MONARO REGION, NEW SOUTH WALES

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INTRODUCTION

The Monaro is an area of substantially treeless plain in the highlands of southeastern New South Wales (Figure 1). As there are many definitions of the Monaro, we define it as encompassing the region lying between Bredbo and Delegate in a north–south direction and Cathcart and Berridale in an east–west direction. The Monaro region has been the subject of considerable geological, landscape and ecological study since the Reverend W.B. Clarke undertook his "Explorations of the Southern Goldfields of New South Wales" during the summer of 1850–51. Many famous names are associated with geological work in the region including Griffith Taylor, W.R. Browne, Edgeworth David and Frank Craft. Since these early days of geological investigation little attention was paid to landscape evolution and it is only in the last quarter of the Twentieth Century that the baton was again picked up.

In this summary we pick up on the work in the Monaro done since 1975 and its potential in mineral exploration.

PHYSICAL SETTING

Geology

The Monaro region lies in the southern part of the Lachlan Fold Belt. Local geology consists of Ordovician flysch sequences that host two significant regional metamorphic complexes: Cooma (Joplin, 1942; Hopwood, 1976; Munksgaard, 1988; Johnson *et al.,* 1994); Jerangle (Best *et al.,* 1964; Richardson, 1979; Hayden, 1980); and Cambalong (McQueen *et al*., 1986). Sequences of Silurian sedimentary and volcanic rocks occur in the northern and southern Monaro. Major late Silurian granitoid intrusions of the Berridale Batholith and the late Silurian to early Devonian Bega Batholith intrude these sequences. Late Devonian to early Carboniferous terrestrial sediments overlie the earlier Palaeozoic rocks across the southern Monaro (Sircombe and McQueen, 2000).

There are several mid-Jurassic (McDougall and Wellman, 1976) intrusive complexes in the Monaro region including the Myalla Road Syenite near Cooma (Veijaratnam, 1970, Barnes and Herzberger, 1975), the (Snodgrass) Delegate breccia pipes (Pittman, 1910; Rose, 1960; Lovering and White, 1969; Irving, 1974; White and Chappell, 1989) and the Jingera Rock Syenite Com-

