Quaternary of South-West England

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Chapter 4

Granite landscapes

INTRODUCTION

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This chapter examines the granite terrains of South-West England, and contains descriptions of two groups of sites: 1. those with a direct bearing on the genesis of major granite landforms; and 2. those which have allowed a detailed reconstruction of Devensian late-glacial and Holocene environmental changes in such terrains (Figure 4.1). The granite landscapes of the South-West, particularly those of Dartmoor, are some of the best known and most intensively studied in Britain: the principal GCR sites selected to represent the geomorphology of non-glaciated granite terrains are located here. In contrast, GCR sites demonstrating key features of glaciated granite landscapes have been selected in north-east Scotland and in the Cairngorms (Gordon and Sutherland, 1993). The distinctiveness of the non-glaciated granite landscapes of the South-West, the controversies over their evolution and the importance of the selected GCR sites, merit the detailed introduction given below. In addition, an introduction to the geomorphology of Dartmoor and a brief history of relevant local research is given as a preface to the selected GCR sites.

A synthesis of Devensian late-glacial and Holocene environmental history for South-West England is provided in Chapter 2: only a brief introduction to the sites pertaining to this interval, and occurring within granite terrains, is given here.

Two further GCR sites on the Isles of Scilly – Peninnis Head (granite landforms) and Higher Moors (Holocene vegetational history) – also have a bearing on the evolution of granite landscapes. For convenience, they are considered in a regional account of the geomorphological development and Quaternary history of the Isles of Scilly (Chapter 8).

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 Bellever Quarry on Dartmoor provide some of the finest examples of granite landforms (e.g. tors and clitter) 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 geomorphological 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 snow-line, 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

