Granite landforms and weathering products

S. Campbell, A.J. Gerrard and C.P. Green

The granite terrains

Accounts of the characteristic tors and associated landforms and deposits, developed largely in and from granite, have occupied a substantial part of the geomorphological literature on South-West England. The granite intrusions of the South-West Peninsula (Figure 4.1) form the basis of a distinctive landscape: the selected GCR sites at Merrivale, Two Bridges Quarry and Believer Quarry on Dartmoor provide some of the finest examples of granite landforms (e.g. tors and cutter) and associated weathering products (e.g. decomposed granite or growan, and slope deposits) anywhere in Britain. The scale and superb development of these features led to a number of pioneering geo-morphological studies in the region (e.g. Linton, 1955; Te Punga, 1956; Palmer and Neilson, 1962; Waters, 1964).

The origin of the rugged landscape of upland South-West England has been speculated upon for many years. Many early workers suspected that glacier ice had played at least some part in the evolution of the landscape (e.g. Nathorst, 1873; Belt, 1876; Somervail, 1897; Worth, 1898; Pillar, 1917; Pickard, 1943). The postulated evidence for glacial activity on Dartmoor, however, has never been substantiated, and the landforms have usually been explained in other ways (Gerrard, 1983). Although unglaciated, it was subject to periglacial activity during the cold phases of the Pleistocene, and many of the landforms are relicts from such activity. Manley (1951) has argued that the permanent snowline, at the period of maximum glaciation, was about 30 m above the highest Dartmoor summits.

As the only unglaciated upland region in Britain, its importance in elucidating late Tertiary and Pleistocene landform evolution is considerable (Brunsden *et al.,* 1964). The landscape of Dartmoor, and other parts of South-West England, has thus seen a continuous geomorphological development since at least early Tertiary times without the imprint of glaciation. Dartmoor in particular has long been seen as a key to understanding both Tertiary and Quaternary landscape evolution (Wooldridge, 1950, 1954; Gerrard, 1983). Intense chemical weathering of the granite under warm climatic conditions probably occurred during parts of the Tertiary. It was also probably subjected to weathering under warm conditions in the 'interglacial' stages of the Pleistocene, as well as to intense cryonival (periglacial) processes during a number of the cold Pleistocene stages. Some workers have argued that the landforms and deposits seen in the Dartmoor area today evolved above all else in response to periglacial conditions (e.g. Waters, 1964, 1974). While there is a firm foundation for arguing that many of the characteristic landforms such as tors and clitter, screes, valley-side buttresses, terraces of 'rubble drift' and benched hillslopes were formed, or at least substantially modified, by periglacial processes, other landforms, particularly some of the tors, are likely to have a much more protracted and complicated history.

The various mechanisms, processes and possible timescales involved in the evolution of the distinctive granite landscape of the South-West are considered fully within the individual site accounts (Merrivale, Two Bridges Quarry and Bellever Quarry): these sites alone have attracted considerable scientific interest and illustrate many of the theories on granite landscape evolution. Of fundamental importance to understanding this evolution, however, is the nature and origin of the granite and its weathering products.

The granite

The granite intrusions of the South-West have been described in considerable detail (e.g. Reid *et al.,* 1912; Brammall and Harwood, 1923, 1932; Brammall, 1926a, 1926b; Worth, 1930; Exley, 1959, 1965; Stone and Austin, 1961; Exley and Stone, 1964; Durrance and Laming, 1982; Floyd *et al.,* 1993), and are widely held to be linked at depth in one huge batholith, a continuous body of rock some 250 km long by 50 km wide (Durrance and Laming, 1982; Floyd *et ca.,* 1993; (Figure 4.1)). The intrusions have caused the surrounding Devonian and Carboniferous 'country' rocks to become folded, faulted and, to varying degrees, metamorphosed in an 'aureole' between 1 km and 3 km wide (Durrance and Laming, 1982). The granites of the South-West were intruded as the result of a much larger-scale tectonic episode — the Variscan or Hercynian Orogeny, occasioned by substantial plate movements.

The first map showing an outline of the Dartmoor granite was published by De la Beche (1835), and the origin of the mass attracted considerable early interest (e.g. De la Beche, 1839; Henwood, 1843; Ormerod, 1869; Ussher, 1888; Hunt, 1894). In general, an igneous origin was suggested, and Ussher argued that the intrusion was probably laccolithic in form. Hunt (1894) disagreed with this origin, preferring a metasomatic explanation, namely that the mass had arisen through *in situ* alteration of sedimentary material by 'silicic alkalic' fluids.

From the earliest work it was accepted that the pluton consisted of two main rock types, a coarse-grained granite and a fine-grained variety. Further subdivisions were proposed by Reid *et al.* (1912), and the detailed work of Brammall and Harwood in the 1920s and 1930s added significantly to the knowledge of the various mineralogical and chemical properties of the rock. Brammall and Harwood (1923, 1932) recognized that the granite was a composite intrusion which had involved successive sheet-like injections. Initially, they considered there had been four major intrusive phases, but later this was reduced to three, which had resulted in the formation of: (a) the 'giant granite', characterized by abundant large feldspar phenocrysts; (b) the 'blue granite', with fewer large phenocrysts; and (c) a variety of minor intrusions, commonly aplitic and finer-grained (Durrance and Laming, 1982). The giant granite forms most of the tors, and as a result it is sometimes referred to as the 'tor granite'. The principal conclusions of Brammall and Harwood's work were that the pluton was igneous, composite, probably laccolithic (cf. Ussher, 1888), and that the magmas had been derived from the melting of sedimentary rocks at depth, although they had undergone extensive changes as the result of assimilating material at higher levels.

Numerous studies have since been published on the granites of the South-West. These have dealt in detail with many diverse topics including: the nature of the granites; their field relations with the surrounding country rock and with regional structures; aspects of petrogenesis, including metasomatism and recrystallization; and alteration of the granites including tourmalinization, greisening and kaolinization. Excellent reviews are provided by Exley and Stone (1964) and Durrance and Laming (1982) among others. It is useful here, however, to consider some broad structural aspects of the Dartmoor granite, since these have a direct bearing on landscape evolution.

The outcrop of the Dartmoor granite is irregular in shape. According to Bott *et al.* (1958), the magma may have risen in the south and spread northwards as a laccolithic 'tongue'. Another possibility is that it rose through relatively resistant Devonian rocks in the south-central region, spreading out on reaching the Carboniferous–Devonian interface both to the north and, to a lesser extent, southwards (Durrance and Laming, 1982). It has often been suggested by geologists that the upper domed surface of the intrusion represents the original roof of the pluton (Durrance and Laming, 1982). Contacts between the granite and the country rocks are generally sharp, but rarely exposed.

Joints and faults

Jointing in the granite has been seen as a major factor influencing the development of granite landforms such as tors (e.g. Waters, 1954, 1957; Gerrard, 1974, 1978, 1982; Durrance and Laming, 1982). Indeed, the shapes of most tor outcrops are closely controlled by major joint planes which fall into two main categories: high angle or vertical plane joints; and subhorizontal joint planes usually termed floor or sheet joints (Gerrard, 1974, 1982; Durrance and Laming, 1982). A third set of less well-developed joints, inclined broadly at angles between 20 and 80°, is also present. Although these three sets probably have different origins, all show one common feature, namely that they occur in greater frequency (that is in greater numbers per unit volume of rock) towards the top of exposures (Durrance and Laming, 1982). Gerrard (1982) has argued that the relationship between landforms and jointing is also complicated because some joints are of primary origin, whereas others are secondary, and that it is essential to be able to distinguish between the two main types.

It is normally accepted that the jointing in these rocks results, at least partly, from stored stress: the upward increase in the number of open joints is therefore a reflection of pressure release caused by the erosion of overlying rock (e.g. Gilbert, 1904; Jahns, 1943; Kieslinger, 1958; Bradley, 1963; Bruriner and Scheidegger, 1973). Such a mechanism is appropriate for explaining the floor or sheet joints of the Dartmoor granite, although some may be primary sheet structures formed during emplacement and cooling (e.g. Oxaal, 1916; Meunier, 1961; Gerrard, 1982). These joint planes are approximately horizontal where seen on ridges and hill tops, and are inclined on the flanks of hills towards neighbouring valleys at angles of up to 20–25° (Durrance and Laming, 1982). Consequently, the Dartmoor granite is characterized by broadly curved sheet or floor joints which closely mirror the surface contours of the landscape (Gregory, 1969; Gerrard, 1974, 1982).

Although the unloading process theory is difficult to test in the field and should not be assumed to be the universal cause of such joints (Addison, 1981; Gerrard, 1982), the sheet joints or so-called 'pseudo-bedding planes' are widely seen in the tor outcrops of Dartmoor, and have been regarded as having a major bearing on their genesis (Gerrard, 1974, 1978, 1982, 1983, 1989b; see below).

On the other hand, the high angle and vertical joints strike in all directions, although with marked maxima running in broadly N–S, E–W, NW–SE and NE–SW directions: according to Durrance and Laming (1982), they show no geometrical relationship with the boundary of the pluton, and indeed there is considerable doubt as to their mode of origin: a variety of mechanisms involving both tensional and compressive forces has been suggested (Crosby, 1893; Becker, 1905; Hodgson, 1961; Roberts, 1961; Blyth, 1962). Whatever their origin, the spacing and frequency of these vertical and near-vertical joints has clearly influenced the detailed form of granite landforms such as tors (Linton, 1955; Palmer and Nelson, 1962; Gerrard, 1974, 1982, 1989b).

