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Discussion: Landscape evolution and tectonics in southeastern Australia (Ollier & Pain 1994)

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Ollier & Pain (1994) have presented an interesting and provocative essay on the evolution of the landscapes of southeastern Australia. A number of their ideas, particularly the broader scale interpretations, are worthy of further detailed study. There are also a number of aspects that we feel require discussion and clarification.

One of our major misgivings with the article is the almost total lack of consideration of earlier work, carried out by numerous geologists and geomorphologists in southeastern Australia, and the stated intention to ignore most existing data and interpretation. Ollier & Pain have sought to demonstrate the landscape antiquity in southeastern Australia, but have neglected, or failed to acknowledge, much of the work which has already demonstrated this, including Craft (1933), Bishop et al. (1985), Taylor & Walker (1986), Taylor & Ruxton (1987), Ruxton & Taylor (1987), Taylor et al. (1990), Brown et al. (1992) and many others. Some diagrammatic data are also presented without full acknowledgement. For example the primary source of Figure 10 is an unpublished diagram from Sharp (1980) not Ollier & Wyborn (1989) as stated in the caption.

Ollier & Pain further promote the notion of a 'Monaro Volcano' as a large circular structure, now mostly eroded away. This was originally proposed by Ollier and Denis Taylor (Ollier & Taylor 1988) on the basis of a poorly defined radial drainage pattern, for which other causes have been suggested (Taylor et al. 1989). The notion ignores the large body of data indicating the Monaro Volcanic Province is an irregular lava field that did not extend significantly farther east than its present limit (Taylor et al. 1989, Brown, et al. 1993; Roach 1994; Roach et al. 1994). In the caption to their Figure 6, Ollier & Pain claim 'eruption of a huge volcano centred on Brown Mountain initiated radial drainage on its surface'. They show the outline of this proposed volcano, which, according to the scale on the map, is 54 km in diameter. However, the scale shown is incorrect. If the correct map scale is used, the diameter of the structure is 90 km. They do not specify the height of the mythical edifice nor the volume of lavas extruded. In the following sections some detailed data from the Monaro are reviewed and compared to data from other large volcanic structures. The implications for Ollier & Pain's hypotheses are then considered.

Some statistics on circular volcanic structures

Information of varying detail and accuracy about the shapes, slopes and heights of various volcanoes is available in the literature. A compilation of data is presented below for Mt Etna, a composite volcano above an active subduction zone, and Mauna Loa, a shield volcano with similar rock types to the Monaro (Table 1).

Table 1. A compilation of data on the size and slopes of Mt Etna and Mauna Loa.

Source	*Mt Etna*	*Mauna Loa*
Cotton (1952)	no data	2.5–3° to 11° slope at mid-flank
Ollier (1969)	no data	4000 m ASL 100 km average? diameter (shields <7° slope)
Macdonald (1972)	no data	25 average slope
Bullard (1977)	3242 m ASL 64 km maximum diameter	13,680 feet ASL 30 by 60 miles diameter
Hall (1987)	3300 m ASL 40 km diameter	4169 m ASL 93 km approx. least diameter
Francis (1993)	3308 m ASL	no data

Applying simple trigonometry to these figures gives the following ranges of average slope for the two different volcanoes:

	Mt Etna	*Mauna Loa*
Hall (1987)	9.3°	5.1°
Ollier (1969)	no data	4.5°
Macdonald (1972)	no data	2.5°
Bullard (1977)	5.7°	2.5–4.9° (av. 3.7°)

By any reckoning, Mt Etna has a steeper slope than Mauna Loa, reflecting its more silica-rich nature (e.g. more viscous lavas, larger ratio of ash to lava). The more effusive nature of the Hawaiian volcanoes and development of lava tubes also contribute to their gentler slopes.

