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Structural control in the evolution of granite landscape

PIOTR MIGOŃ

University of Wrocław, Department of Geography and Regional Development, Poland

Abstract

Granite landscapes owe much of their diversity to the variations within the rock itself. Intrusions differ in terms of mode of emplacement, texture, mineralogy, fracture patterns and deformation history, and these geological factors control both the shape of individual landforms and the evolution of large-scale landform assemblages. Rock control is also evident in the course of slope processes acting on rock slopes and in weathered terrains. Structural control usually assumes a hierarchical pattern. Regional landscapes tend to reflect lithological and large-scale structural variations, whereas individual landforms develop under pervasive influence of fracture systems. The primacy of rock control explains why adjacent granite landscapes can be fundamentally different, and why those in contrasting morphoclimatic zones can be very much alike.

Key words: granite, structural control, joints, rock slopes, mass movement

1. Introduction

Granite supports some of the most spectacular landforms and landscapes that exist on Earth. At a large scale, these landscapes can be classified as multi-concave, multi-convex, plains and all-slopes, on which minor landforms are superimposed (Thomas, 1974; Twidale, 1982). Approaches to explain this variety appear to fall into two major categories: structural (e.g. Lageat, Robb, 1984) and environmental (e.g. Wilhelmy, 1958). Another explanation is process-based and is championed by Twidale (1982) who emphasizes the key role of deep subsurface weathering in sculpting granite landforms. On the other hand, Lidmar-Bergström (1995) showed that in the southern part of the Baltic Shield time was the principal control in the evolution of granite landscapes in the Mesozoic. Depending on the duration of exposure of basement rocks, different types of relief developed.

An apparent repetition of individual landforms in different morphoclimatic zones implies that geological factors acquire primacy in controlling the evolution of granite landscapes. This hypothesis is strengthened by the observation that different types of granite landscapes may co-exist in a relatively small area of uniform climate, and that similar assemblages of landforms can be found in contrasting environments. Domes serve as an excellent example of a form that can be found worldwide, in no evident relation to climatic zoning of the globe (Fig. 1). They occur in the humid tropics (Bakker, 1960; Thomas, 1965), seasonally humid savannas (Pye et al., 1986), semi-arid and arid lands (Selby, 1982), mid-latitudes (White, 1945) and towards the polar circle (Schrepfer, 1933). Moreover, they are present in a range of geomorphic settings, from plains to high mountain relief. Likewise, many small-scale landforms have global distribution. Weathering pits typify granite surfaces in the tropical rainforests (Bakker, 1960) and deserts (Goudie, Migoń, 1997) alike. As Twidale's (1982) survey has revealed, many other granite landforms show similar, global distribution patterns. Landform inheritance and environmental changes are occasionally invoked to account for this wide range of occurrence, but they fail to explain all cases. Moreover, hypotheses of climatic control often take the form of "guilt by association". It is assumed that because certain landforms, e.g. inselbergs, evolved in a geological period typified by a certain climate, then these climatic conditions were instrumental in shaping those landforms.

The full understanding of the role of rock control in the evolution of granite landforms is yet to achieve. This paper aims to contribute to this line of research and serves three principal purposes. One is to show the range of rock controls, using examples from different geographical settings. Another one is to demonstrate how structure can influence processes at work and this is done by referring to slope development. Finally, the concept of hierarchical structural control is outlined.