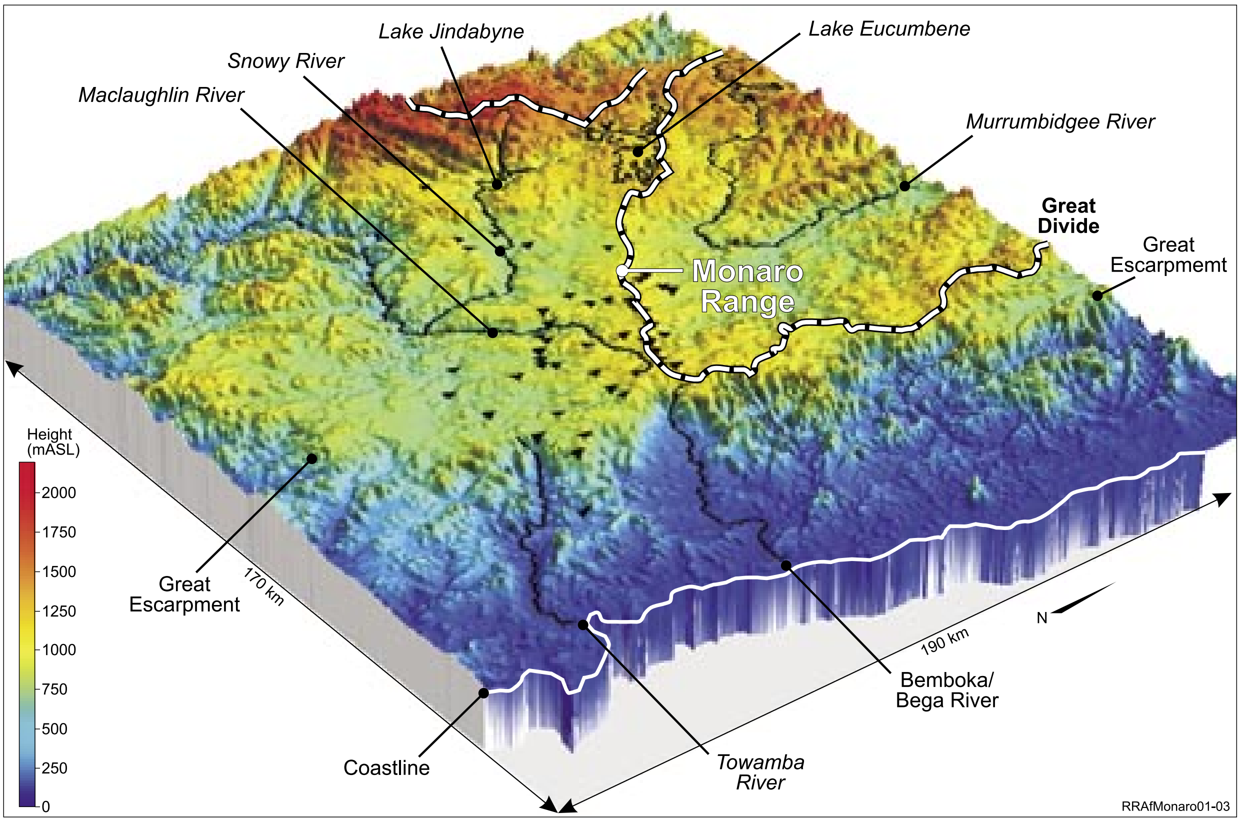

Figure 1. Digital elevation model of the Monaro region highlighting some of the major landscape elements described in the text. The Monaro occupies the tableland between the Great Escarpment (east) and the Snowy Mountains (west). The locations of eruption sites in the Monaro Volcanic Province are marked with filled black triangles, the Great Divide by the white line. Elevation data are from the AUSLIG/Geoscience Australia 9-second (250 m) DEM. (Modified after Roach, 1999)

plex (Beams, 1975), although this is somewhat removed from the Monaro.

From the earliest Eocene or latest Palaeocene to the early Oligocene (~58–34 Ma; Taylor *et al.,* 1990), basaltic lava field volcanism occurred throughout much of the Monaro, building a thick lava pile consisting largely of inter-locking lava shield and scoria cone volcanoes and some maars. About 65 volcanic eruption sites are now known within the lava field, named the Monaro Volcanic Province (Roach *et al*., 1994; Roach, 1999). The basalts have preserved pre-eruption landscapes and intra-basaltic lakes, stream sediments (Taylor *et al*., 1990) and other features including pre- and syn-eruptive weathering features.

Geomorphology

The Monaro forms a high plain between the great escarpment or coastal range and the Snowy Mountains (Figure 1). The main plateau is at an elevation of ~900 m with isolated hills and low ranges reaching a maximum elevation of 1 234 m (Hudsons Peak). These hills are generally inliers of older Palaeozoic rocks surrounded by basalt or the remnants of eruption centres (e.g. Hudsons Peak). Palaeozoic rocks tend to form low ranges as contact metamorphic aureoles around granitoids of the Berridale Batholith, whereas eruption site remnants (volcanic plugs) tend to form stand-alone hills with round-topped, flat-topped or conical forms. The high plain is traversed by many large rivers, some incised (e.g. Snowy, Murrumbidgee) and some flowing in broad open valleys (e.g. Bombala, Delegate, Numeralla, Maclaughlin).

The Great Divide follows the coastal range along the eastern margin of the northern Monaro south to about Nimmitabel, from where it turns northwesterly, cutting across the middle of the Monaro to Kiandra in the Snowy Mountains (Figure 1). Here it resumes its north–south trend. The northwest-trending segment is named the Monaro Range and consists primarily of remnant eruption sites linked by high-standing lavas along the "Bemboka Zone" of Roach *et al.* (1994). The "Bemboka Zone" is one of two linear, northwest-trending concentrations of eruption sites in the Monaro Volcanic Province, which is a ca. 4 200 km^2 intraplate basaltic lava field that dominates the Monaro landscape.

The basalt plains of the Monaro are characterised by scattered lakes, some formed by damming of headwater stream tracts by basalt flows (e.g. Arable Lake) while others are deflation features (Pillans and Walker, 1987), perhaps initiated by solution of the basalt. The majority of the deflation lakes occur along the Monaro Range part of the Great Divide, suggesting that wind is the primary erosional agent.

Climate and vegetation

Most of the Monaro region lies in a rain shadow caused by the Snowy Mountains to the west and the Coastal Range to the east (Figure 1). Annual rainfall varies from about 580 mm in the west to 700 mm in the east. Mean annual temperatures are about 10ºC, with winter temperatures ranging from -1 to 11°C and summer temperatures rising to an average of 25°C.