The third group of joints (less well developed) merges at one extreme with the high-angle and vertical joints, and at the other with the subhorizontal floor or sheet joints (Durrance and Laming, 1982). Although their strike directions are not yet well documented, they may have been caused by an imbalance of rock densities within the Dartmoor pluton (Bott *et al.,* 1970; Durrance and Laming, 1982). Further understanding of the joints has been provided by a fractal analysis (Gerrard, 1994a).

Some joints are grooved (slickensided) showing a limited degree of movement (Durrance and Laming, 1982; Gerrard, 1982). Larger-scale faulting, however, has produced more significant movements from a geomorphological point of view: towards the centre of the pluton, rivers have become incised into N–S and NW–SE courses con trolled by pronounced fracturing and weakening. Estimating the lateral and vertical displacements in this central area is difficult, and clear evidence of measurable faulting is restricted to the granite boundary (Durrance and Laming, 1982). This wrench-faulting, affecting both the granite and its envelope of surrounding rocks, is believed to be of Tertiary age, although it may also have rejuvenated older structures (Dearman, 1963, 1964; Shearman, 1967; Durrance and Laming, 1982).

Early work on granite landforms

The granite landforms of the South-West, and particularly the tors of Dartmoor, have long attracted the attention of writers. De la Beche (1839, 1853) propounded that tors had formed by differential weathering: an early phase of formation underground was envisaged, followed by erosion of the more decomposed parts. MacCulloch (1848) also provided a useful early account, supplemented by Ormerod in 1858; superb illustrations of many of the tors were provided both by Ormerod (1858) and Jones (1859). The latter account gives some perceptive views on the formation of 'tors, cheesewrings and logging stones' — and clearly relates their formation to frost and associated sub-aerial weathering guided along both vertical and horizontal joint planes, followed by subsequent removal of the weathered detritus. On the other hand, Mackintosh (1867, 1868b) argued that tors were relict sea stacks, and Woodward (1876) ascribed them to the action of 'wind-driven sand'. There was also much speculation on the importance of the decomposed granite. Indeed, Reid *et al.* (1910) argued that the decomposed or 'kaolinized' granite on Bodmin Moor strongly influenced the distribution of all major landforms. In effect, the kaolinized areas appeared to coincide with valleys and marshy depressions, whereas upstanding hills were composed of intact and unaltered granite. Peat has subsequently accumulated in many of these 'kaolin-floored' depressions (see Hawks Tor).

Other early writers were much taken with the apparently layered structure of the Dartmoor granite and its manifestation in the tors (De la Beche, 1839; Mackintosh, 1868a; Ormerod, 1869; McMahon, 1893; Albers, 1930). Ormerod (1869) observed that the dips of many of these curved or 'pseudo' beds mirrored the form of the local hills, an association later viewed to be of great importance in models of landform genesis (Gerrard, 1974). Both Ormerod and Mackintosh also observed sections where weathered and unweathered granite were juxtaposed and argued that selective 'spheroidal' weathering had played an important part in the formation of the tors, much as Brayley (1830) had earlier argued using evidence from Cornwall. Sub-surface weathering was also invoked to account for the tors by Dawkins (in Sandeman, 1901; see below).

Bate (1871) described the 'cater of the tors of Dartmoor', and noted that 'Around the base of most of the huge tors that give a mountainous character to Dartmoor cluster large masses of granite rocks in wonderful confusion' (Bate, 1871, p. 517). He argued that the clitter had been derived from the surface of the tors by frost-action. Where the masses of angular rubble occurred at some distance downslope from the tors, he suggested that the upper hillslopes had been 'glazed' by the perennial accumulation of thin layers of ice. This had facilitated the downslope movement over the ice of even quite large granite boulders to lower levels, where they accumulated in piles in much the same manner as a protalus rampart. A similar mechanism, but involving snow patch rather than ice accumulation, was also later suggested by the Geological Survey (Reid *et al.,* 1912).

Alternatively, Belt (1876) suggested that large granite blocks sprinkled all over the surface of Dartmoor had been glacially transported, and then deposited from floating ice in an immense pro-glacial freshwater lake, which he believed had covered much of northern Europe. This echoed a widespread early view, noted previously, that Dartmoor had been glaciated, and indeed Campbell (1865) thought that the tors themselves had been shaped by 'floating ice'. Whitley (1885) argued that the crater surrounding the tors in both Cornwall and Devon was flood-formed, 'large masses of solid granite having been severed from their native beds and swept down the slopes of local hills' by a catastrophic 'post-glacial flood'.

Albers (1930), also much taken with the clitter accumulations of Dartmoor, argued that the material occurred on both level ground and in distinct piles towards the base of slopes. He suggested that it had been pushed downhill by 'some force', and invoked Hoegbom' s (1913–1914) mechanism of solifluction to account for the accumulations. The cater was thus believed to be the result of downhill sludging of sediment and granite blocks over a permafrost layer, comparable to that found in tundra regions today. In arguing for a freeze-thaw/solifluction origin for the clitter, Albers also thought it reasonable to suggest that the tors them selves had been formed, probably substantially, by frost-action during the Pleistocene — 'Thus the evidence would point to the tors and cutters of Dartmoor being due to the splitting action of frost, and to movement occasioned by solifluction' (Albers, 1930; p. 378). Albers' study forms an important landmark in the development of thought pertaining to landscape evolution on Dartmoor, particularly in its use of a modern-day analogue (Spitsbergen) to explain relict (periglacial) landforms. The same arguments were later to form the basis of one of the main theories of tor formation put forward by Palmer and Neilson (1962) (see below).

Models of tor formation

Since the work of Albers (1930), a steady stream of papers and textbooks has attested to continued interest in the genesis of Dartmoor landforms, especially tors (Linton, 1955; Waters, 1957, 1964, 1966a, 1966b; Palmer and Neilson, 1962; Linton and Waters, 1966; Brunsden, 1968; Perkins, 1972; Gerrard, 1978, 1982; Twidale, 1982): various 'models' of tor formation have been propounded, the most notable being those of Linton (1955) and Palmer and Neilson (1962), which, to a large extent, have formed the basis for most subsequent theories and discussion. However, the suggestion that retreat of scarps across bedrock to leave tors and pediments (King, 1958) is also worthy of consideration. King argued that his theory was only applicable to skyline tors and that tors in other positions might have formed differently.

Linton's (1955) paper is a classic, although in many ways it enunciates ideas less explicitly formulated by earlier workers (e.g. De la Beche, 1839, 1853). The significance of this paper has been assessed recently by Gerrard (1994b). Linton proposed a two-stage model for the formation of tors. First, deep chemical weathering under warm humid conditions (Linton favoured the Neogene, but the bulk of recent evidence would suggest the Palaeogene) produced a thick regolith, with corestones (ellipsoidal masses of granite separated from the bedrock by regolith) occurring where joint planes were most widely spaced (Figure 4.2). He argued that vertical joints and pseudo-bedding planes were fundamental in guiding this rotting, which itself had been effected by percolating acid groundwater. Second, the products of weathering (the regolith) were removed by mass-wasting processes, leaving the 'sound' granite and corestones as upstanding tors (Figure 4.2). Linton proposed that tors had probably been exhumed under periglacial conditions during the Pleistocene when solifluction and meltwater would have been efficient agents in removing the regolith. During this period, periglacial activity may also have modified the tors. Linton thus defined a tor as ' … a residual mass of bedrock produced below the surface level by a phase of profound rock rotting effected by groundwater and guided by joint systems, followed by a phase of mechanical stripping of the incoherent products of chemical action.' (Linton, 1955; p. 476). Such processes were believed to have operated over large areas and protracted timescales, producing the distinctive tors in the Pennines, at Trefgarn and Preseli in Wales, and at the Stiperstones, Shropshire, as well as on Dartmoor (Linton, 1955). The two-stage process on a larger scale has been embodied in Budel's double surface of planation. But, as developed by Thomas (1978) and suggested by Lewis (1955), in the discussion of Linton's article, the process is likely to be more continuous.

Following work on the 'gritstone' tors of the Pennines (Palmer and Radley, 1961) and a brief note on the origin of those on Dartmoor (Palmer and Neilson, 1960), Palmer and Neilson (1962) put forward a single-stage periglacial mechanism to account for the Dartmoor tors: their model has since formed the principal alternative to the two-stage process of Linton (1955). They argued that the tors and associated clitter were formed by frost-action and solifluction which occurred throughout the Pleistocene. They argued that the distribution of the tors and cutter was related to the origin and depth of the incoherent or decayed granite. Unlike Linton, who argued that the granite decomposed by sub-surface chemical weathering during the Tertiary, Palmer and Neilson suggested that the incoherent granite had, in most cases, been kaolinized by pneumatolytic processes. Some might also have been produced by physical processes, namely frost-shattering along crystal and cleavage boundaries (see below). Thus the two sets of processes (pneumatolysis and physical disintegration) were believed to be quite distinct and unrelated. In support of this argument, Palmer and Neilson cited the occurrence of decayed granite on ridges where tors were absent, and the fact that the weathered material was never found around the tors themselves. The rounded nature of some constituent 'blocks' in the tors was explained by post-glacial, atmospheric chemical weathering. The tors were thus regarded as 'upward projections of solid granite left behind when the surrounding bedrock was broken up by frost-action and removed by solifluction' (Palmer and Neilson, 1962; p. 337). They could thus be termed 'palaeoarctic tors'.