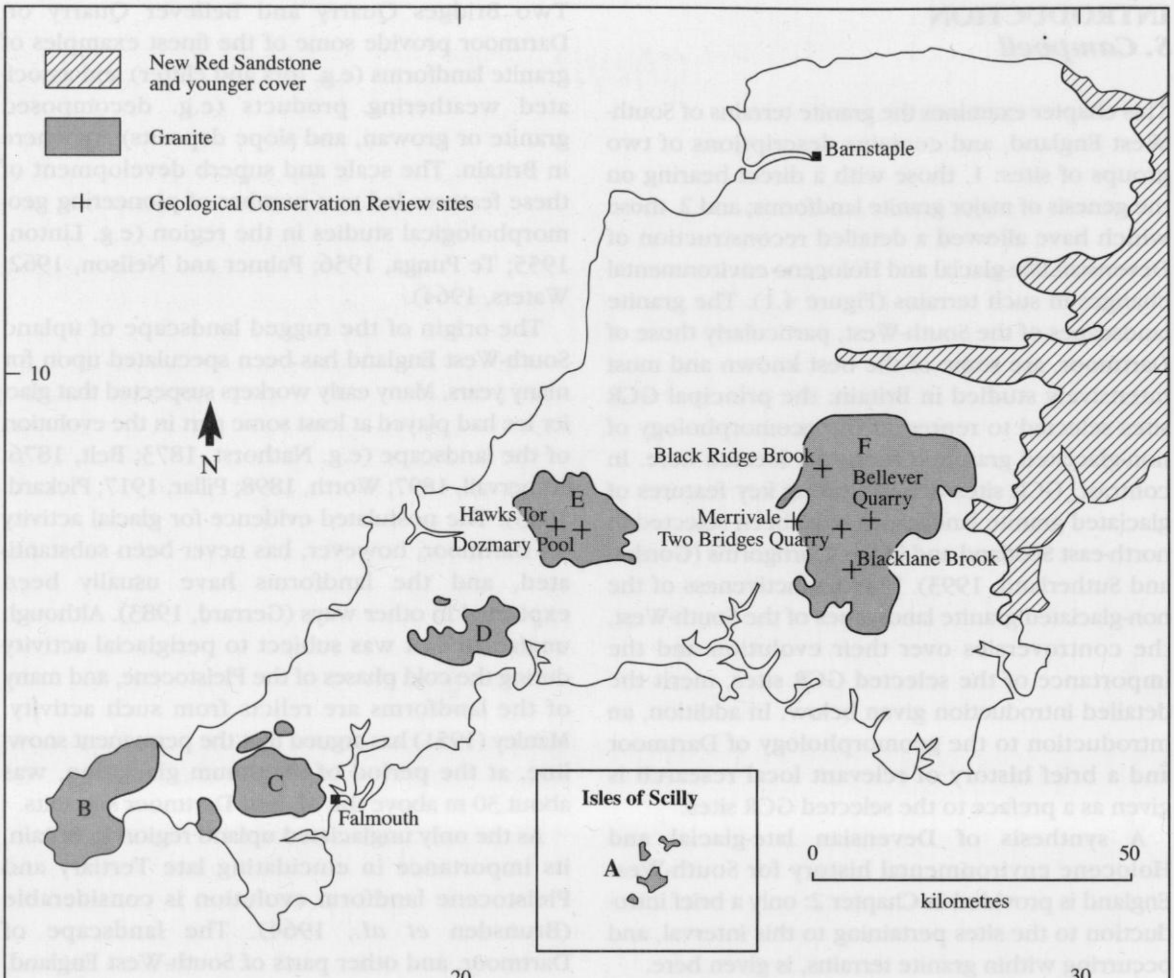

Figure 4.1 Location of GCR sites in relation to: A, Isles of Scilly Granite; B, Land's End Granite; C, Carnmellis Granite; D, St Austell Granite; E, Bodmin Moor Granite; and F, Dartmoor Granite. (Adapted from Floyd *et al.*, 1993.)

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 al.*, 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; Brunner 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 Neilson, 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 controlled 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 subaerial 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 'clitter 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 proglacial 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 clitter 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 clitter 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/soliflucted origin for the clitter, Albers also thought it reasonable to suggest that the tors themselves had been formed, probably substantially, by frost-action during the Pleistocene – 'Thus the evidence would point to the tors and clitters 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