The vegetation of the Monaro is mainly controlled by geology and aspect, and has been described in detail by Costin (1954). The open grasslands of Costin's *Stipa scabra – S. bigeniculata* Alliance, so typical of the region, are generally restricted to areas of basalt (Figure 2) and were a boon to early graziers (Hancock,

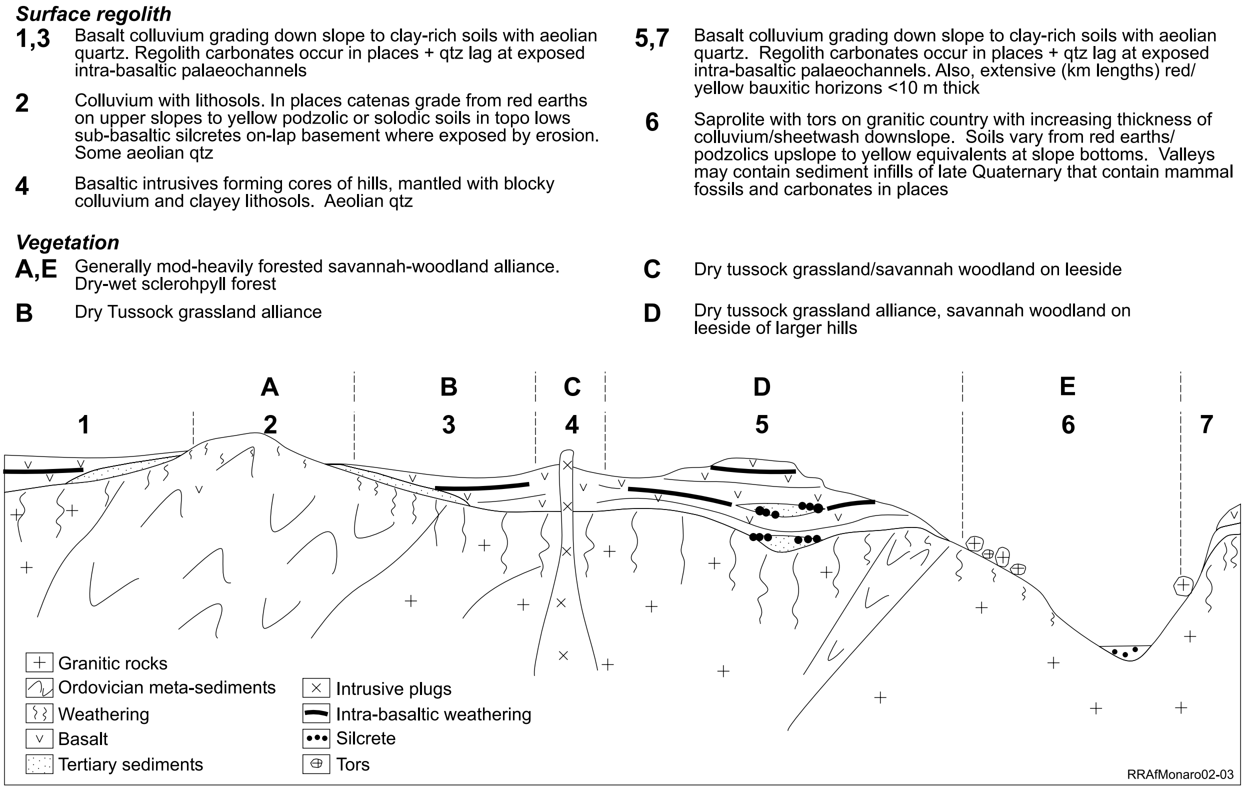

Figure 2. Schematic cross-section illustrating rock, regolith and vegetation relationships on the Monaro.

1972). Inliers of Palaeozoic rocks support a savannah woodland of Costin's *Eucalyptus pauciflora* (snow gum) – *E. stellulata* Alliance and open dry sclerophyll forest of the *E. Macrorhynca – E. rossii* Alliance, as do south-facing slopes and basalt-derived stony lithosols in the southern Monaro. The treeless grassland is natural — early explorers (e.g. Currie, 1825) noted the "*chain of clear downs"* that now forms the rich grazing lands of the Monaro.

REGOLITH-LANDFORM RELATIONSHIPS

A number of regolith types occur on the Monaro. These are either: (1) associated with the contemporary landscape, (2) included within the basalt pile, or (3) buried beneath the basalts. Figure 2 shows the regolith types and their relationship to the landscape.