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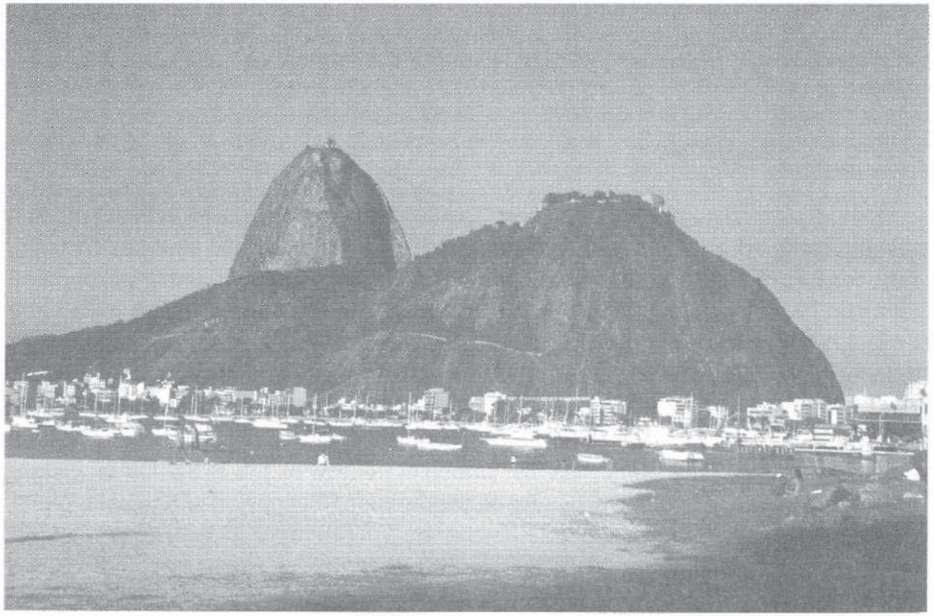
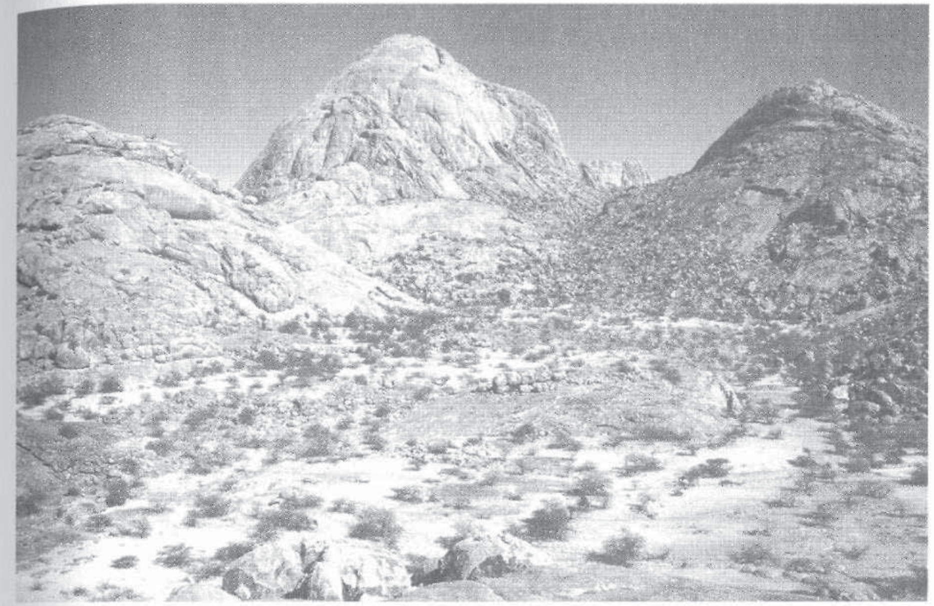


Fig. 1 Granite domes (bornhardts) occur in all climatic zones and topographic settings, hence they are the prime example of a structural landform. Their form reflects the presence of an extremely massive rock compartment and progressive development of sheeting joints. ▲(**a**) – Pao de Acuçar and Morro da Urca, Rio de Janeiro; ►▲(**b**) – Spitzkoppe group, Namibia; ►▼(**c**) – Half Dome, Sierra Nevada, California



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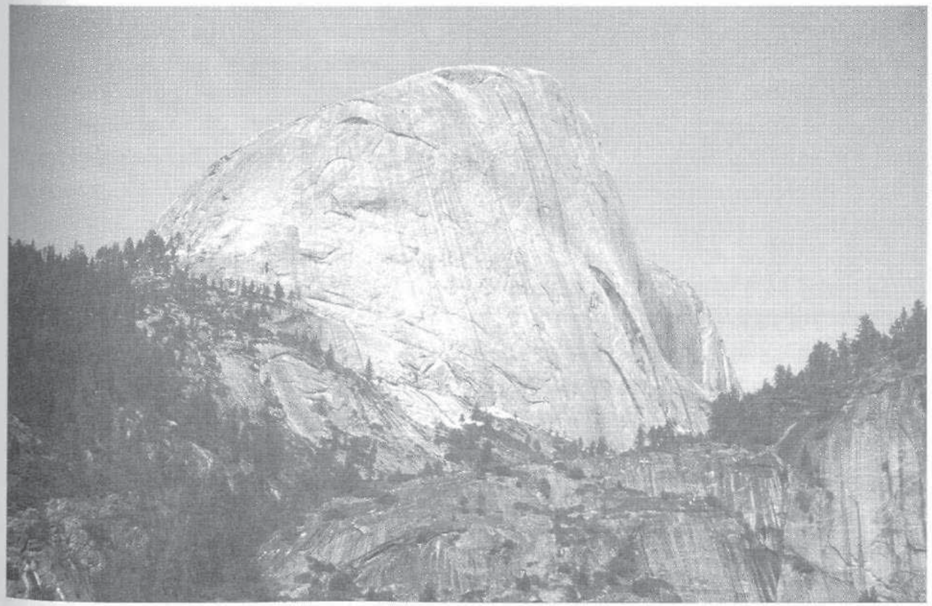

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2. Variety of rock controls

2.1. Textural differentiation

Texture is usually defined as the term pertinent to the degree of crystallinity, grain size and shape, and the geometric relationships between constituent minerals (Cobbing 2000). Hence, textures are small-scale features which can be observed and described at a hand specimen scale.