Many workers have since suggested that all three main sets of processes — pre-Tertiary pneumatolytic and hydrothermal alteration of the granite, Tertiary (and later) sub-surface chemical weathering, and physical weathering and disintegration (periglacial) — have probably been involved in the formation of the tors and associated features (e.g. Brunsden, 1964, 1968; Gerrard, 1978). Nonetheless, the two main models of tor formation have since provided the basis for much discussion, and considerable efforts have been made to determine the crucial origin(s) of the weathered granite or 'growan' (see below; Two Bridges and Believer quarries).

A further concept regarding tor formation, however, is worthy of note. As previously observed, many tors demonstrate prominent floor or sheet joints (pseudo-bedding) running parallel to the surface of the tor or local hill. Likewise, many tors consist of several rock masses arranged in an avenue, often with the central part absent. Brunsden (1968) has argued that, if reconstructed, these separate rock masses with their missing centres, would form a large, single dome structure, with the linked floor joints demarcating once-continuous sheets of granite. Consequently, it has been suggested that the original form of the tors was neither a pile of corestones (Linton, 1955) nor a soil-covered hill (Palmer and Neilson, 1962), but rather a granite dome analogous to the granite inselbergs of Africa (Brunsden, 1968).

These arguments have been extended by Twidale (1982) who has suggested that domed, block-strewn or castellated structures worldwide are generically related: the dome structure is the starting point of an evolutionary sequence (encompassing landforms such as nubbins (analogous to tors), castle koppies and castellated inselbergs) in which the major differences are based simply on the radii of the original domes, as well as the relative depth of sub-surface formation. St Agnes Beacon in Cornwall has also been interpreted as an inselberg exhumed from a deep Tertiary saprolite (Walsh *et al.,* 1987; Jowsey *et al.,* 1992).

Kaolinization or Tertiary chemical weathering?

The presence of decomposed or altered granite throughout the South-West is little disputed. However, there has been very little firm agreement as to its origin, and opinion has alternated between deep chemical weathering and hydrothermal and physical alteration processes. Further, there has been a proliferation of technical terms which has perhaps further added to the confusion. The nature and origin of these 'altered' granitic materials, however, are of prime importance to understanding the evolution of granite landforms: many workers (e.g. Waters, 1954, 1957; Linton, 1955) have attempted to relate Dartmoor landforms (including the tors, erosion surfaces and drainage nets) to the presence or absence of the altered granite and to the differential action of chemical and mechanical weathering (Brunsden, 1964).

The main arguments have arisen as to whether the altered granites are due to post-emplacement weathering (mainly chemical but also physical processes) or to effects penecontemporaneous with the intrusion of the granite (e.g. hydrothermal processes). The latter, of which kaolinization is perhaps the most important, involves chemical alteration of the granite by heated and superheated waters. In this respect, it may be distinguished from pneumatolytic processes, the latter more strictly being the action of hot gases associated with the igneous activity. Although the distinction is perhaps arbitrary, it is useful since distinctive minerals and rock types are produced. The term 'chemical weathering' is used here to mean alteration of the granite by supergene processes, that is normal subaerial weathering effected largely by the circulation of weakly acid groundwater. 'Physical' weathering is taken to mean alteration of the granite by mechanical processes, primarily frost-action.

It has long been held that the kaolin deposits of the South-West are distinct from any altered material that may have been formed as a result of chemical weathering (Exley and Stone, 1964). The hypothesis that kaolinization was the result of weathering has had few early supporters, an exception being Hickling (1908), and a good case has been put forward for a hydrothermal origin (e.g. Collins, 1878, 1887, 1909; Reid *et al.,* 1910; Exley, 1959, 1964; Exley and Stone, 1964). However, the controversy was re-opened by the suggestion that the china clay (kaolin) deposits have a weathering or supergene origin (Sheppard, 1977). Thus clear differentiation in the field between hydrothermal and supergene weathering products is still tenuous.

For clarity, the arguments over the nature and origin of the altered materials can be divided into three main 'schools'. First, there are those who have argued that there is evidence for the widespread development of a substantial, chemically weathered regolith or saprolite, probably during warmer, more humid, conditions in the Tertiary (Waters, 1954, 1957; Linton, 1955; Linton and Waters, 1966). This view is central to the Linton theory of tor formation (see above), and has wide repercussions for general landscape evolution including the development of erosion surfaces, tor and basin topography and drainage nets (Waters, 1954, 1957, 1960c, 1960d, 1960e, 1964). A second school holds that the altered granite is largely hydrothermal in origin (e.g. Reid *et al.,* 1910; Palmer and Neilson, 1962; Exley and Stone, 1964), and it can therefore accommodate landscape development without invoking a thick, chemically weathered regolith; other mechanisms, principally physical weathering (frost-action and solifluction) are deemed to have played a substantial, if not dominant, role in landform genesis (Te Punga, 1957; Palmer and Neilson, 1962). Finally, many workers have suggested that a combination of all three main sets of processes — hydrothermal alteration, chemical and physical weathering — has been involved in the evolution of granite landforms and the Dartmoor landscape (e.g. Brunsden, 1964, 1968; Eden and Green, 1971; Doornkamp, 1974; Gerrard, 1983). This school deals with the conflicting evidence by invoking a sequence of events involving both hydrothermal and supergene processes, with hydrothermal activity 'softening-up' the granite and rendering it extremely susceptible to later supergene alteration (e.g. Bristow, 1977, 1988; Sheppard, 1977; Durrance and Laming, 1982). Most recently, Floyd *et al.* (1993) have provided a detailed evolution and alteration scheme for the St Austell Granite.

Many early workers favoured the first school of thought, and argued that the granite had been rotted differentially by chemical action (e.g. De la Beche, 1839, 1853; Reid *et al.,* 1910, 1912; Ussher, 1912; Worth, 1930), and these arguments were to reach their fullest expression with Linton (1955). Others have argued that at least some of the altered or incoherent granite is hydrothermal or pneumatolytic in origin (e.g. Reid *et al.,* 1912; Worth, 1930; Guilcher, 1950; Dines, 1956). Resolution of these problems clearly requires precise parameters against which the field and laboratory evidence can be assessed. Although many recent studies have provided classifications and diagnostic characteristics for recognizing the various alteration products caused by weathering or hydrothermal processes (e.g. Brunsden, 1964; Dearman and Baynes, 1978; Irfan and Dearman, 1978a), there is still no firm agreement. If anything, opinion in general appears to have swayed farther away from the seemingly well-established view that much of the kaolin and altered granite is purely of hydrothermal origin.

Perhaps the strongest arguments put forward for hydrothermal alteration of the granite are: 1. the great depth and form of some deposits — in particular the fact that unweathered rock overlies kaolinized granite which itself can reach great depths. Some china clay pits work areas of altered granite well over 500 m in diameter. Proven depths of such material in the St Austell Granite are in excess of 250 m (Exley, 1959, 1976; Brunsden, 1964; Bristow, 1977; Durrance and Laming, 1982); 2. the often close association of the altered material with greisen-bordered quartz-tourmaline veins; the crystallinity index of the kaolinite increases towards such major quartz-tourmaline veins (e.g. Brunsden, 1964; Durrance and Laming, 1982; Gerrard, 1983). Good reviews of the characteristics to be expected in hydrothermally/pneumatolytically altered granites are given by Brunsden (1964), Exley and Stone (1964), Durrance and Laming (1982) and Floyd *et al.* (1993).

However, there is a large and growing body of data which suggests that the contribution of hydrothermal processes to altering the granites of the South-West may have been overestimated. Many workers have long suspected that the effects of hydrothermal and chemical weathering processes often occur together (e.g. Reid *et al.,* 1910, 1911, 1912). Brunsden (1964) argued that the evidence on Dartmoor showed that the decomposed granite had been formed by a combination of chemical weathering, frost-pulverization and pneumatolysis. Evidence for all three processes was deemed to occur within single profiles (Two Bridges Quarry), although distinguishing between them was not easy, since the lines of weakness in the granite (the joints and fissures) had provided a focus for all the processes (Brunsden, 1964): Brunsden, however, proposed a classification to distinguish between the processes. He argued that if a section showed evidence of mineral breakdown (e.g. a biotite weathering front, eluviation of clay minerals, progressive stages of physical disintegration, spheroidal weathering and grus formation, a zoning of the weathering horizon, an increase of solid rock, and corresponding decrease of decayed rock with depth), then chemical weathering had been the cause of decomposition. On the other hand, physical weathering (frost-action) would be characterized by a comminution of particles (without a loss of mass), by leaching of minerals in solution and by eluviation of clays. Frost-wedges, involutions and head deposits were considered to aid identification, but in reality the two former features are virtually absent on the granites of South-West England, and the latter feature is so widespread that none of them has diagnostic value in this context. Finally, he suggested that hydrothermal/pneumatolytic alteration could be recognized by tourmalinization and ore deposits although this could be confirmed only if the sections of altered material increased and widened with depth, if a cover of solid, unaltered granite is present or if there is an upward increase in alteration products (Brunsden, 1964).

Although some details of Brunsden's work have been questioned (Eden and Green, 1971; Green and Eden, 1973), subsequent studies have shown clearly that chemical decomposition has played a role in the development of altered profiles. A variety of detailed classifications of weathering grades, based largely on engineering properties, has been proposed (Fookes *et al.,* 1971; Dearman and Fookes, 1972; Dearman and Fattohi, 1974; Dearman *et al.,* 1976, 1978; Baynes and Dearman, 1978; Dearman and Baynes, 1978; Irfan and Dearman, 1978, 1979a, 1979b). Dearman and Baynes (1978) devised a system for differentiating the alteration products based on a combination of field mapping and engineering grades. It was argued that by mapping the distribution of grades of 'equal intensity of effect', the effects of hydrothermal alteration, chemical weathering and frost-shattering could be distinguished. It was admitted, however, that ascertaining the precise extent to which each of the three potential processes had affected the rock was still difficult to determine (Dearman and Baynes, 1978). Laboratory techniques (including the use of Scanning Electron Microscopy) have also been used to improve the recognition of different weathering grades in sound and altered granite (Irfan and Dearman, 1978, 1979a, 1979b). These grades have been based on recognizing changes in the microfabric of the granite, and they have been used to show that the initial ingress of weathering agencies occurs along primary cracks, pores and open-cleavages (Baynes and Dearman, 1978).