The proposal of near-circular volcanic structures is of key importance to the interpretation of landscape evolution put forward by Ollier & Pain and earlier by Ollier & Taylor (1988). Ollier & Taylor (1989) suggested that their 'Monaro Volcano' was similar in form to Mt Etna, comprising a circular structure with numerous parasitic cones. Petrological and geochemical studies of the remnant Monaro lava pile indicate that it is composed of transitional basalt, alkali olivine basalt, nepheline basanite and minor olivine nephelinite and olivine tholeiite. Lava of these compositions is moderately to very fluid, similar to Hawaiian-style shield-forming lavas. Field evidence in the Monaro indicates many thin flows, of the order of a few metres to a few tens of metres thick, supporting this assumption (Brown et al. 1992).

A circular shield volcano of Hawaiian style, 90 km diameter, centred on Brown Mountain with the minimum slope of 2.5° would have peaked 1965 m above the existing land surface. Applying the average slope of 3.7, the height would have been 2910 m. A composite volcano similar to Mt Etna would have been between 4490 m and 7370 m high, using the minimum and maximum slopes for Mt Etna—certainly an imposing edifice!

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What was the average erosion rate in southern NSW over the last 34 million years?

At Brown Mountain there is currently a cap of basalt less than 140 m thick on Palaeozoic basement, implying the removal of a significant amount of overlying rock if this area was once the centre of a large volcano of whatever form. For a Mt Etna-style composite volcano, the erosion rate necessary to remove a minimum of 4.4 km of overburden would have been 0.13 mm/yr, or 4 times the maximum regional erosion rate of 3 km in 90 million years (0.03 mm/yr) established using apatite fission track analysis (Moore et al. 1986; Dumitru et al. 1991; Fabel & Finlayson 1992; Kohn & Gleadow 1994). Given a shield volcano with elevation 1825–2270 m above present, the erosion rate would have been 0.05–0.08 mm/yr, still far more than this maximum rate.

Most workers believe that erosion rates in southeastern Australia during the Cainozoic were generally much less than the maximum values suggested by fission track analysis. Ollier & Pain state that 'basalts show only a few hundred metres of erosion on most of the palaeoplain'. They also note that 'there has been less than 1 km of erosion at the Great Escarpment'. The preservation of numerous deep weathering profiles within the Monaro lava sequence (Brown et al. 1992) also suggests low rates of erosional stripping, at least for the Palaoecene to the Oligocene. Nott & Purvis (1995) have shown that 100 Ma lavas in the Mt Dromedary igneous complex sit on their original palaeosurface at current sea level and, consequently, that this area of the coastal plain was already well established by the Early Cretaceous. While Nott & Purvis (1995) do not indicate the erosion rate of the highlands, they do show that the landscape is far older than previously thought, and a consequent drastic reduction in the erosion rate is implied. Ollier & Taylor (1988) suggested that the Great Escarpment did not reach its current position until well after 50 Ma (in fact well after 35 Ma) where it was responsible for removing the eastern half of the towering 'Monaro Volcano'. This implied rapid removal of material appears to be inconsistent with the data on erosion rates.

Some physical characteristics of southeast Australian shield volcanoes and lava fields

Ollier & Pain group the 'Monaro Volcano' with 'major shield volcanoes on or near the Great Divide', including the Ebor and Barrington volcanoes and the Canobolas Volcano on the 'Canobolas Divide'. Ebor is defined by Duggan (1989a) as a central volcano with a life span of about 1 million years (19.2–18.2 Ma). It is composed of various basic to evolved rock types ranging from feldspar-phyric basalt to quartz-trachyte/rhyolite. Ebor is surrounded by radial drainage (Ollier 1982) and had a maximum volume of about 300 km^3. Barrington is defined by Mason (1989) as a lava field, although only one vent is known at present, with a life span of around 11 million years (55–44 Ma) and a volume of around 700 km^3. Barrington is composed of similar rocks to the Monaro (Ol-tholeiite, transitional basalt, alkali basalt, basanite, nephelinite, hawaiite) which appear to be largely primary or near-primary (like the Monaro). Canobolas had a life span of around 2 million years (13–11.2 Ma) and is composed of about 50 km^3 of evolved rocks, ranging from hawaiite to peralkaline rhyolite and syenite. Canobolas had a complex series of vents centrally distributed in a 210 km^2 area and appears to be a small-scale model of what the 'Monaro Volcano' should have been according to Ollier & Pain. Based on existing data, the Monaro Volcanic Province had a life span greater than 24 million years (58–34 Ma) and consisted of at least 630 km^3 of mafic lavas covering more than 4200 km^2 erupted from at least 65 separate vents (Roach et al. 1994). Rock types in the Monaro are almost identical to those at Barrington. While the Monaro Volcanic Province compares closely to Barrington in terms of volume and geochemistry, Ebor and Canobolas do not. Describing all these volcanic piles as major shield volcanoes is misleading, as it suggests that they were all originally nearly circular in shape. Any present irregularities in shape are thus implied to be largely the result of post-volcanic erosion.