For geomorphological purposes, a texture classification which emphasizes the size of minerals seems most appropriate as it is the crystal size and strength of grain boundaries which directly bear on rock resistance. A standard distinction is between fine-, medium- and coarse-grained granites but these terms are often loosely used by geomorphologists. In igneous petrology fine grained rock would be one with the average crystal diameter less than 1 mm whereas the average diameter in excess of 5 mm would classify the rock as coarse grained. If the average crystal size exceeds 3 cm, such rocks are spoken of as very coarse. Textural variants with large (> 2 cm) potassium feldspars amidst much smaller crystals are called porphyritic. Another approach is to distinguish between granites which are equigranular, i.e. constituent minerals are of similar size, and those which are not.

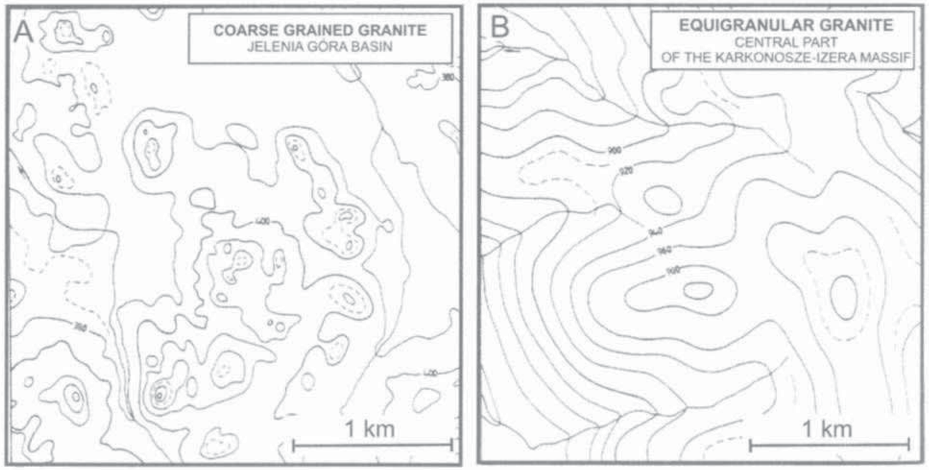

Fig. 2 Representative topographies developed on fine grained (left) and coarse grained granite (right) in the NE part of the Karkonosze-Izera granite massif

Landscapes supported by fine and coarse variants of granite usually differ from each other. The former tend to be subdued, whereas the latter are much more diversified and typified by residual hills, boulder clusters and basins. A good example is provided by the Karkonosze-Izera granite massif, West Sudetes (Fig. 2). Its northernmost part, the Jelenia Góra Basin, has developed in coarse porphyritic granite with K-feldspar megacrysts. The landscape is hilly, with abundant inselberg-like elevations interspersed with elongated basins, and relative relief up to 150 m per one kilometre square. By contrast, upland surfaces of the Karkonosze and Izera Mountains are typified by long planar slopes and shallow troughs, whereas more prominent hills are few (Migoń, 1996). The reasons probably reside in the relative uniformity of textural properties in fine grained granite, which are crucial for the progress of weathering. Moreover, fine grained granite is usually more regularly fractured than coarse variants, again allowing for a uniform advance of the weathering front. The latter observation shows also that structural influences in landscape development are difficult to isolate from each other.

2.2. Mineralogy

Granite mineralogy has long been rather neglected in geomorphology, although its role in deep weathering received due attention (e.g. Harriss, Adams, 1966; Eggler et al., 1969). Mineralogical control in landscape development has been directly addressed by Brook (1978) in respect to the basement regions in Transvaal, South Africa. He observed that inselbergs have preferentially developed in granite complexes which either have an elevated content of potassium feldspar, or have undergone potassium metasomatism. A similar relationship has been found in the Kora area of central Kenya (Pye et al., 1986). Likewise, residual landforms in Swaziland abound in potassium-rich porphyritic granites, but are significantly less common in granodiorites (Gibbons, 1981). The Bega batholith in Australia is largely granodioritic and forms a topographic basin, whereas higher ground with tors has developed on variants with higher content of quartz and orthoclase (Dixon and Young, 1981).

2.3. Joints and fractures

Granites are cut by discontinuities which may be planar or curved, of variable length, orientation and distinctiveness. They are usually referred to as 'joints' and geomorphologists tend to speak about 'joint-controlled' geomorphic features. However, this is not always correct because joints, strictly speaking, are discontinuities which are purely extensional and exhibit no shear along the strike. If a shear component occurs, however small, a term 'fault' would apply (e.g. Price and Cosgrove, 1990). In field situations it could be very difficult to identify this shearing component and therefore the use of the more neutral term 'fracture' is recommended.

Four main groups of primary discontinuities have been defined by Cloos (1925). These are cross fractures (Q-type), formed in the direction perpendicular to the magma flow, longitudinal fractures (S-type) striking parallel to the flow, horizontal or low-angle (< 20°) flat-lying fractures (L-type), and diagonal fractures striking at an angle of about 45° to the flow. Q, S, and L type fractures cross each other at right angles, hence they form an orthogonal fracture system which is present in many granite bodies of the world. However, fracture spacing in each set could be unlike in the other sets, and may significantly change within a single set if analysed in a wider spatial context. All these phenomena have significant geomorphological implications.