Eden and Green (1971) applied textural and mineralogical investigations to samples of the altered or decomposed granite from sites throughout Dartmoor, and distinguished between the products of pneumatolytic/hydrothermal alteration and chemical weathering. They argued that the altered granite or 'growan' was less decomposed than true kaolin deposits elsewhere, for example in the St Austell Granite (Exley, 1959; Exley and Stone, 1964), for which they felt a hydrothermal origin had been securely established. Their results showed that the growan had originated as a weathering product: in comparison with the kaolinized material it contained much less silt and clay, more intact feldspar crystals, and quartz and mica constituents showing little alteration. They suggested that occurrences of pneumatolytically altered granite on Dartmoor were rare (cf. Two Bridges Quarry). Even the presence of tourmaline in the sections at Two Bridges Quarry, which Palmer and Neilson (1962) had associated with 'kaolinized granite', was rejected as an indication of hydrothermal alteration: tourmaline is found widely in solid, unaltered granite and is likely to have been formed prior to kaolinization (Exley, 1959; Eden and Green, 1971; Floyd *et* al., 1993). In conclusion, Eden and Green suggested that the occurrences of growan on Dartmoor were only 'moderately decomposed'. This, they argued, indicated that the material had probably not been formed in a hot humid environment (Waters, 1954, 1957; Linton, 1955; Linton and Waters, 1966), although in warmer conditions than today, perhaps in a meso-humid, subtropical climate (see Two Bridges and Believer quarries). Although this led Eden and Green (1971) to accept Linton's two-stage hypothesis of tor formation, they suggested that chemical weathering had been less effective and widespread on Dartmoor than previously thought: the tors had been exhumed from a sandy, not clayey, weathering zone, principally located in or near the main river valleys, and thus any deep weathering had been extremely localized.

Eden and Green (1971) therefore argued that the growan bore little resemblance to the kaolin deposits, stressing the lack of clay, high feldspar content and lack of feldspar alteration as prime evidence. X-ray diffraction studies also revealed the presence of gibbsite, which Green and Eden (1971) suggested was further evidence of chemical weathering. This mineral has frequently been noted in weathered granite in the humid tropics, and its occurrence in France has been used in support of a former hot and humid climate (Maurel, 1968): subtropical (Bakker, 1967) and temperate (Dejou *et al.,* 1968) weathering regimes have also been invoked to explain its presence elsewhere. Gerrard (1994d) has asked a number of questions. Does its presence in the Dartmoor weathered granite imply that humid tropical conditions formerly existed or is our understanding of the factors favouring gibbsite formation at fault? Are there special circumstances which have led to its production? In comparisons with tropical areas, Green and Eden concluded that the gibbsite in the Dartmoor growan occurred as an initial product of weathering, showing that any weathering here was at an early stage; its presence did not necessarily imply a humid tropical environment. The production of gibbsite is an example of where it is difficult to relate a specific clay mineral to specific climatic characteristics. It seems to be related to the stage of the weathering process and the particular leaching conditions. Gerrard (1994d) concludes that gibbsite, in appreciable amounts, probably indicates lateritic-type weathering, but small amounts can be produced under a variety of conditions. Such a view is supported by recent work in northeast Scotland where two main granite weathering products have been differentiated (Hall, 1983; Hall *et al.,* 1989). These comprise 'clayey grus' (the pro posed product of intense weathering, possibly under subtropical conditions between Miocene and mid-Pliocene times) and 'grus' (the product of less intense weathering perhaps during warm interglacial conditions in the Pleistocene). In the context of these Scottish granite weathering products, Mellor and Wilson (1989) have concluded that gibbsite is a feature which pre-dates the last glaciation, but its precise time of formation is uncertain; it could have formed under humid, warm-temperate to subtropical conditions during the Tertiary and/or during Pleistocene interglacials (Hall, 1983). However, its status as an indicator of warm environments is uncertain because the mineral is also believed to form at the initial stages of rock breakdown (Hall *et al.,* 1989).

Doornkamp (1974) studied micromorphological characteristics of weathering products from Dartmoor (head deposits, bedded growan and *in situ* growan) using Scanning Electron Microscopy (SEM). He concluded that most material showed evidence of mechanical weathering. Evidence for granite which had been altered chemically was found, however, at Two Bridges Quarry. Doornkamp suggested that these results supported Eden and Green's view that chemical weathering had occurred, but had been much more selective than previously thought.

Gerrard (1983) has argued that the most critical evidence for chemical weathering comes from oxygen and hydrogen isotope studies (e.g. Sheppard *et al.,* 1969; Savin and Epstein, 1970; Sheppard, 1977) which have enabled differentiation between hydrothermally formed kaolin and that formed by chemical weathering (supergene) processes. On this basis, Sheppard (1977) has argued that some of the kaolin deposits of South-West England owe their origin to weathering, and similar conclusions have been drawn from SEM studies (Keller, 1976), and by Oilier (1983). Because weathering is a widespread phenomenon and occurrences of hydrothermal alteration rare (cf. Konta, 1969), Oilier argued that the former should always be assumed unless the latter could be rigorously proven. Thus, even many economic deposits once attributed to hydrothermal activity could now be related to weathering (e.g. Amstutz and Bernard, 1973; Oilier, 1977, 1983). In particular, the presence in altered material of chlorite and some cracked quartz grains (e.g. Moss, 1966; Bisdom, 1967; Baynes and Dearman, 1978) … falls far short of proof, and even short of a reasonable suggestion' (Oilier, 1983; p. 58).

Similar changes of view have been happening in work on other granite areas. Bird and Chivas (1988), using oxygen isotopes in Australian weathering profiles, were able to distinguish profiles formed in the late Mesozoic and early Tertiary from profiles formed in post-mid-Tertiary times. The deeply altered Bega Granite of south-east Australia was once attributed to hydrothermal alteration, but isotope studies have shown it to be weathered. However, alteration of the Conway Granite, in New Hampshire, has now been shown to be due to hydrothermal alteration and not weathering. Therefore there is still much work to be done. For South-West England granites, Durrance *et al.* (1982) have suggested that, although alteration resulted from reaction with meteoric water, the system was driven by geothermal heat.

Further, although more indirect, evidence for Tertiary chemical weathering comes from elsewhere in the region. Bristow (1968) has shown the presence of a weathered mantle beneath Late Oligocene sediments in the Petrockstow Basin. Chemical and mineralogical analyses have shown that these weathered deposits formed under humid subtropical or warm-temperate conditions (Bristow, 1968). Similar types of weathering have been described elsewhere in the South-West (Fookes *et al.,* 1971; Dearman and Fookes, 1972; Dearman and Fattohi, 1974; Dearman *et al.,* 1976). Isaac (1979, 1981, 1983a, 1983b) has also provided evidence for Tertiary weathering profiles in the plateau deposits of east Devon: the distribution of laterites and silcretes reflects a complex pedological, diagenetic and geomorphological history (Chapter 3). If the evidence presented above is correct, then there would appear to be an ample basis for arguing that chemical weathering did occur on Dartmoor during the Tertiary (Gerrard, 1983), irrespective of any previous hydrothermal effects.

Notwithstanding the growing evidence for chemical weathering as an important process in the alteration of the Dartmoor and other granites, and in the formation of the 'growan', other workers have propounded that physical weathering also produces similar material. Te Punga (1957) originally argued that the weathered Bodmin Moor Granite (see Hawks Tor) had been formed by Pleistocene frost-shattering. Comparable material in the Massif Central has been ascribed to processes operating in a cool-temperate environment (Collier, 1961). Incoherent granite in the Sierra Nevada has also been attributed to frost-riving (Prokopovich, 1965), but Wahrhaftig (1965) has shown that the chemical alteration of biotite to chlorite in this material produces a 14A-size clay residue which causes expansion and mechanical shattering of the rock. It has thus been suggested that similar processes may have produced the Dartmoor growan which, it is claimed, resembles 'sandy weathering products' elsewhere in Europe (Jahn, 1962; Bakker, 1967; cf. Eden and Green, 1971). However, such a 'grussification' process has not been accepted by all workers.

These deliberations will continue, because the nature and origin of the 'altered' material are central to theories of granite landscape evolution. The view is taken here that the evidence most probably reflects the operation of hydrothermal, chemical and physical weathering processes, sometimes all combined, over an extremely protracted timescale: the evolution/alteration sequence proposed by Floyd *et al.* (1993) would seem to offer an appropriate working model for geomorphologists. Whatever the relative contribution of each process, there is no doubt that the nature and distribution of the altered granite itself have strongly influenced the operation of periglacial processes and the development of characteristic landforms during the Pleistocene (Gerrard, 1983).

Periglaciation, slope development and landform assemblages

Most recent workers, while commenting on the controversial origin of the altered granite, have simply accepted its occurrence as a fact. At the simplest level, the weathered granite is treated as a soft material extremely susceptible to erosion, particularly by periglacial mass wasting processes. The material's importance in influencing the development of granite landforms is therefore fully acknowledged, but the main emphasis since the 1950s has been the role of periglacial conditions and processes. Certain landforms and deposits can be shown to have originated from these processes, and there is little doubt that distinctive elements of the granite landscape were produced during various cold phases of the Pleistocene.

