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Mineralogy maketh mountains: Granitic landscapes shaped by dissolution

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ABSTRACT

In tectonically quiet regions, the shape of the landscape is controlled by the erosion resistance of the rocks. Erosion largely depends on the release of particles from the weathering rock, which in turn requires a degree of dissolution of the more soluble grains. The rate of dissolution of the common rock forming minerals allows the construction of a numerical Rock Weatherability Scale (RWS) based on the rock's modal mineralogical analysis. Applied regionally to three granitic landscape regions of the Bega Valley of southern New South Wales, the Tate Batholith and Featherbed Volcanics of north Queensland, and granitoids in the Beaufort region of Victoria, the mean elevation of the larger plutons in each region correlates highly ($r = 0.83$–0.93) with their RWS. Variation in composition within a pluton also shows there is a clear connection between changes in RWS and relief within the pluton. From these results it is apparent that the landscape of such granitic terrains is determined very largely by mineral dissolution rates, with plagioclase composition and content being a major factor.

1. Introduction

In regions where there is little active tectonism, probably the most obvious and well-known relation between geology and landscape is that hard rocks make up the hills, soft rocks the lowlands. Introductory texts make this point, citing for example quartzites as resistant to erosion, shales as more susceptible. Not so much, however, has been made of elevation differences across terrain where the bedrock such as granite is, at least in a general classification, homogeneous.

Much is known about how rocks weather, how the component minerals break down, and of the chemical and mineralogical changes that take place; see for example Nahon (1991) and Taylor and Eggleton (2001). Much less is known about how these processes lead to landscapes of varying relief, yet such landscapes have evolved through the selective removal by erosion of susceptible rocks. Three processes cause or allow rocks to erode:

- direct erosion by grinding, such as by ice or sand-blast or by movement following fracturing;
- direct erosion by dissolution, such as seen in limestones and marbles; and
- loss of some part of the rock, either of a cement or matrix binding more weathering resistant grains, or by the partial breakdown of a component that acted as a keystone in a crystalline rock such as granite. The particles, once released from their interlocking fabric, become susceptible to erosion by agencies such as water and gravity.

It is the third mechanism that is investigated in this study. Gerrard (1988, p. 121–2) writes:

"In some granites, the early stages of weathering may be dominated by small amounts of accessory minerals such as calcite. ... The removal of calcite would lead to a lessening of coherence and of the restraint on grain movement".

Although calcite is a most unusual mineral in granite, exactly the same effect could be expected in any granite following the weathering of plagioclase and mafic minerals. Plagioclase, for example, has been shown to weather by dissolution, with the grain surface gradually altering to clay via a poorly crystalline precursor (Banfield and Eggleton, 1990). Etching and dissolution at grain surfaces eventually separates the minerals from each other, allowing mechanical processes to erode the weathered rock.

That the first step in the erosion igneous of rocks is the loss of material by dissolution has been shown by many of studies of rock weathering. Initially the rock retains its overall coherence as it weathers isovolumetrically to saprolite. While this is happening mass is lost, largely in solution, as is clear from the gradual reduction in density of progressively weathered rocks (e.g. Braga et al., 2002; Eggleton et al., 1987; Gardner et al., 1978; Patino et al., 2003; White et al., 2001). Beyond the saprolite stage of weathering the rock loses its coherence and original fabric, and from this point the constituent mineral grains are subject to movement and ultimately to erosion.

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The concept that the broad shape of granitic landscapes may be partly related to variation in rock type has been reviewed by Migoń (2006) in a discussion of the geological controls on granite landscapes. He cites several such analyses, and points out that "lithological difference only becomes geomorphically significant if a general trend of landscape development has been maintained over very long timescales." In summarizing those studies Mignoń finds that granites rich in quartz and K-feldspar tend to underlie higher ground whereas granodiorite country is typically undulating and has a thicker weathering mantle.

Klaer (1956) records that on Corsica the highest mountains are of rhyolite with two-mica granites. Pye (1986) investigated the composition of inselbergs in granitic terrains and found that potassium-rich granitoid rocks are relatively more resistant to weathering than their less potassic counterparts, attributing this difference to the greater resistance to weathering of potassium feldspar compared with plagioclase. Migoń (1996) in a study of granite landscapes in the Sudetes of central Europe noted: "In the Jelenia Góra Basin the correlation between the landscape, relief energy, and elemental composition is most obvious, in relation to potassium and sodium content. The highest potassium content (over 4.00%, up to 5.10%) is associated with higher ground and inselberg-like landscapes, which occur in the central and eastern part of the basin. In these parts sodium and calcium values are intermediate and low, reaching 1.70–2.00% and below 1.00% respectively. Undulating lowlands and depressions are characterized by low potassium content (3.50–3.70%) and by increasing content of sodium (2.40–3.00%). Rare inselbergs which occur within depressions are connected with isolated outcrops of fine-grained granites or aplogranites". Migon concludes that such landscapes are controlled by the lithological, mineralogical and chemical properties of bedrocks.