Examples of fracture control on the appearance of granite landscapes are common in the literature, although relatively seldom supported by quantitative data presentations. Fracture control is identified at a range of spatial scales, perhaps most often with

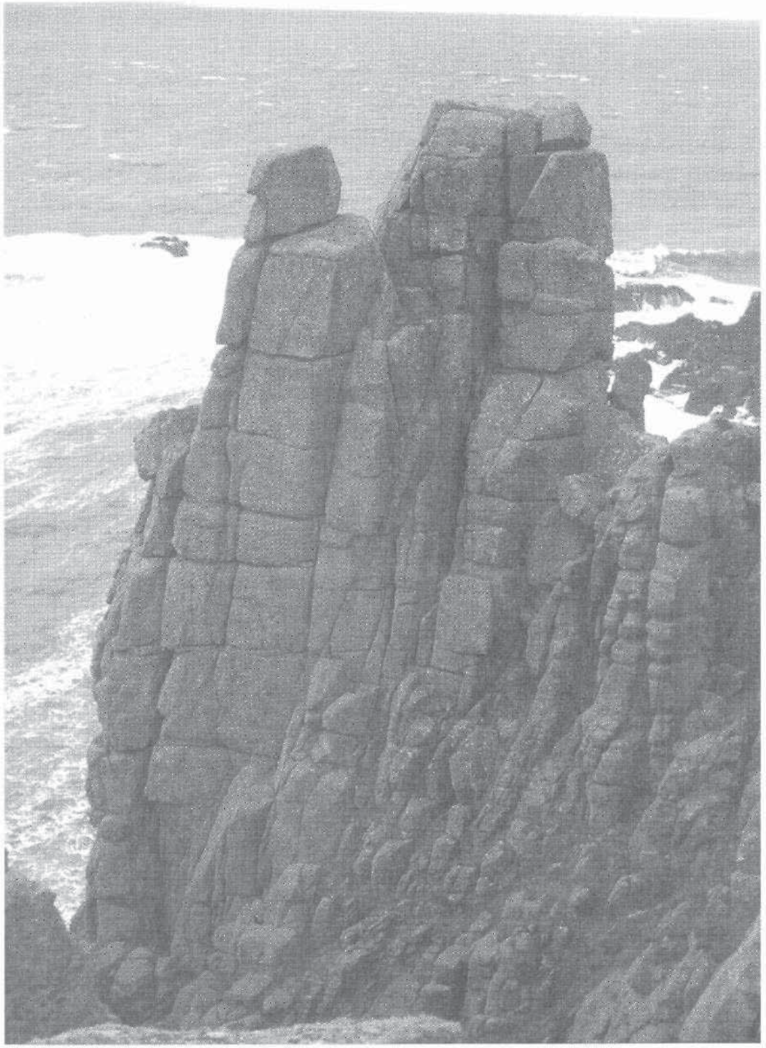

Fig. 3 Cliffed coastline at Land's End, SW England, shows an orthogonal pattern of fracturing, but individual tower-like residuals are evidently associated with localized decrease of fracture density within this pattern

reference to tors and inselbergs. Localized decrease in fracture spacing is an essential component of each conceptual model of their development, even if the processes are considered to be different (Linton, 1955; Twidale, 1964; Thomas, 1965; King, 1975) (Fig. 3). The presence of domes in particular is attributed to the occurrence of large massive compartments, perhaps in the state of lateral compression (Twidale, 1982), and this evident structural relationship explains their worldwide distribution (see Fig. 1). But fracture control has also been demonstrated at larger spatial scales. Drainage lines often follow fracture zones of regional importance (Mabbutt, 1952; Chapman and Rioux, 1958; Gerrard, 1974), whereas topographic basins can be located at their intersections (Thorp, 1967; Johansson et al., 2001). On the other hand, Selby (1982) showed how orientation and spacing of joints decisively control the shape of granite inselbergs in the Namib Desert.

Prominent fracture control is not restricted to oldlands subjected to protracted periods of deep weathering that has had ample time to exploit lines of structural weakness. The granite landscape of the Sierra Nevada, California, provides the evidence that the evolution of mountainous relief is strongly fracture-controlled too (Huber, 1987; Ericson et al., 2005). Geomorphic features guided by discontinuities include fluvial and glacially remodelled valleys, slope ravines, passes and half-circular topographic basins. Joints, whether primary or secondary, related to pressure release, play a key role in the evolution of individual slopes, influencing their shape and form. By contrast to plains and uplands, fluvial and glacial erosion rather than deep weathering have likely been the major processes exploiting fractures in the Sierra Nevada.

In the context of the Bohemian Massif, fracture control in the development of granite massifs has been shown by Votýpka (1970, 1974), although with reference to minor landforms such as castellated tors, frost-riven cliffs, pedestal rocks and pseudo-cirques.