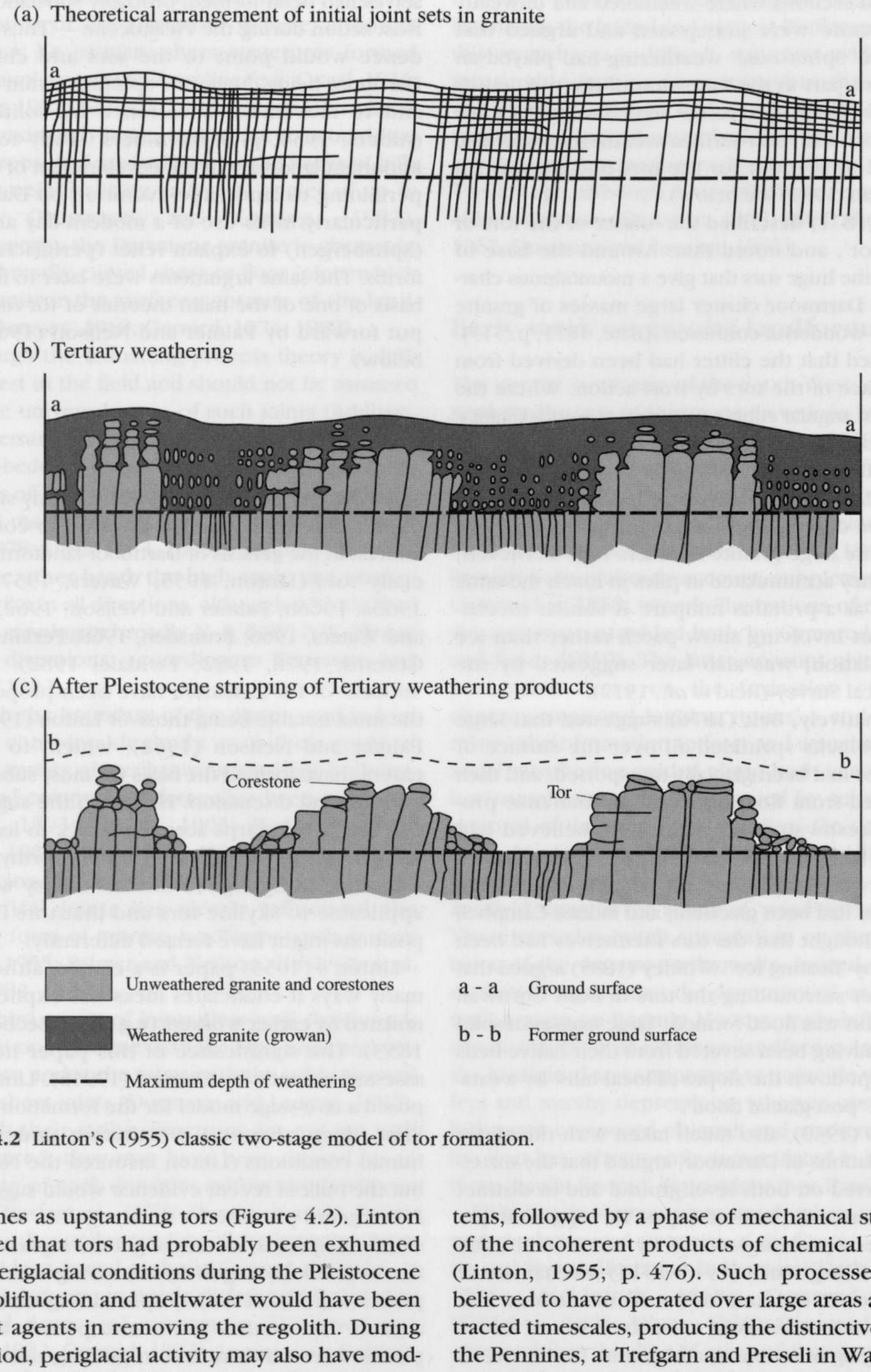

Figure 4.2 Linton's (1955) classic two-stage model of tor formation.

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 clitter 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 'palaeo-arctic 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 Bellever 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 Bellever 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 north-east Scotland where two main granite weathering products have been differentiated (Hall, 1983; Hall *et al.*, 1989). These comprise 'clayey grus' (the proposed 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 Ollier (1983). Because weathering is a widespread phenomenon and occurrences of hydrothermal alteration rare (cf. Konta, 1969), Ollier 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; Ollier, 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' (Ollier, 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 14Å-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 clitter 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 altiplanation 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,