Examples of established shield volcanoes in eastern Australia, such as the Tweed and Warrumbungle volcanoes, possess a wide variety of volcanic structures and rock types not seen in the Monaro. Both the Tweed and Warrumbungle volcanoes contain a series of ring dykes, radial dykes and sills composed of various fractionated intrusive rock types (Stevens et al. 1989; Duggan 1989b). Given that the Monaro Volcanic Province is older than both the Tweed and Warrumbungle volcanoes, hypabyssal rocks within the core of the 'Monaro Volcano' should now be exposed. The possibility that the Bondo Dolerite (Pratt et al. 1993; Roach et al. 1994) represents a large sill has been discounted by the Myalla drill hole (Bega (BMR) No. 7, Brown et al. 1992; 1994) and by stratigraphic work (Roach, unpublished data), which clearly demonstrate that the Bondo Dolerite is topped by a Tertiary bauxitic weathered horizon. Furthermore, the Bondo Dolerite is found within a sequence of moderately to highly weathered basalts with at least seven individual bauxite horizons, implying that all these rocks were deposited as lavas.

Parasitic volcanoes and the Palaeozoic basement

In reply to discussion, Ollier & Taylor (1989) suggested the Monaro Volcanic Province was a complex circular volcano with parasitic cones centred on Brown Mountain to account for the numerous vents, an idea carried over to Ollier & Pain. Roach et al. (1994) showed that the volcanic vents in the Monaro (now plugs, dykes and maars) are concentrated in two main northwesterly trending zones, probably controlled by similarly oriented basement structures. Vent structures are found along the northern Bemboka Zone from west of Cooma to Brown Mountain. If the volcanic province formed as a circular shield around Brown Mountain, there should be a distribution of vents around this centre. Given the structural restrictions of the Palaeozoic basement, most vents should be concentrated along a northwesterly line over the Bemboka Zone northwest and southeast of Brown Mountain. No remnant vents have been located further southeast of Brown Mountain and, while there is a possibility that some exist in the rugged country on the Great Escarpment, all of the known vents are concentrated well to the west of the Great Escarpment and Brown Mountain. Most are within the lava pile and the concentration of eruption sites along the Bemboka zone defines part of the present Great Divide. The focus of volcanic activity in the Monaro Volcanic Province thus lay west of Brown Mountain and the distribution of known eruption sites does not support the idea of a circular shield volcano centred on Brown Mountain.

The whole notion of a circular 'Monaro Volcano' (Ollier & Taylor 1988, 1989; Ollier & Pain, 1994) is really only based on a pseudo-radial drainage pattern around Brown Mountain. Careful analysis of basement structures and the proximity of the lava pile in this region reveals that drainage has followed a series of orthogonal fractures within the Bega Batholith on the eastern side of Brown Mountain and the general structural grain in the Palaeozoic basement to the north and south, and is controlled by the Great Divide and position of the lava field to the west (Fig. 1). Brown Mountain itself is also one of the highest points of basement on the Monaro. The drainage pattern can thus be explained without

Figure 1. Map of the Monaro region, showing drainage, position of the Great Divide, location of the Great Escarpment, present outcrop of the Monaro lava field, pattern of basement fractures, and outline of the proposed 'Monaro Volcano' of Ollier & Pain. Data are from Brunker et al. (1970) and Ollier & Pain (1994).

invoking a large circular volcano, now mostly eroded away. To emphasise the point that radial drainage can form without the prior existence of a volcano, we have included a figure of the Broken Hill area (Fig. 2) which shows two centres of radial drainage on mineralised high-grade metamorphic rocks where there is no evidence of volcanoes before the development of the landscape.