2.4. Deformation history

Rocks in the crust are subject to constant stresses of variable origin and respond to those stresses by strain. In consolidated rocks of limited elasticity, such as granites, crustal deformation is usually of brittle nature and leads to the development of intra- and transgranular cracks, weakening of the fabric, jointing, and finally shattering if specific lines within the rock accommodate most of the stress imposed. Deformation can be particularly severe if an older intrusion becomes a part of a new mobile belt. Therefore, older granites tend to have weaker fabric and more closely spaced fractures than younger intrusions, which have suffered less from crustal stress after their emplacement. Structural contrasts between granite massifs of various age and deformation history are then revealed in geomorphology.

A good illustration is the Central Namib Desert, where two major granite bodies occur. Spatially more extensive is the Older Granite, which is 500–600 Ma old and has been subjected to deformation during the Damara orogeny and the continental break-up in the Mesozoic. After the break-up, a number of younger intrusions of early Cretaceous age were emplaced as southern Africa was passing above a mantle plume. Among the two granites, the younger granites are much more massive. Whereas fracture spacing in the Older Granite is 1–2 m on average, then joint-free compartments tens of meters across typify outcrops of the younger ones (Fig. 4).

Not surprisingly, landscapes supported by the two granites are very much unlike each other. The Older Granite underlies an extensive plain, the monotony of which is only occasionally interrupted by low shield-like outcrops and boulder fields. Inselbergs are very few and generally low, less than 100 m high. By contrast, the younger granites build a cluster of huge inselbergs of Spitzkoppe and elevated massifs of Brandberg and Erongo. Boulders are common in the younger granites too, but their diameter is not uncommonly 10 m (Migoń, Goudie, 2003).

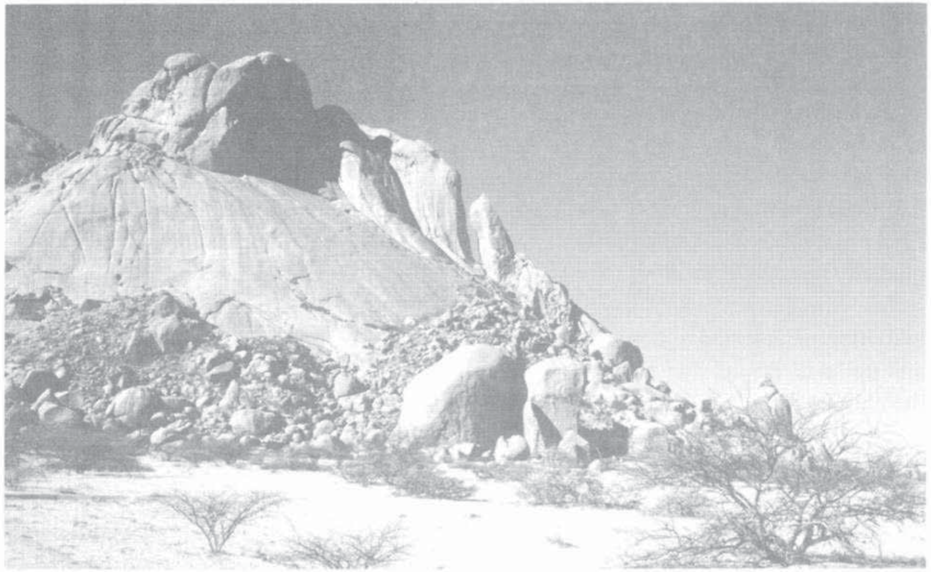

Fig. 4 Massive domes in the Spitzkoppe group, Central Namib, are built of Cretaceous granite that has never been subject to significant tectonic deformation since the emplacement. Note the extremely wide spacing of fractures and extensive talus, which is the testimony of episodic but voluminous rock falls and slides

The Bohemian Massif offers further examples that older granites with a long history of deformation are associated with subdued topography. Gently rolling upland landscape of Krumlovský les near Brno has developed upon the late Proterozoic granite (Migoń, Roštinský, 2003), as has a similarly subdued upland terrain around Znojmo (Ivan, Kirchner, 1994). By contrast, more pronounced inselberg-like landscapes of the Žulova Highland and Novobystřicka Highland (Czudek et al., 1964) are supported by more massive Carboniferous granites, emplaced during the final stages of Variscan deformations.

3. Rock control and slope processes in granite

Mass movements play an important part in the subaerial evolution of inselbergs, but exactly how they are reduced in height and extent, depends on their fracture patterns (Thomas 1965; Jeje, 1973). Massive domed inselbergs are subject to mega-exfoliation due to opening of sheeting joints. Individual slabs are separated from the underlying rock mass and, according to slope inclination, fall or slide off the slopes, forming debris aprons near the piedmont angle (Fig. 4). In orthogonal patterns, vertical joints open too, topples occur, and the summit part assumes ruiniform relief. If the two fracture patterns co-exist, then both mega-exfoliation and vertical joint opening are present and degradation into a boulder-strewn inselberg may occur at a particularly fast rate. This has probably been the case of a boulder inselberg of Mt. Witosza in the Jelenia Góra Basin, which shows a dome-like structure superimposed on an orthogonal fracture pattern (Migoń, 1993).