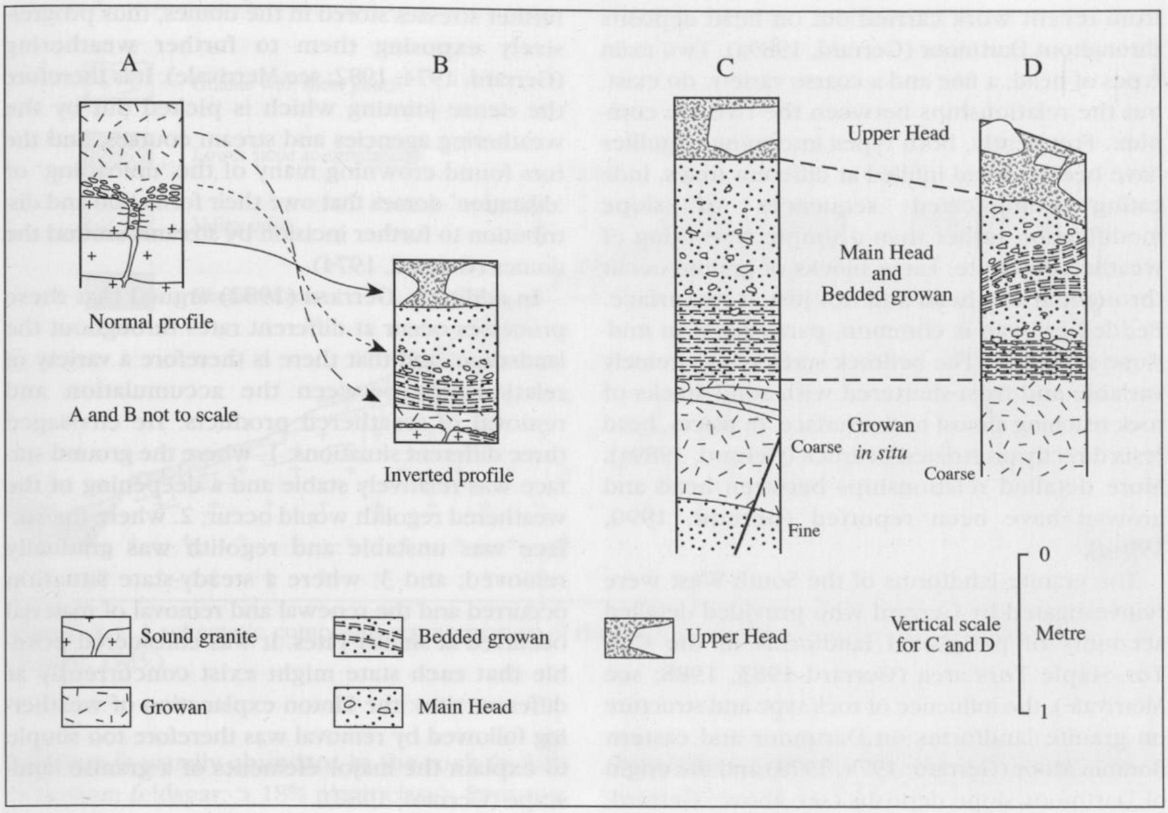

Figure 4.3 A model of slope development for Dartmoor, after Waters (1964). Profiles: (a) Products of *in situ* weathering on a granite substrate; (b) Inversion of normal weathering profile following two separate periods of periglacial mass wasting; (c) and (d) Measured sections at Shilstone Pit (SX 659902), Dartmoor. Many slope configurations, however, do not conform to this model (see text).

more recent research in the area has confirmed the widespread role of periglacial processes on landform 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 Bellever 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.

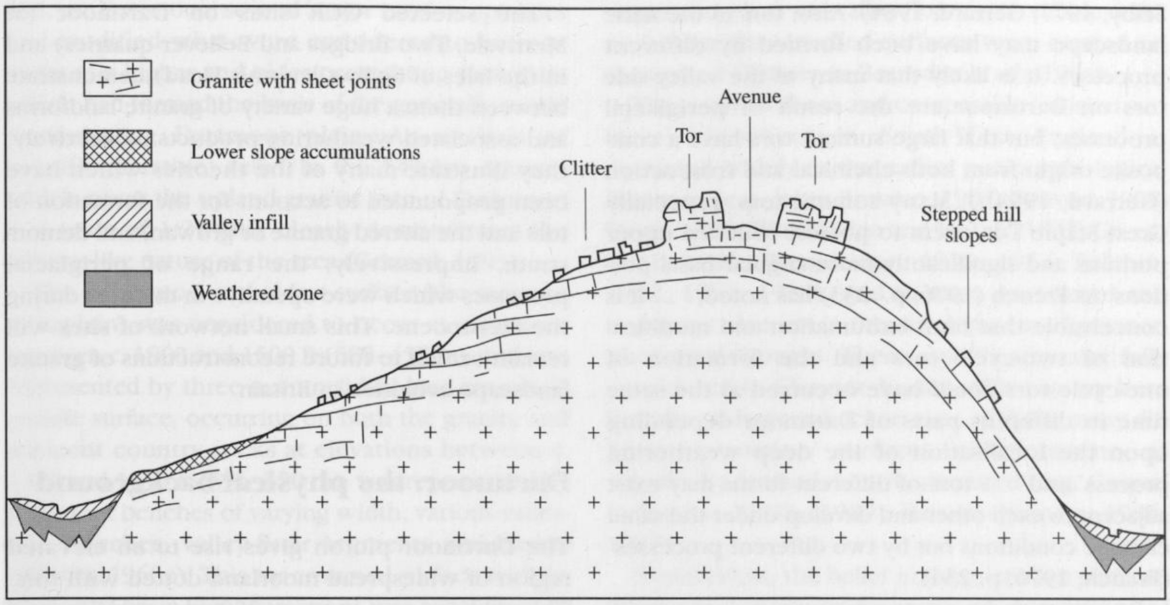

Figure 4.4 A schematic composite representation of the main geomorphological features of Dartmoor. (After Gerrard, 1983.)

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 Bellever 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). However, 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.

MERRIVALE

S. Campbell

Highlights

Merrivale is one of the classic British localities for tors and associated periglacial landforms. It exhibits many of the most significant features of tor morphology, and demonstrates their relationships to bedrock lithology and structure. It demonstrates some of the most widely accepted evidence in Britain for cryoplanation.