Although the effects of frost-action on the granites of the South-West were appreciated long ago, Albers (1930) provided the definitive link between modern-day periglacial processes (principally frost-shattering and solifluction) and fossil landforms (see above). Preliminary descriptions of a wide range of fossil periglacial features within the region were subsequently given (Dines *et al.,* 1940), and the role of frost-action was considerably heightened by the work of Guilcher (1949, 1950) and Te Punga (1956, 1957) who described periglacial landforms and deposits throughout southern England, including Dartmoor. The evidence they described included fossil ice-wedges, involutions, stone polygons, blockfields, loess and, on Dartmoor itself, altiplanation terraces and earth hummocks (see Merrivale). Te Punga (1957) concluded that much of the landscape had been severely denuded during different periglacial episodes and had been subject to 'vigorous down-wearing by mass wasting', mainly solifluction. He argued that 'It seems probable that the effects of successive periglacial episodes were cumulative, each later episode emphasizing the landforms produced in earlier episodes; it is unlikely that interperiglacial erosion, seeing that it was restricted essentially to linear processes, was competent to obscure or obliterate earlier developed periglacial landscape form' (Te Punga, 1957; p. 410).

The fact that the present relict periglacial landscape is so obvious would add weight to this argument. Significant to later ideas was Te Punga's belief that vast quantities of material had been transported during periglacial conditions to produce a subdued landscape characterized by convex upper slopes and concave lower slopes: following Tricart (1951), he argued that the convex upper slope had been a zone of wastage, while the lower slope had been a zone of deposition. Periglacial features were widely preserved because present-day processes were relatively ineffective, due to binding vegetation, and because the duration of post-periglacial time had been relatively short (Te Punga, 1956).

These concepts were reinforced by Waters during the 1960s (e.g. Waters, 1960a, 1960b, 1961, 1962, 1964, 1965, 1966b, 1971), who attempted to link individual deposits in the region (head and solifluction deposits) to specific periglacial episodes. Although periglacial landforms and deposits were widespread in Britain, he considered that the wholesale redistribution of pre-Pleistocene, deeply weathered regolith by periglacial, mainly solifluction, processes, made Dartmoor ' … probably the purest relict periglacial landscape in Britain' (Waters, 1960a; p. 174). He argued that two main sets of these processes had been operative in the South-West during the Pleistocene: 1. gelifraction or the weathering of coherent rock (mainly freeze-thaw activity); and 2. 'geliturbation' — the disturbance and removal of material principally by solifluction. The effects of these processes were manifested in landscape features such as tors, the modification of slopes, patterned ground and solifluction debris or head (Waters, 1964).

Returning to the ideas of Tricart (1951) and Te Punga (1956), Waters suggested that two separate phases of periglacial activity could be discerned in various head layers throughout Dartmoor. The most complete sections showed evidence for two cryogenic episodes (Figure 4.3), each of which was marked by the downslope transfer ('geliturbation') of different debris types. Thus, during the first cold episode, successive layers of the existing weathering profile (growan) were removed from upper slopes and deposited in reverse order lower down, forming layers of 'bedded growan' and the main head (Figure 4.3). Not judged to have been significantly affected by subsequent weathering (either interglacial or interstadial), material on the upper slopes again became exposed to periglacial processes. This time, more coherent blocks of bedrock, derived from tors and other surface exposures, were detached by frost-action and removed by solifluction to lower levels, where a second, 'blocky' or upper head accumulated on the older deposits (e.g. Waters, 1964, 1965; Linton and Waters, 1966). This inversion of the weathering profile was believed to be widespread on Dartmoor (Waters, 1964, 1965) and the presence of two separate head deposits, formed during different periglacial phases, was widely accepted at the time (e.g. Brunsden, 1968; Gregory, 1969).

Waters therefore paints a picture of the evolving Dartmoor landscape where a pre-existing weathered regolith (the growan), of variable thickness, is transferred from higher to lower levels, creating a smoothed topography punctuated only by tors and buttresses of the most massive and resistant materials. Many upstanding masses of sound granite were completely destroyed by frost-action, and cutter accumulated where the rate of frost destruction exceeded the rate of removal: some of this material was rearranged into patterned ground consisting of stripes and nets (Waters, 1964). The removal of material from the higher levels by solifluction caused aggradation of head on lower slopes and the development of large valley-floor terraces. Where suitable lithological conditions prevailed (see Cox Tor, Merrivale), benched hillslopes or alti-planation terraces were formed. Likewise, Brunsden (1968) concluded that three main types of periglacial landform and deposit were present on Dartmoor: 1. frost-shattered rock outcrops and boulder-strewn slopes; 2. frost regoliths of head and soliflucted debris; and 3. small-scale landforms cut into upland slopes.

Building on the work of Te Punga and Waters, more recent research in the area has confirmed the widespread role of periglacial processes on land-form development, and stressed the importance of structural control (particularly jointing patterns in the granite) (e.g. Green and Eden, 1973; Cullingford, 1982; Gerrard, 1983, 1989b). Detailed analysis of slope deposits within the region, however, shows Waters' two-stage periglacial inversion model to be an oversimplification. Green and Eden (1973) studied the sources and distribution of material in the slope deposits of Dartmoor. They showed that all parts of the slope contributed material to the deposits and that a simple two-fold division of slopes into 'source' and 'accumulation' areas was therefore untenable. They demonstrated that even on lower slopes, movement of slope deposits had been accompanied by erosion of the underlying granite (see Merrivale), and that this basal material had been incorporated into the transported layer: widespread inversion of the weathering profile was not apparent. These principles also applied to the 'bedded growan' commonly found on Dartmoor. Green and Eden suggested that this material was locally derived having been displaced downslope by solifluction deposits moving over weathered granite (see Two Bridges and Believer quarries). An origin as surface-wash sediment (cf. Waters, 1971) was therefore ruled out. Green and Eden's study also provided new information on the relationship of the clitter to local head deposits. Clitter and its rock sources were encountered in a variety of different slope positions. The clitter was not therefore simply derived from ridges, summits and tors as had been suggested previously (Waters, 1964).

Green and Eden concluded that because the clitter, head deposits and bedded growan were present in a wide variety of locations on Dartmoor slopes, they could not be the product of progressive stripping of a normal weathering profile — that is, from the upper parts of valley-side slopes to the lower ones. Support for this contention comes from recent work carried out on head deposits throughout Dartmoor (Gerrard, 1989a). Two main types of head, a fine and a coarse variety, do exist, but the relationships between the two are complex. Frequently, both types intermingle: gullies have been cut and infilled at different times, indicating complicated sequences of slope modification rather than a simple reworking of weathered granite. Large blocks of granite occur throughout the head and not just at its surface. Bedded growan is common, particularly in mid-slope situations. The bedrock surface is extremely variable and frost-shattered with solid stacks of rock reaching almost to the surface. In places, head rests directly on striated bedrock (Gerrard, 1989a). More detailed relationships between head and growan have been reported (Gerrard, 1990, 1994c).

The granite landforms of the South-West were reinvestigated by Gerrard who provided detailed accounts of periglacial landforms in the Cox Tor–Staple Tors area (Gerrard 1983, 1988; see Merrivale), the influence of rock type and structure on granite landforms on Dartmoor and eastern Bodmin Moor (Gerrard, 1974, 1978) and the origin of Dartmoor slope deposits (see above; Gerrard, 1989a). Considerable emphasis has been placed on the effects of granite jointing on the distribution of landforms, particularly tors (see above — joints and faults; see below — erosion surfaces and drainage development). On the basis of the density and pattern of jointing, Gerrard devised a classification of tors into: 1. summit tors; 2. valley-side and spur tors; and 3. small tors cropping out on the flanks of low convex hills. He has argued that areas with closely spaced joints become the focus of initial weathering and erosion. This leads to 'compartmentalization' of the landscape into positive and negative areas (cf. Waters, 1957). Erosion, guided by joint density, has long been a matter of speculation, but Knill (1972) has shown that joints in some valley-floor areas are separated by only *c.* 0.5 m. Gerrard suggests that joints in the areas of upstanding relief (ridges and domes) would initially have been in a state of compression, but as erosion occurred along lines of weakness (stream erosion along zones with dense joints), the joints in the domes themselves would open and allow weathering (Gerrard, 1982). Such a mechanism provides the basis for a model of tor formation, and its emphasis on the spacing of joints makes it similar to Linton's (1955) in this respect. It differs because the continued removal of weathered material, especially from the valley areas, is seen as releasing further stresses stored in the domes, thus progressively exposing them to further weathering (Gerrard, 1974, 1982; see Merrivale). It is therefore the dense jointing which is picked out by the weathering agencies and stream courses, and the tors found crowning many of the 'unloading' or 'dilatation' domes that owe their formation and distribution to further incision by streams around the domes (Gerrard, 1974).

In addition, Gerrard (1982) argued that these processes occur at different rates throughout the landscape, and that there is therefore a variety of relationships between the accumulation and removal of weathered products. He envisaged three different situations: 1. where the ground surface was relatively stable and a deepening of the weathered regolith would occur; 2. where the surface was unstable and regolith was gradually removed; and 3. where a steady-state situation occurred and the renewal and removal of material occurred at similar rates. It was considered possible that each state might exist concurrently at different sites: the Linton explanation of weathering followed by removal was therefore too simple to explain the major elements of a granite landscape (Gerrard, 1982).