Similarly, the form and evolution of high mountain slopes are much influenced by fracture characteristics as demonstrated by Kalvoda (1994) for the Tatra Mountains. In the Polish part of the High Tatra scree cones in the formerly glaciated valleys are dominated by debris of moderate size (up to 1 m long), while huge blocks which would be the vestige of singular catastrophic rock fall events are comparatively rare

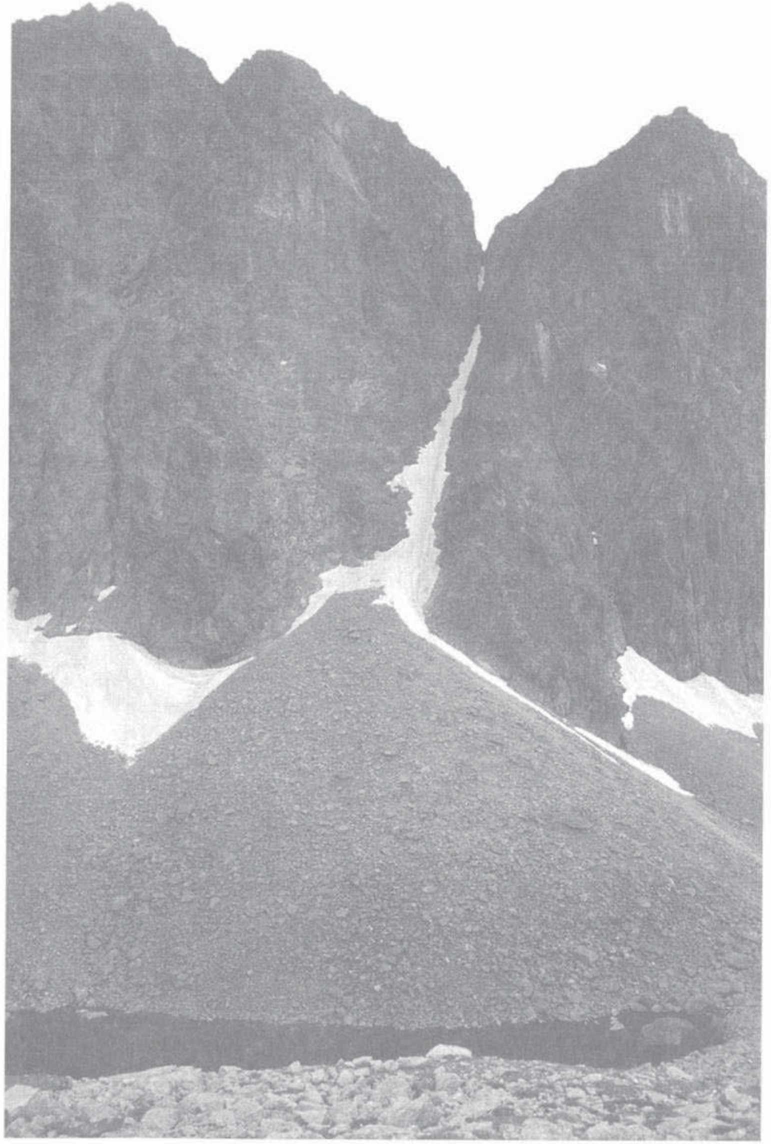

Fig. 5 Scree cones in the Javorova valley, Slovak High Tatra. The majority of debris is of moderate size (up to 1 m long), but bigger blocks occur too and are probably the testimony of large-scale rock falls

(Kotarba, Strömquist, 1984). The slopes above the scree aprons are steep (50–70°), but oversteepening is not common despite significant glacial erosion. The reason probably lies in dense fracturing of the granite mass, which seems hardly able to support vertical slopes and therefore fails through minor events after achieving critical slope inclination of around 50–70°. In the Slovak part, however, large blocks up to many metres long locally constitute a significant proportion of talus and have apparently been derived from more massive rock compartments (Fig. 5).