Regolith associated with the contemporary landscape

Regolith formed on pre-Cenozoic rocks in the contemporary landscape falls into two groups. One group is associated with open rolling hills with a relief of 20–30 m, whereas the other group is associated with steeper landscapes of higher relief (30–50 m). The former group is associated with granitoid saprolite, generally overlain by red to yellow podzolic soil profiles. The saprolite is of variable thickness (0.5–30 m) and rarely passes through a plasmic or arenose zone below the soil C horizon. On some granitoid plutons tors are common (e.g. the Wullwye Granodiorite of the Berridale Batholith).

Regolith typically thickens away from hillcrests, with the thickness of transported regolith overlying saprolite increasing down slope. Accumulations of transported regolith along footslopes are up to 5 m thick. Valley bottoms are filled with alluvium, in some cases with three terraces. The steeper landforms are dominated by slightly to moderately weathered Palaeozoic bedrock with down-slope thickening colluvial mantles. Streams are generally erosional or alluviated where formed outside of the Palaeozoic rocks.

The majority of the Monaro landscapes are plateaux with stepped margins. The plateaux tops have disrupted drainage, but an integrated drainage occurs between them. The regolith in these areas is dominated by stony clay soils underlain by basaltic saprolite and saprock. The slopes of the plateaux are mantled by basaltic pebble colluvium that in places forms rock streams, rock and mud slide debris, or solifluxion deposits. Another significant landform associated with the plateaux is lakes. These are filled with fine-grained smectitic clays that crack and deflate during dry phases (Pillans and Walker, 1987). These lakes are flanked on their down-wind (eastern) side by low relief (0.4 m) lunettes of silt-sized aggregates of lake-derived clay minerals.

Several regions of the Monaro are occupied by large alluvial and/or lacustrine plains, for example at Jincumbilly, Cathcart, Bunyan, and south of Bombala. These form flat to slightly undulating plains with a low relief (<10 m), and are underlain with transported regolith varying from coarse quartzose gravels and sands to very fine-grained clays.

Intra-basaltic regolith

Extrusion of the Monaro basalts occurred over a period of at least 25 million years. At Myalla Lake, the basalt pile is 197 m thick (Brown *et al*., 1992) and is made up of about 22 individual flows. Of these, 7 are topped by weathering profiles up to 12.5 m thick, including bauxite caps up to 3.5 m thick. The intra-basaltic weathering profiles indicate that volcanism was discontinuous, with flows exposed to the atmosphere for intervals of probably up to 5 million years before being buried by new flows.

Intra-basaltic weathering profiles can be found throughout the Monaro, some mappable over distances of more than 10 km. Most profiles are bauxitic at the top grading down to saprolite, saprock and fresh basalt (Taylor *et al*., 1992). The profiles vary in thickness from about 1 to 6 m, though profiles up to 15 m thick occur. At Middle Brother Hill, a volcanic plug near Bondo Station south of Cooma, the progressive weathering of basalt to bauxite is ideally expressed in the Bondo Ankaramite (Roach, 1999), a lava rock of doleritic appearance with large pyroxene, plagioclase and olivine crystals. Road-side exposures show fresh basalt passing upwards into moderately weathered saprolite with pseudomorphs of all three primary minerals. This grades upward into highly weathered saprolite with pseudomorphs of plagioclase only, and then massive red–brown bauxite with relict angular domains of saprolite.

At Hazeldean, a metamorphosed ancient soil occurs close to the Hazeldean plug (Lambert and White, 1965), a remnant eruption site. The soil is preserved adjacent to a small deposit of quartzose sand and gravel, now transformed to silcrete. Before being metamorphosed, the soil was 'mature' consisting primarily of Fe_2O_3 and Al_2O_3 with minor silicate minerals (Taylor and Smith, 1975). It is now a dense rock containing magnetite, corundum (sapphire), mullite and other high-temperature forms of Fe- and Al-rich minerals.

Alluvial and lacustrine sediments within the basalt pile mark the positions of streams and lakes that occupied topographically low parts of the evolving basalt-dominated landscape. Most of the sediments in the alluvial tracts are dominated by quartzose gravels and sands, indicating that many of the streams had their headwaters outside of the volcanic terrain. This in turn suggests that the basalts of the Monaro Volcanic Province predominantly accumulated within existing topographic lows. Geological mapping by Taylor *et al.* (1985) shows that the basalts filled substantial valley systems with a relief of up to 400 m.