Introduction

Merrivale GCR site encompasses the Cox Tor and Staple Tors area of Dartmoor, and provides one of

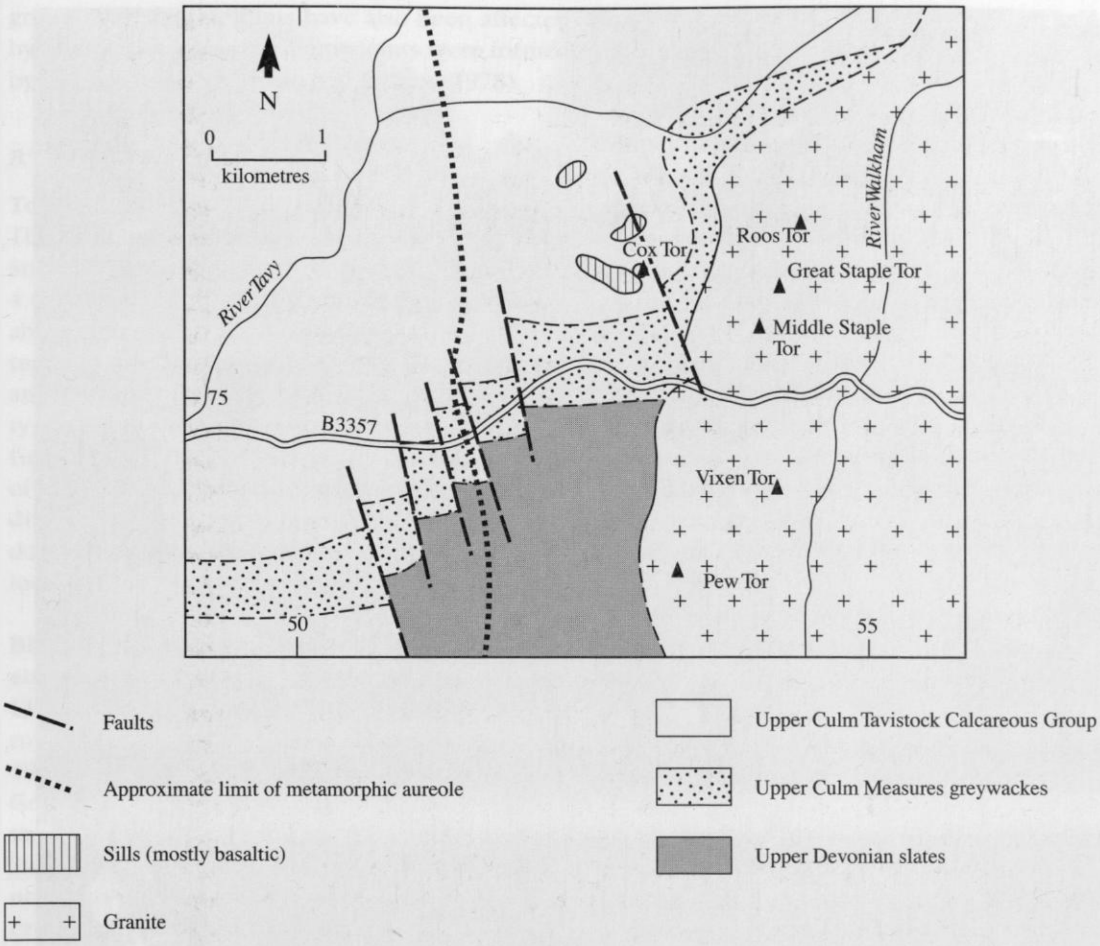

Figure 4.5 Simplified geology of the Merrivale area. (Adapted from Gerrard, 1983.)

the most spectacular assemblages of granite landforms anywhere in Britain. The site appeared in Linton's (1955) classic paper *The problem of tors*, while altiplanation terraces around Cox Tor were among the first examples to be described in the British landscape (Te Punga, 1956, 1957; Waters, 1962). Merrivale is also notable for one of the most extensive occurrences in southern Britain of fossil periglacial earth hummocks (Te Punga, 1956; Gerrard, 1983; Bennett *et al.*, 1996). The site has also featured in many other important geomorphological studies (e.g. Worth, 1930, 1967; Palmer and Neilson, 1962; Brunsden, 1964, 1968; Waters, 1964; Stephens, 1970a; Green and Eden, 1971; Green and Gerrard, 1977; Cullingford, 1982) . More recent accounts of the landforms were provided by Gerrard (1983, 1988, 1989a), Ballantyne and Harris (1994) and Harrison *et al.* (1996). The granite tors also possess excellent examples of rock (weathering) basins.