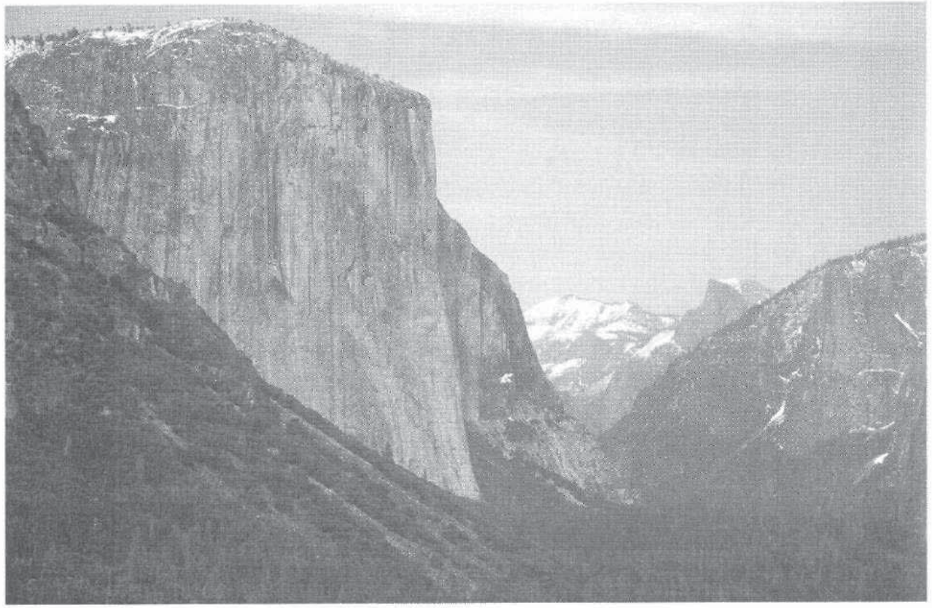

Fig. 6 Contrasting fracture density is responsible for variations in slope form along the north-western side of the Yosemite Valley, Sierra Nevada. Densely jointed diorites in the foreground frequently release medium-size debris that forms an extensive talus apron at the angle of repose. The El Capitan granodiorite in the background is extremely massive and able to support a vertical rock face. The slope fails through low frequency – high magnitude events and probably maintains its form over time

By contrast, triangular scree cones are very rare in another heavily glaciated area, the Yosemite Valley, Sierra Nevada. The principal mode of slope failure are catastrophic falls and slides (Wieczorek 2002). The most recent event, the Happy Isles rock fall from 10 July 1996, involved as much as 23 to 38 × 10^3 m^3 of material. Massive boulders up to 10 m long at the footslope of many rock cliffs provide the testimony of past catastrophic events. The paucity of scree and the abundance of large-scale failures is best attributed to the massiveness of granite exposed in the valley, separated by sheeting joints spaced as much as 10–15 m apart. Being so massive, it can temporarily withstand high tensile stresses and form vertical walls, but eventually the slope fails catastrophically. The most telling evidence of the geomorphic role of fracturing is in the north-western section of the Yosemite Valley, where massive granodiorites and closely jointed diorites occur side by side (Fig. 6). The former build a vertical slope about 500 m high, under which scattered big boulders of rock fall derivation occur. The latter occur within a slope recess, in which a low (< 80 m) rock face grades into an extensive talus sheet.

The influence of lithology and structure is also pervasive in the patterns of mass movement in weathered granite. Landslides are phenomena not readily associated with granite, but in fact they are both frequent and widespread if combination of steep relief, deep weathering and high rainfall occurs (e.g. Au, 1998; Onda, 2004). This is the case of south-east Asia, among others. In the Japanese Alps most slides occur within the superficial cover of grus, because there is usually a well-defined weathering front which acts as a hydrological barrier (Chigira, 2001; Onda, 2004). The grus layer can easily become saturated, whereas relict joint planes and the grus/solid rock interface act as sliding surfaces. Onda (2004) compared the patterns of landsliding in adjacent granite and shale terrains, and found that slides in granite tend to be shallow and spatially restricted, whereas slides in shale are deep-seated and cover larger areas. He explains this difference by referring to the unequal depth of weathering in each lithology and resultant different pathways of groundwater circulation. Localized nature of slope failures and their shallow depth in the granite part of Hong Kong have been commented by Au (1998). He emphasizes significant variations in physical properties of granite saprolites, including the presence of solid rock compartments and less weathered veins, which cause differential saturation and pore-water build-up.

4. Hierarchy of structural control

Structural control appears to take on a hierarchical pattern, as has already been illustrated by the example of the Krumlovský les upland near Brno (Migoń, Roštinský 2003). The primary control on the shape of granite terrain, its spatial extent and relationships with country rock is the mode of emplacement, itself related to wider geotectonic setting. Gross relief and regional altitude differences usually relate to regional tectonics, whereas at medium spatial scale (~10–10^3 km^2) lithological variation appears to play a key role in differentiating granite landscapes. Going into more detail, fracture control becomes crucial both for the shape of residual and erosional landforms (inselbergs, tors, valleys, basins, bedrock channels), and for the progress of deep weathering. However, minor lithological contrasts may guide selective weathering of exposed rock surfaces and account for the variety of microrelief of granite surfaces. Figure 7 presents possible scale relationships between geological controls, landforms and their dimensions. The expression 'Altitude – regional' refers to elevation differences within large granite massifs and between them and their surroundings, whereas 'altitude – local' refers to individual hills and drainage basins. 'Landscape type' is understood as the general appearance of granite landscapes and these can be multi-convex, multi-concave, plain-with-hills, or all-slopes. Their spatial extent is between one and a few hundreds kilometres square.