Hill (1996) noted that the elevation of granitic plutons in Victoria, Australia, tended to be related to their mineral composition, and drew attention to the importance of the contribution that biotite weathering makes to granite erodibility. He further showed that the mean elevation of the granitic plutons in the Ararat-Beaufort region of Victoria was related to their modal mineralogy.

Dixon and Young (1981) demonstrated qualitatively that the landscape of the area of southern New South Wales, Australia, known as the Bega Valley, was clearly related to the weatherability of the various granite types across the region. They recognized that granites rich in quartz and orthoclase produced tor fields across the higher country, whereas those rich in biotite, amphibole and plagioclase produced thick arenaceous mantles in valleys.

At the time of Dixon and Young's work the detailed geology of the granitoids of Bega Valley had not been completed. In his 1980 PhD study of the evolution of the Lachlan Fold Belt, Beams distinguished 75 plutons within the Bega Batholith, each with characteristic chemistry and mineralogy. The variations in rock type and elevation across the coastal lowlands part of that batholith provide an opportunity to refine the general observation made by Dixon & Young that granites form the higher country, granodiorites the lowlands. In so doing, this paper assesses the hypothesis that in the broad sense, the variations in the elevation of the landscape are primarily determined by the weatherability of the minerals comprising the rocks beneath.

2. Mineral weathering

The susceptibility of minerals to weathering has been well documented. Reiche (1943) introduced weathering potential indices for minerals and since then a number of studies have consolidated those conclusions. From comparing survival in weathering profiles to dissolution studies in laboratories, a broadly consistent set of susceptibilities has evolved, summarized in Table 1.

Bandstra et al. (2008) summarized mineral dissolution rates, including plots of the surface area normalized dissolution rates vs. pH. The rates at pH 5 are here selected because that is a common pH of soil water. These values for granite minerals produce a weatherability order similar to those found from field observations. (Table 2).

A first attempt at quantifying a rock's weathering rate can be made by summing the products of each mineral percent by its Mineral Weathering Scale to yield a Rock Weatherability Scale (RWS):

$RWS = \Sigma M_i W_i$ where M_i is the proportion of the i^{th} mineral, W_i its Mineral Weathering Scale.

For plagioclase, the MWS is scaled between albite and anorthite according to the composition of the plagioclase in the pluton.

Such a simple approach clearly leaves out important other factors, principally that because dissolution rates are area dependent, weight for weight fine crystals dissolve faster than coarse ones. Similarly some rocks are more closely jointed or differently foliated than others, leading to differences in the ability of water to penetrate and so effect dissolution. In a general analysis of the granitic terrains considered here, both these issues can reasonably be ignored; the plutons are of comparable grain size, generally unfoliated and widely jointed.

A quantitative estimate of a rock body's erosion resistance can be made on the basis of its mean elevation measured over the area of the body. The purpose of this paper is to compare the mean elevation of each major rock unit in the Bega Valley (almost all are plutons) with the rock's average weatherability based on its mineralogical composition. An obvious inconsistency with this approach is the impact the surrounding topography has on any selected pluton. A small relatively erodible pluton surrounded by more resistant ones cannot erode below the base level of the streams crossing a more resistant pluton.

3. Bega Valley granites

3.1. Geology

The Bega Valley lies in the Lachlan Fold Belt (Packham, 1969; Chappell et al., 1988). To the west this region is bounded by Australia's Great Escarpment, a landscape feature rising of the order of 1000 m from the coastal plain, stretching from north Queensland to Victoria. The eastern boundary of the Bega Valley is the ocean. Minor Cambrian sediments (Wagonga Beds) are overlain by a thick Ordovician sequence of turbidites of the Adaminaby Group (Glen et al., 2004). Folding and granitic intrusion during the Early Devonian was followed by felsic vulcanism forming the Boyd Volcanic Complex to the south east of the region. Terrestrial sedimentation in wide rivers produced the overlying Late Devonian Merrimbula Group conglomerates shales and sandstones, reaching 3 km thickness to the north, but only about 1 km in the south (Steiner, 1975). The uppermost Merrimbula Group sediments are similar to those at the top of other Devonian terrestrial sediments in New South Wales known as the Lambie facies (Thrupp et al., 1991) suggesting these sediments never attained much greater thickness than they now show.

The granitoids (Fig. 1) comprise the major part of the eastern Bega Batholith (Beams, 1980) and the Moruya Batholith, a group of eight small plutons extending southward from Nelligen to Bodalla (Griffin et al., 1978). They range in composition from granite to diorite, with granodiorites and monzogranites (adamellites) dominating (Beams, 1980).

South of the NSW Victorian border, the Bega Batholith extends into the Craigie 100,000 map sheet. Twelve granitic plutons form a block 30 km long and 20 km wide, ranging in elevation from 800 m to about 250 m (Fig. 2). Here the escarpment is 30 km wide, much wider than further north where near Bemboka it is about 6–8 km wide.

3.2. Erosion history

It is critical to testing the hypothesis that a rock's susceptibility to erosion can be estimated from its composition, that the area of the test be one where all the rocks can be shown to have experienced