On this basis, Gerrard devised a classification of tors on Dartmoor and eastern Bodmin Moor (see above). Detailed measurements on 65 tors show major variations with respect to size and intensity of jointing, and the slope angles at their base. Both summit and valley-side tors possess relatively closely spaced vertical joints, whereas those of the emergent tors are much more widely spaced (Gerrard, 1978).

In combining the evidence of structural control with that for periglacial processes, Gerrard (1983) produced a composite diagram to explain the main geomorphological elements seen in the Dartmoor landscape (Figure 4.4). Although individual measured slopes rarely fit the model exactly, those in the vicinity of Great Staple Tors (see Merrivale) show a close correspondence.

A very similar classification of tors was produced by Ehlen (1994). She was able to demonstrate significant differences between these groups. Summit tors generally possessed high relative relief (mean 126 m), the rock was megacrystic and possessed the widest joint spacing. For primary vertical joints, the spacing was usually > 300 cm; for primary horizontal joints the mean spacing was 73 cm and for secondary horizontal joints the mean was 13 cm. Summit tors are usually controlled by vertical joints or by vertical joints and horizontal joints combined.

Feldspar is usually abundant in the rock (> 30% potassium feldspar; > 18% plagioclase). Spur tors generally possess narrower vertical joint spacing and horizontal joint spacing is intermediate. The rocks are fine-grained (< 1 mm) and feebly megacrystic or equigranular. Potassium feldspar abundance is low. Valley-side tors have narrow joint spacing, and horizontal joints control tor shape. The rocks are finer grained (< 2 mm), feebly megacrystic and quartz abundance is low.

In terms of spatial distribution within Dartmoor, multivariate analysis produced five tor groups. Tors in the first group occur mainly south of a line from Great Mis Tor to Bell Tor. They are characterized by medium to high numbers of megacrysts, medium- to coarse-grained feldspar, narrow to intermediate vertical joint spacing and low to intermediate quartz abundances. Most of the tors are summit tors. Tors of the second group are scattered across Dartmoor, many of them lamellar in form. They are characterized by fine- to medium-grained feldspar, widely spaced vertical joints, low secondary joint spacing ratios and low to intermediate quartz abundances. Only two tors are present in the third group and occur to the north-west and east. The rock possesses no megacrysts and vertical joint spacing is narrow. Most of the tors in the fourth group occur in the east and possess medium to high numbers of megacrysts, intermediate vertical joint spacing, low quartz abundances, moderate to highly abundant plagioclase and occur in the form of summit tors. The fifth group is the largest and the tors are present throughout Dartmoor, although there is a tendency for them to occur near the granite boundary. The rock has few megacrysts, narrow to intermediate vertical joint spacing, low to intermediate plagioclase abundances and forms summit and valley-side tors. Tourmaline veins are typically present. In general throughout the granite of Dartmoor, relationships exist between grain size, rock texture, jointing and landforms (Ehlen, 1989, 1991, 1992).

Towards a composite model of landscape evolution

Theories on granite landscape evolution have ranged widely, and a variety of mechanisms has been proposed to account for the tors and associated landforms of the South-West. The significance of periglacial processes in shaping this landscape seems to be the only major area of agreement: less has been reached regarding the precise origins of the decomposed or altered granite (growan), and the classic models of tor formation are perhaps too simple to explain wide variations in slope and tor morphology. The possibility must also exist that tors are an example of equifinality (White, 1945; Selby, 1977; Gerrard, 1984). Also, tors in the same landscape may have been formed by different processes. It is likely that many of the valley-side tors on Dartmoor are the result of periglacial processes, but that large summit tors have a composite origin from both chemical and frost action (Gerrard, 1994b). Many summit tors, especially Great Staple Tor, seem to possess rounded upper portions and significantly more angular basal portions. As French (1976; p. 233) has noted, ' … it is conceivable that both exhumation and modification of two-cycle tors and the formation of one-cycle tors could have occurred at the same time in different parts of Dartmoor depending upon the localisation of the deep weathering process' and … tors of different forms may exist adjacent to each other and develop under the same climatic conditions but by two different processes' (French, 1976; p. 234).

Recent work, however, goes some way to providing an integrated approach to the study of these landforms. The complexity of depositional sequences now demonstrated is at variance with former reconstructions where perhaps only one or two main phases of periglacial modification were envisaged. Although the basic configuration of the 'dome and basin' topography may have been inherited from the Tertiary (and earlier), the smaller (and some meso-scale) details of the slopes and landforms reflect clearly the cumulative operation of periglacial and other processes during the Pleistocene. Since it is widely agreed that Dartmoor was never glaciated, it is reasonable to assume that substantial landscape changes occurred during the multiple periglacial phases now known to have affected the region (Bowen, 1994b): as a result, depositional evidence is likely to be complicated, and the effects of the periglacial modification cumulative. Little, however, is known about the age(s) of the various slope deposits in granitic inland areas, and their relationship to the better-dated coastal 'head' sequences has yet to be firmly established (cf. Mottershead, 1971; Stephens in Linton and Waters, 1966). In some areas, the legacy of Pleistocene periglacial activity may be substantial. The efficacy of such processes, however, is not universal as attested by the survival of relatively fragile sands and 'clays' at St Agnes, west Cornwall (Chapter 3), and the selective survival of given landscape features is, as yet, unexplained. There is good reason to believe, however, that the morphological detail of much of the present landscape is the result of periglacial activity during the various cold episodes which have characterized the Devensian Stage alone.

The selected GCR sites on Dartmoor (at Merrivale, Two Bridges and Believer quarries) and in the Isles of Scilly (Peninnis Head) demonstrate between them a huge variety of granite landforms and associated weathering products: collectively, they illustrate many of the theories which have been propounded to account for the formation of tors and the altered granite or growan, and demonstrate, impressively, the range of periglacial processes which were operative in this area during the Pleistocene. This small network of sites will remain central to future reconstructions of granite landscape evolution in Britain.

Dartmoor: the physical background

The Dartmoor pluton gives rise to an elevated region of widespread moorland dotted with tors. The granite areas cover *c.* 250 square miles, and extend some 22 miles from north to south and 18 miles from east to west (Worth, 1930). The highest ground occurs in the north-central parts of the granite where most of Dartmoor's radially draining rivers begin their courses. Here, the principal summits range between *c.* 1600 to 2000 ft (488–610 m) above sea level; in the southern area they range between 1200 and 1600 ft (366–488 m) (Worth, 1930).

Worth's (1930) early work on the physical geography of Dartmoor is worthy of special note. He divided the area into different terrains based on relief and elevation, and provided comprehensive accounts of the landforms, peatlands and present vegetation. In his superb illustrations of the many famous Dartmoor tors (e.g. Littaford, Chat, Blackingstone, Bowerman's Nose, Staple, Great Mis, Cox, Thornworthy, East Mill and Oke tors, among others) lay the key to his belief that the present form of the region was largely inherited from the upper surface of the granite when it cooled in contact with the overlying sedimentary rocks (Worth, 1930, 1967). His principal line of evidence for this assertion was the striking coincidence of the 'pseudo-bedding planes' (sheet or floor joints) with the slopes of local hillsides and summits.

Erosion surfaces and drainage development

The difference in elevations between the north and south parts of Dartmoor, noted by Worth, was seen as evidence by Waters (1957, 1960c, 1960d, 1960e; and *in* Brunsden *et al.,* 1964) for a series of erosion surfaces. These were related to different base levels and, on Dartmoor, several major erosive episodes had modified what were considered to be remnants of a higher and older pre-existing peneplain which had formed the basis of the generally southward-sloping Dartmoor plain. An analysis of specific (relative) relief in the 541 km squares which cover the upland granite area of Dartmoor, at a scale of 1:25 000, clearly demonstrates the plateau-like nature of the area (Gerrard, 1993).

The uppermost and oldest surface (the remnant peneplain) was considered to occur at elevations between *c.* 1900 and 1500 ft (580–457 m), and was represented by three main residual land masses. A middle surface, occurring on both the granite and adjacent country rocks at elevations between *c.* 1300 and 1050 ft (396–320 m), was represented by piedmont benches of varying width, various valley-side benches, valley-floor segments and basins (Waters, 1960c). This tor-crowned surface with its elongated basin-like depressions was considered to show considerable dissection, and had been much affected by differential erosion and weathering. A further, much more pronounced and extensive surface (the lower surface), was separated from the middle surface by a group of facets or relatively steep slopes. Lying between *c.* 950 and 750 ft (290–229 m) it was, according to Waters, represented on Dartmoor only by river terraces and valley-floor segments, although it was extensively developed elsewhere (the 'Bodmin Moor Platform' of Green (1941)).

The final surface (690 to 550 ft (210–168 m) OD), widely developed in south-west Devon, was also present on Dartmoor, and was shown by bevelled spurs to the north of the moor and, even less reliably, by an accordance of summit heights to the south (Waters, 1960c). Waters argued that the highest upstanding 'residuals' (those above *c.* 1500 ft (457 m)) had survived as the most resistant elements of an extensive chemical etch plain. This subaerially formed and much dissected peneplain, bearing tors and rotted granite (growan), was believed to have been created over a protracted period through Miocene and even into Pliocene times. It was considered to form the basis of the gently sloping Dartmoor plain into which the later, successively lower, surfaces had been cut (Waters 1957, 1960c, 1960d; Brunsden *et al.,* 1964). The latter were also considered to be of late Tertiary age, having formed by a variety of subaerial and marine processes. Waters argued that only relatively minor modification to this basic landscape occurred during the Pleistocene, and although mass wasting 'exposed summit tors, moulded slopes and plastered valley floors with rubble-drift', no further base-levelled surfaces were created on the upland (Waters in Brunsden *et al.,* 1964).

