesicular basalt bombs overlies 1.4 m of pure diatomite. The diatomite rests on a thick sequence of coarse white tuff. This is underlain by 2.4 m of brecciated diatomite similar to that at Chalk Mountain. This rests on approximately 6 m of light green tuff, 6 m of light brown clayey diatomite and 6 m of impure light brown diatomite (Herbert 1968b).

4.4.3.7 Wandiallabah Creek diatomite

Diatomite also occurs at Wandiallabah Creek (also known as Wantiallabah, Wantialaba, Wantialable, or Wantial Creek) south of the Oxley and Newell Highway (GR945199; Figure 1.2). David (1896) described two outcrops of diatomite in Wandiallabah Creek. Jensen (1907) recorded that diatoms of the genus *Melosira* were dominant in diatomite deposits in the Warrumbungle Mountains. He indicated that specimens of *Melosira sp.* at Wandiallabah Creek were smaller than those at Chalk Mountain and that spicules of the freshwater sponge *Spongilla* were more abundant at Wandiallabah Creek than at Chalk Mountain. This suggests that the water of the palaeo-Wandiallabah Creek/Lake contained more material in suspension than that at the Chalk Mountain site. Wandiallabah Creek was selected for palaeolimnological analysis largely because it is the most stratigraphically variable and undisturbed deposit of diatomite in association with the Warrumbungle Complex. Thus, it has the greatest potential to yield the most meaningful data on aspects of geomorphic evolution.

The Wandiallabah Creek diatomite sequence forms the basis for palaeoclimate and palaeoenvironmental interpretation. This site was selected over the other deposits for several reasons:

1. access;
2. safety: both Paddy McCullochs Mountain and Chalk Mountain have been previously mined and are unstable in some areas;

3. the relationship of the deposit to adjacent, interbedded, underlying and overlying volcanic and volcanoclastic deposits;
4. the presence of volcanic bombs throughout the sequence, with the potential for K-Ar dating;
5. ease of sample collection; and
6. the site was intact, with no mining having taken place.

4.5 Conclusion

The purpose of this and the preceding two chapters has been to review the volcanic history of the eastern Australian highlands and to investigate the geomorphic development of volcanic landscape elements within the framework of eastern highland development. This review has shown that there is considerable variation in the type and volume of igneous activity, as well as the subsequent erosional expression of this volcanism. Clearly, hotspot models, mechanisms of highland evolution and geomorphic and geological evidence have not yet been comfortably related into a single dynamic model which accounts for all of the intraplate volcanism in the eastern highlands. Moreover, the relationship of volcanic activity to uplift has not been suitably explained and without this it is difficult to test the validity of models of highland evolution.

The resolution of the conflicting hypotheses presented here must await further information, some of which will come from the geomorphic investigation of individual volcanic provinces. This research therefore aims to reconcile some of these difficulties by providing an account of the volcanic and geomorphic development of the Warrumbungle landscape as outlined in Section 1.5. This is undertaken with a view to clarifying the processes which may be responsible for producing the variations in the expression of Miocene central-type volcanism. These results may then be used to explain the morphological development of other Miocene central-type activity by placing some constraint on volcanic processes. The following chapter provides the necessary methodological outline of palaeovolcanic studies and discusses their application within the context of this study.