Lacustrine sediments preserved between the basalt flows are dominated by quartzose sand and silt with a kaolinitic matrix, once again suggesting derivation, at least in part, from outside of the volcanic pile. Many of the lake deposits have been disrupted by the basalt flows forming pods of sediment rucked up into the basalt or isolated bodies of basalt enclosed by the lake sediments. At a site 5 km west of Cathcart, basalt entered a lake and explosively disrupted the clayey sediments (containing mega-floral remains). Fragments of whitish lake sediments now occur in a matrix of massive hyaloclastite, with pillows of more solid basalt

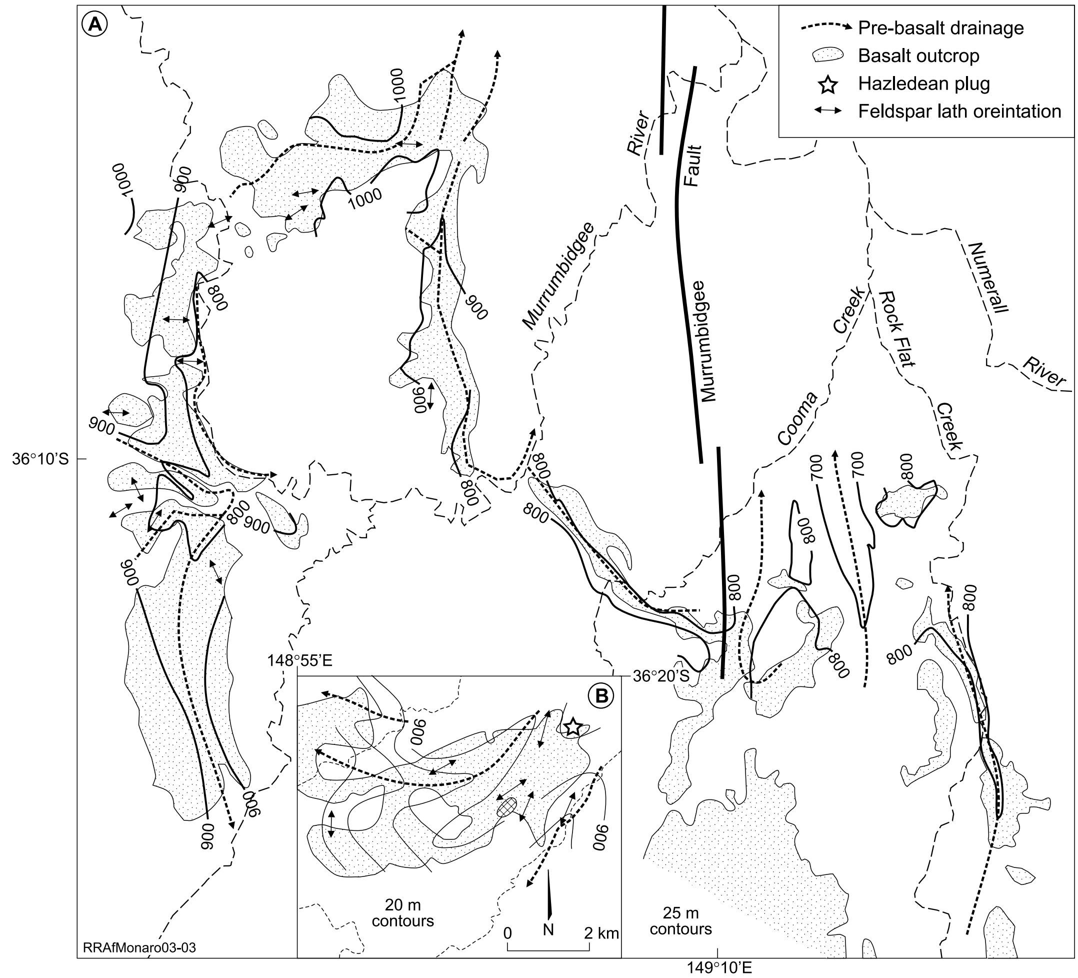

Figure 3. Maps showing the present and pre-basaltic drainage patterns with contours on the pre-basaltic surface. Feldspar lath orientation provides an indication of basalt flow direction. Part A shows Murrumbidgee River system north of the Great Divide or Monaro Range. Part B shows part of Snowy River System south of the Monaro Range. (from Taylor *et al*., 1985)

formed as the lava entered the lake. Above this, a thick layer of pillow basalt and jigsaw-fit hyaloclastite occurs, with individual pillows varying from a few centimetres to a metre or so in diameter. The pillow basalts are separated from the lower massive hyaloclastite by a thin layer of whitish lacustrine sediments signalling a pause in basalt eruption. Hyaloclastites are known from three separate localities within the Monaro Volcanic Province (Cathcart, Poddy Hut Creek near Ando, and Wambrook Hill towards Adaminaby).