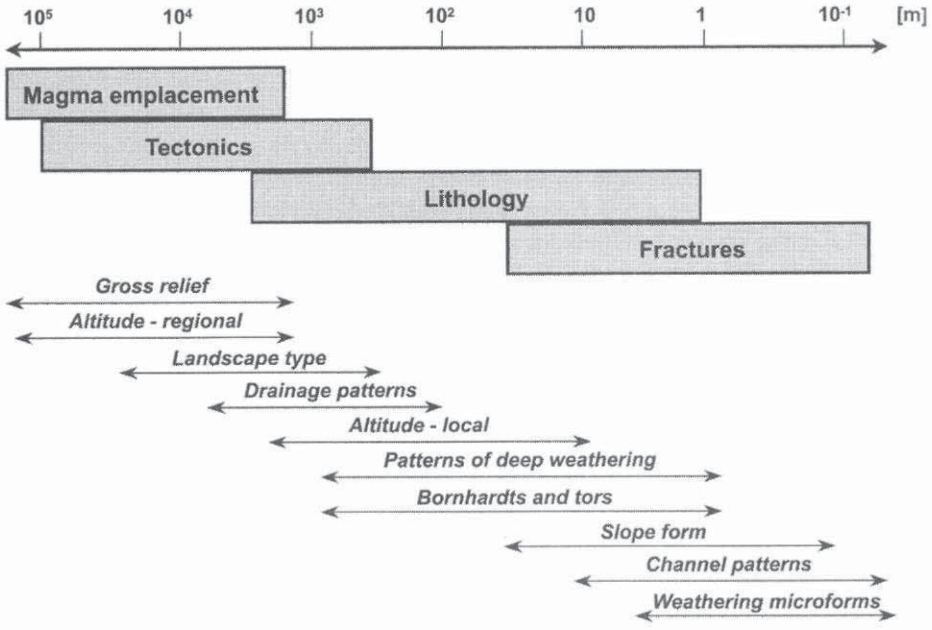

Fig. 7 Hierarchy of structural control in the evolution of granite landscapes. The diagram shows possible scale relationships between structural factors, forms and processes, and the size of landforms under control

5. Conclusions

Pitcher (1997) emphasized the diversity of granites saying simply that 'there are granites and granites'. One can easily apply this statement to geomorphology and argue that 'there are granite landscapes and granite landscapes'. The similarity of expression is not merely formal. It is the different granites, different by the origin, shape of intrusion, texture, mineralogy, fracturing and post-emplacement deformation history, that create conditions for the evolution of different landform assemblages. Geological structure sensu lato usually provides an answer why specific landscapes have evolved in specific places and how their evolution proceeds nowadays.

Granite terrains show an amazing variety of form, hence it appears impossible to define a 'typical granite landscape'. The literature is evidently biased towards such spectacular landforms as tors and inselbergs, hence an impression might arise that granite landscapes are everywhere dominated by them. This is not true. Rock-cut plains and multi-convex hilly relief developed in solid or weathered rock are far more widespread. Nor have the attempts to identify granite landform assemblages distinctive for particular climatic zones been entirely successful. Environmental factors are important controls on surface process dynamics, but the repetition of many landforms across the world shows that similar landscapes can be the outcome of various processes, unless complicated scenarios of landform inheritance and long-term environmental change are assumed. However, as both the convincing evidence for such scenarios is often missing, and causal relationships between past environments and landforms can hardly be demonstrated, equifinality and diversity in granite landscapes are best attributed to geological structure.

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STRUKTURALNE UWARUNKOWANIA ROZWOJU KRAJOBRAZÓW GRANITOWYCH

Résumé

Zróżnicowanie krajobrazów granitowych wynika w znacznym stopniu ze zróżnicowania w obrębie samego granitu. Intruzje granitowe różnią się między sobą sposobem posadowienia, teksturą, składem mineralogicznym, stopniem spękania i historią późniejszych deformacji. Te czynniki geologiczne wpływają zarówno na kształt pojedynczych form rzeźby, jak i na prawidłowości rozwoju dużych zespołów form. Wpływ podłoża skalnego ujawnia się także w przebiegu procesów stokowych na stokach skalnych i w obrębie pokrywy zwietrzelinowej. Wpływ czynnika strukturalnego przybiera zwykle układ hierarchiczny. Regionalne zespoły form odzwierciedlają głównie zróżnicowanie litologiczne i wielkoskalowe różnice strukturalne, natomiast pojedyncze formy rozwijają się pod znaczącym wpływem systemów spękań. Nadrzędność wpływu czynnika strukturalnego wyjaśnia zasadnicze odmienności morfologiczne pomiędzy sąsiadującymi intruzjami, jak i podobieństwa pomiędzy krajobrazami granitowymi rozwiniętymi w kontrastujących strefach morfoklimatycznych.