The origin of these and comparable 'erosion surfaces' elsewhere in South-West England is discussed widely in the earlier geomorphological literature (e.g. Jukes-Browne, 1907; Barrow, 1908; Davis, 1909; Wooldridge and Linton, 1939; Green, 1941, 1949; Wooldridge, 1950, 1954; Balchin, 1952, 1964, 1981), and forms a protracted and important element in the development of geomorphological thought. These aspects are more fully considered in Chapter 3, and suffice to say here that the widespread occurrence of these many different 'planation' surfaces, either marine- or subaerially formed, is now disputed (e.g. Coque-Delhuille, 1982, 1987; Battiau-Queney, 1984, 1987).

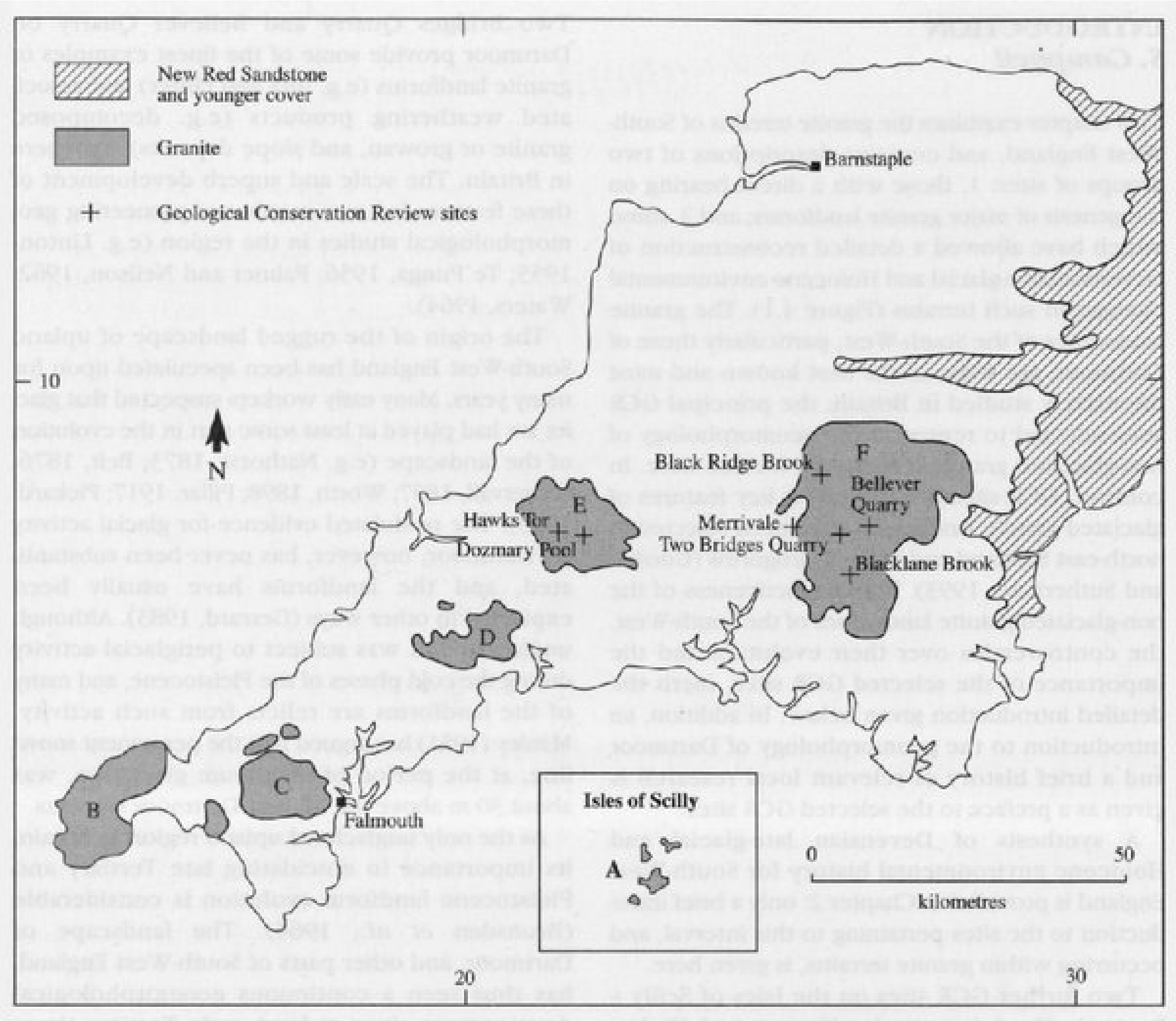
Nonetheless, the belief in these erosion surfaces has formed the basis for many interpretations of the Dartmoor landscape, including models of drainage development as well as attempts to link the characteristic granite landforms into lengthy models of landscape evolution and denudation chronology (Waters, 1957; Brunsden *et al.,* 1964). Waters (1957), for example, related the pattern of Dartmoor rivers to the form of the upper erosion surface, characterized by a 'basin and tor' topography. He argued that the region's rivers were quite incapable of producing the basins in which they now lie, and that basins were therefore in existence before the drainage net. Waters suggested that differential chemical weathering of the granite, strongly influenced by variations in joint spacing, had resulted in the creation of basin forms where the weathered granite was most deeply developed (cf. Linton, 1955; see above; models of tor formation). Brunsden (*in* Brunsden *et al.,* 1964) suggested that the earliest drainage pattern on Dartmoor probably ran eastwards, and indeed that it had been a major agent in producing the summit plain or the highest erosion surface. Subsequent uplift and southward tilting of this surface may have led directly to the next phase of planation which created the middle erosion surface (*c.* 1300–1050 ft (396–320 m)), and to the initiation of dominantly north to south drainage lines.

Many studies of the rivers of Dartmoor and adjacent areas have been made, based on reconstructions of valley long-profiles and terrace gradients (e.g. Green, 1949; Waters, 1957; Kidson, 1962; Brunsden, 1963; Brunsden *et al.,* 1964). HoWeyer, treating drainage evolution in the wider context of denudation chronology, and relating knick-points and various gradient curves to particular Tertiary and Pleistocene base levels, has involved a number of assumptions now believed to be false or, at least, highly dubious (Cullingford, 1982). A detailed morphometric analysis of all third-order drainage basins on Dartmoor has been conducted by Gerrard (1989b). This analysis demonstrated the essential uniformity of basin characteristics. Groupings of basins, obtained from a hierarchical cluster analysis, seem to be related to size and relative relief. However, groups combine at an early stage in the clustering process, indicating the integration and stability of the drainage net. The small variation in drainage density and the high correlation between the total stream length and area also suggest that the drainage networks are relatively stable. The grouping of the basins has added to the interpretation of long-term evolution based on remnants of erosion surfaces, river terraces and river long-profiles.

In more recent studies, greater emphasis has been placed on the role of jointing in the Dartmoor granite in influencing the pattern of streams (Blyth, 1962; Palmer and Neilson, 1962; Gregory, 1969; Gerrard, 1974, 1978). Gregory (1969) argued that the arrangement of valleys and interfluves shows a generally rectilinear pattern, reflecting very strongly the influence of jointing. This argument has been carried further by Gerrard (1974) who argued that the influence of jointing on the evolution of the Dartmoor landscape had been dominant. The horizontal joints or pseudo-bedding planes, which closely follow the contours of the land surface, evolved, Gerrard argued, as the land surface was denuded, thus reducing primary confining pressures in the granite. This resulted in a series of 'unloading' or dilatation domes, picked out clearly by the evolving drainage net. The dominant vertical joints, trending both north to south and east to west, had been the focus of subsequent weathering and were therefore instrumental in determining the local pattern of drainage (cf. Blyth, 1962; Palmer and Neilson, 1962; Gregory, 1969). Indeed, Gerrard (1974) argued that the tors crowning many such domes, had evolved as stream incision and erosion removed overburden, thereby releasing further compressive stresses in the granite. (Hawkes (1982) suggests that the granite was originally intruded beneath a cover of at least 1–3 km thickness.) This unloading in turn opened up additional joints to weathering processes, and continued a progressive cycle of landform development. Gerrard argued that the tors, located on the summits of these unloading domes, therefore owed their distribution and formation, at least in part, to stream incision, although their form was also related to sub-surface chemical weathering and cryonival processes (Gerrard, 1974). In his synthesis, the horizontal and vertically developed joints were of the utmost significance, first in guiding the developing drainage net and thus delimiting the evolving unloading domes and, secondly, in governing the form and distribution of the tors (Gerrard, 1974).