Many of the alluvial sediments are now silicified forming extensive sheets of silcrete. Silcrete outcrops are common throughout the Monaro, lining the courses of pre- and syn-basaltic streams. Interestingly, they contain no basalt relics even though the streams providing the quartzose sediments must have flowed across the basalt. Silicification appears to have been accompanied by dealuminification. The silica was partly sourced from the quartzose sediments and probably also in part from the weathering of the basalts, for which there is abundant evidence including intrabasaltic bauxites and deep weathering profiles developed on present-day basalt exposures.

Sub-basaltic regolith

The contact between the bedrock and overlying Cenozoic basalts has been examined and mapped by Taylor *et al.* (1985) and Brown *et al*. (1992). These studies clearly show that the basalts to have filled pre-Palaeocene valleys and in the process of doing so have preserved many of the landscape and regolith features in existence at that time.

Prior to basalt eruption, the landscapes of the Monaro had slightly more relief than now (>800 m), with the maximum relief occurring along the eastern flank near the Great Escarpment. Relief farther west was closer to that of today (Figure 3). Many of the major and minor streams flowed in similar directions to the extant drainage. Although Brown (1994) and others argue for localized drainage reversals, evidence for this is minimal. Mapping of these early Palaeogene/late Cretaceous landscapes has also shown that the basalt pile has been locally deformed by Cenozoic tectonism, including faulting and gentle folding.

The sub-basaltic regolith is varied, but it is clear that deep weathering profiles (10–35 m thick) existed on the granitic and metamorphic landscapes of the time. The Palaeozoic sedimentary rocks had a varied regolith with the more resistant quartzose rocks having a very thin regolith, whereas the more labile rocks were covered by a moderately deep regolith (~5 m).

The late Cretaceous landscape was well-vegetated with a cool to cold climate rainforest (Taylor *et al.,* 1990). The landscape was also traversed by numerous streams. Alluvial sediments are well preserved and it is in these that much of the fossil wood used in the vegetation interpretation occur. Lakes also formed a significant component of the landscape. Their sedimentary deposits are also well preserved, locally yielding spores and pollens that provide further information on the vegetation cover.

POST-BASALTIC DEPOSITS AND REGOLITH

Lake Bunyan

During the Neogene, movement on the Murrumbidgee Fault near Bredbo dammed the Murrumbidgee River forming a large lake that was maintained from about 20 Ma to about 10 Ma. This lake, named Lake Bunyan (Taylor and Walker, 1986a,b), accumulated deposits in a down-warp along the Murrumbidgee, eventually accumulating in excess of 165 m of sediment. The sediments consist of five main facies: clays; volcanogenic debris (basaltic ash); marginal gravels and sands; coal; and, diatomite. The deposits are confined to valleys of Cooma Creek east of the Murrumbidgee Fault, the Numeralla River and its tributaries, Rock Flat and Middle Flat Creeks. In each case, the lacustrine deposits form an extensive series of plains incised by the modern drainage.

Palynological studies from Lake Bunyan (Tulip *et al*., 1982) show that this part of the northern Monaro was drier than adjacent regions during the Neogene, which suggests that the main range of the Snowy Mountains was already at a higher elevation than the Monaro at this time. This rain shadow has persisted to the present.

Quaternary regolith

Ride *et al*. (1989) and Armand *et al*. (2000) have described Quaternary deposits and soils in the Monaro region in detail, noting the presence of three depositional terraces with different soil types developed on each. Costin (1954) mapped the soils of the Monaro and much of the Quaternary cover. Most of the Quaternary regolith is either alluvium, colluvium or aeolianite. Weathering and soil overprints occur on all but the youngest materials, and many of the Quaternary (and in places older) regolith units contain carbonate overprints (calcrete). The calcrete formed in the rain shadow zone that occurs east of the Snowy Mountains between Bunyan and Bombala. Contemporary rainfall in this area is in the order of 600 mm/yr. This must have persisted for some time in order to allow for the development of the thick calcrete profiles that occur throughout much of the Monaro region.

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