Geochemical considerations

A large circular volcano of central or composite type implies a large, centrally located, underlying magma chamber. Mauna Loa, Mt Etna and many other central volcanoes have such large magma bodies beneath their apices, where fractionation takes place. At Mauna Loa, fractionation is evidenced by phonolitic residua of alkali basaltic parents and, rarely, quartz-bearing alkali rhyolites (Wilson 1989). Fractionation is represented in Mt Etna as a complex series of rocks, ranging from tephrite to alkali basalt to hawaiite to mugearite. The presence of large magma chambers beneath shield volcanoes is commonly indicated by localised seismicity, which can also be modelled to reveal the shape of the chamber (e.g. Ryan et al. 1981).

As volcanism ceased in the Monaro during the mid Tertiary, it is not possible to use seismic tomography to model underlying magma structures. However, evidence of any large magma chamber should be present in the form of fractionated rocks. Comparing volcanic rocks in the Monaro Volcanic Province to those of Mauna Loa and other central volcanoes leads to the inescapable conclusion that there is no large central magma chamber beneath the Monaro. The Monaro does not possess the highly fractionated quartz-normative rocks found in Mauna Loa, nor any of the common hypabyssal rocks found in the Tweed and Warrumbungle volcanoes (cf. Stevens et al. 1989; Duggan 1989b). Monaro basalts are largely primary or near-primary, indicating short residence times in the upper mantle/lower crust and high ascent rates without the intermediate pause in an upper-level magma chamber.

Geophysical evidence

There is no geophysical evidence (gravity or magnetic) to support the idea of a major central volcano centred on Brown Mountain. The geophysical characteristics of the Monaro have been previously discussed by Taylor et al. (1989), in reply to Ollier & Taylor (1988), and by Roach et al. (1994).

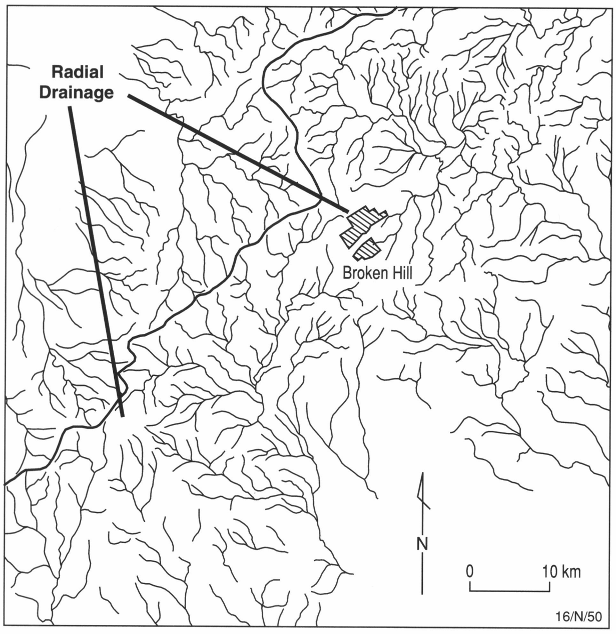

Figure 2. Drainage map of part of the Broken Hill area, showing radial drainage around Broken Hill (an original landscape high related to the Broken Hill orebody?) and a second radial drainage pattern near Thackaringa. Map is from Hill et al. (1994) based on data from Willis (1988).

Conclusion

In this discussion we have concentrated on refuting the notion of the 'Monaro Volcano' as a large circular shield volcano because we have a large amount of detailed data on this feature. Other features used to understand the landscape evolution of southeastern Australia may also require more rigorous observation and interpretation. We feel it is important that all models for the landscape evolution of this region be constrained by the facts as they are known and modified as new information comes to light.

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