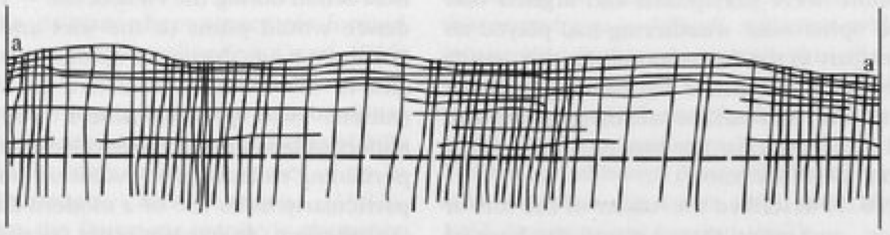
The differential erosion of the Dartmoor granite massif was also stressed by Coque-Delhuille (1982). She argued that the original petrography of the granite had been relatively unimportant in subsequent landscape evolution and argued, like Gerrard, that the role of structure, particularly jointing, had been a prime determinant in the ensuing and selective pattern of erosion. This erosion occurred on what she regarded as only two erosion surfaces: the 'Dartmoor surface', derived from a post-Hercynian/pre-Permian surface, and a lower polygenetic 'Devon-Cornwall surface' which had evolved since Cretaceous times (Chapter 3). Some parts of the Dartmoor landscape have been more sensitive to change than others (Gerrard, 1991). Interfluves and plateaux have been affected by changes in weathering regime but have been essentially unaffected by hillslope changes initiated along river courses. The inner plateaux appear to have changed little in general form throughout the Quaternary and owe their extent to geological factors. Valley-side slopes have been more sensitive and soil and slope materials indicate the scale of landscape change.

References

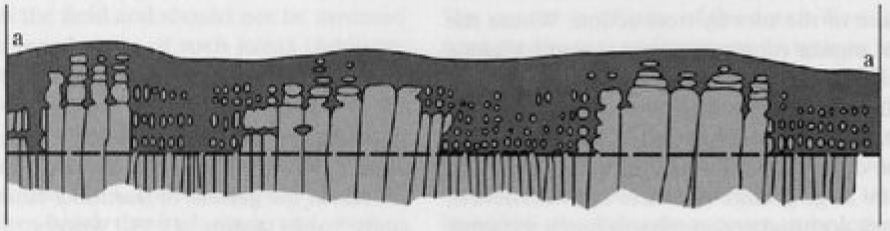


(Figure 4.1) Location of GCR sites in relation to: A, Isles of Scilly Granite; B, Land's End Granite; C, Carrunellis Granite; D, St Austell Granite; E, Bodmin Moor Granite; and F, Dartmoor Granite. (Adapted from Floyd et al., 1993.)

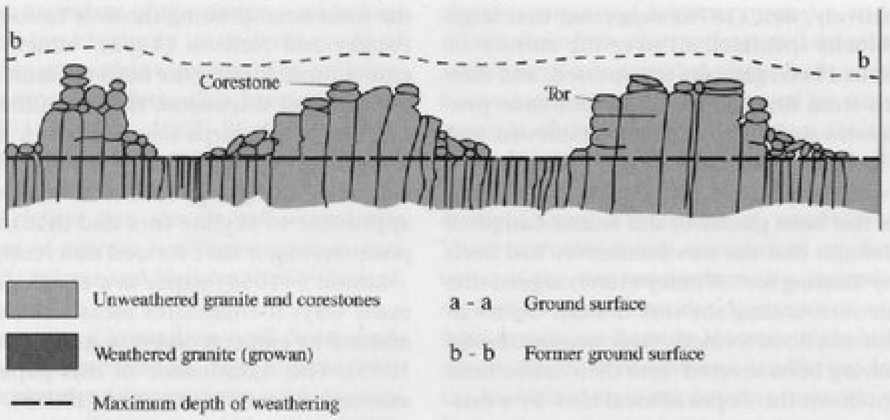
(a) Theoretical arrangement of initial joint sets in granite



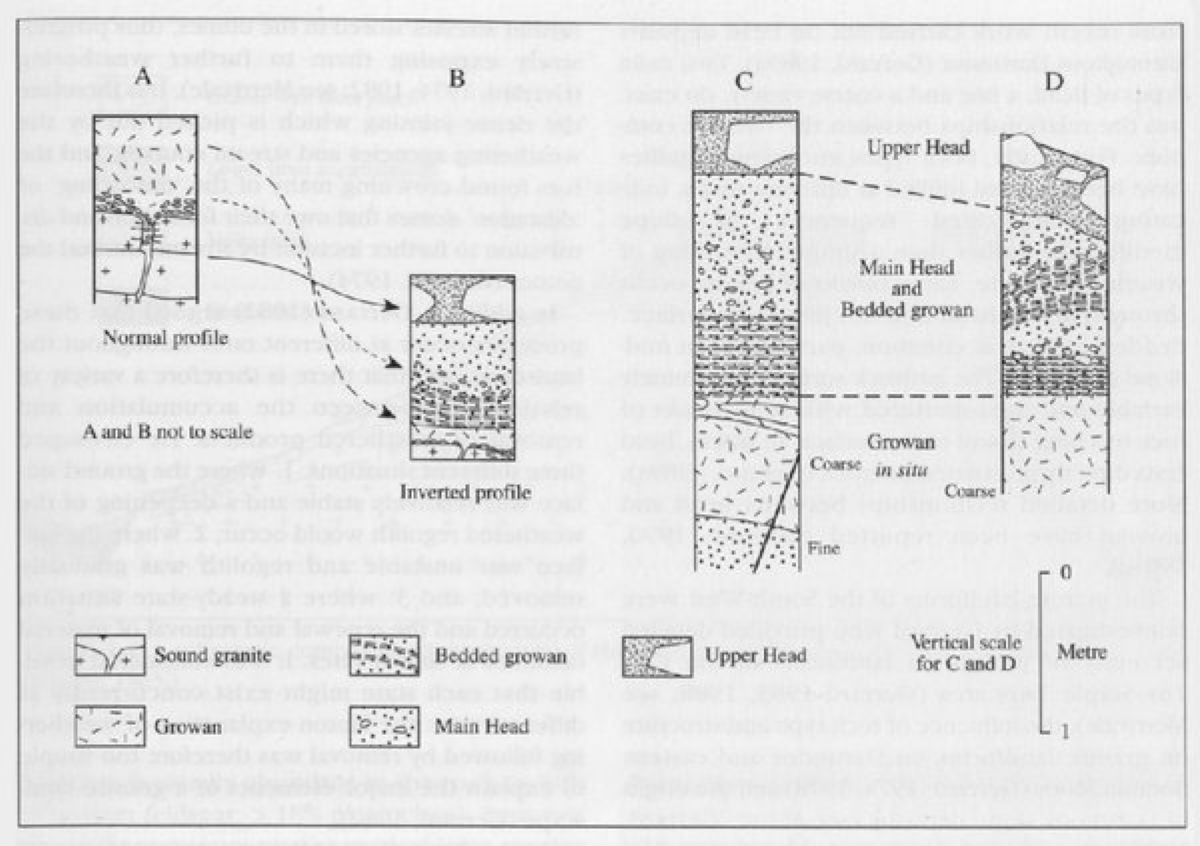
(b) Tertiary weathering



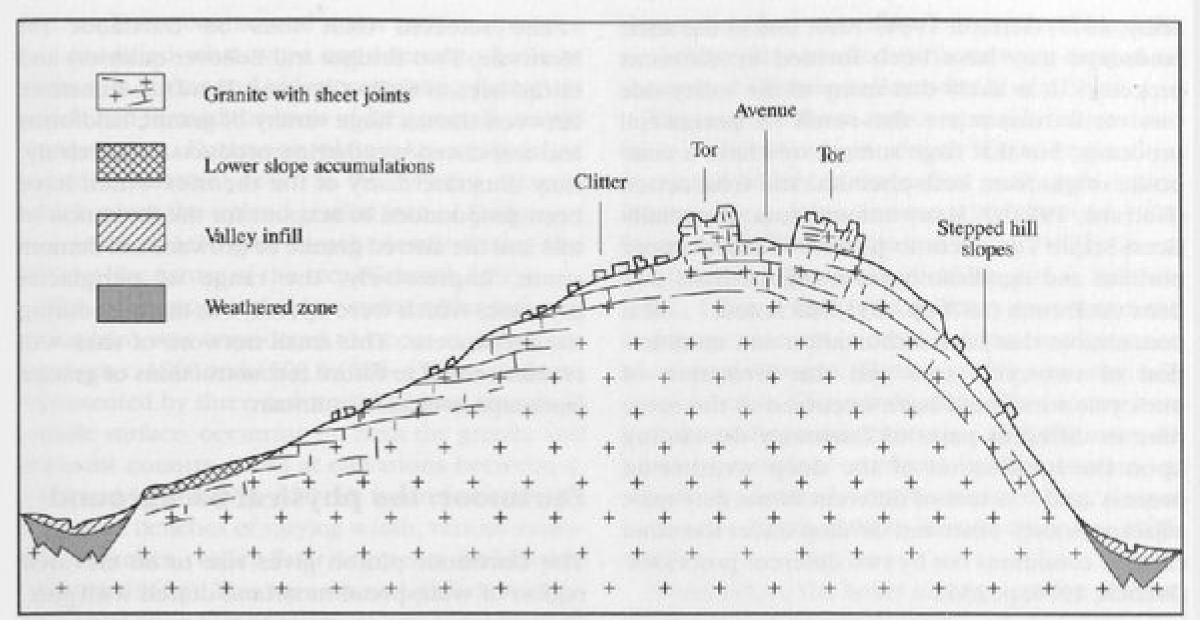
(c) After Pleistocene stripping of Tertiary weathering products



(Figure 4.2) Linton's (1955) classic two-stage model of tor formation.



(Figure 4.3) A model of slope development for Dartmoor, after Waters (1964). Profiles: (a) Products of in situ weathering on a granite substrate; (b) Inversion of normal weathering profile following two separate periods of periglacial mass wasting; (c) and (d) Measured sections at Shilstone Pit [SX 659 902], Dartmoor. Many slope configurations, however, do not conform to this model (see text).



(Figure 4.4) A schematic composite representation of the main geomorphological features of Dartmoor. (After Gerrard, 1983.)