Description

The Merrivale area, encompassing Cox Tor (SX 530761), Staple Tors (SX 542760) and Roos Tor (SX 544765), is located on the western fringe of Dartmoor overlooking the Tamar Valley and adjacent lowlands which separate Dartmoor from Bodmin Moor. The principal landforms exhibited by the site are tors, blockfields and stone stripes (clitter), altiplanation terraces and earth hummocks. The site also shows sections through superficial deposits (head and weathered regolith). The structure and composition of the granite, which underlies part of the site, is well shown in Merrivale Quarry (SX 546753).

A. Geology

The local geology is shown in Figure 4.5 and controls, significantly, the distribution of landforms

Figure 4.6 Aerial photograph (scale *c*. 1:10 000) showing: (a) Cox Tor; (b) Roos Tor; (c) Great Staple Tor; (d) Middle Staple Tor; (e) Little Staple Tor; (f) Merrivale Quarry. Distinct 'boulder runs' of clitter are particularly evident around the Staple Tors. (Cambridge University Collection: copyright reserved.)

(Figures 4.6 and 4.7). The Staple Tors are developed in granite and are separated from Cox Tor by a col cut in metamorphic rocks of the aureole (mainly Devonian slates) (Figure 4.5; Reid *et al.*, 1912; Dearman and Butcher, 1959; Gerrard, 1983). Cox Tor is itself formed of diabase (metadolerite) and is surrounded by a belt of calcareous hornfels, bordered by non-calcareous Culm Measures of Carboniferous age (Figure 4.5). The diabase of Cox Tor is more densely jointed than the granite of the Staple Tors and Roos Tor. The latter consists predominantly of medium- to coarse-grained granite but with common veins, inclusions of tourmaline and dykes of finer-grained granite. A large resistant vein of microgranite (aplite) runs through Roos Tor (Dearman and Butcher, 1959; Gerrard, 1983).

The coarse-grained grey granite, which comprises most of the tors in the Staple Tors complex, is well exposed in fresh faces in the adjacent Merrivale Quarry (Dearman and Baynes, 1978). Near the surface, however, joint surfaces show pitting caused by the decomposition of plagioclase feldspar. Widely spread (3–7 m), orthogonal planar joints occur with granulated selvages 50–100 mm wide, composed of fresh, mechanically disintegrated interlocking granite gravel. Some joints are stained red. The origin of the red staining is believed to be hydrothermal, although near the ground surface the joints have also been affected by chemical weathering. Some joints were formed by stress release (Dearman and Baynes, 1978).

B. Landforms

Tors

The principal tors of this site are Roos Tor, Great Staple Tor, Middle Staple Tor and Cox Tor (Figure 4.6). These tors occupy summits at elevations above 430 m OD: the smaller and lower-lying feature of Little Staple Tor (*c*. 380 m OD) occurs on an interfluve. Great Staple Tor is of the 'avenue' type with a missing central portion (Green and Gerrard, 1977). It consists mostly of massive stacks of joint-bounded blocks. Sheet joints (pseudo-bedding planes) in the granite of this tor dip downslope at an angle slightly less than that of the local ground surface (Green and Gerrard, 1977).

Blockfields, boulder runs and boulder stripes (clitter)

Clitter is present on most of the hillslopes surrounding the principal tors at Merrivale (Te Punga, 1956; Gregory, 1969; Green and Gerrard, 1977; Gerrard, 1988; Bennett *et al.*, 1996), particularly on the western slopes of the granite which forms the Staple Tors complex (Figure 4.6). Many of the north to south-trending valleys exhibit marked cross-valley asymmetry, with west-facing slopes possessing gentler angles. Clitter is often more prominent on these western slopes. Although formerly thought to be randomly distributed, the blocks and boulders (clitter) mantling the local slopes show distinct organization (Te Punga, 1957; Gerrard, 1988; Figure 4.6). First, blockfields are common, particularly towards the base of the main slopes leading from the tors. This detritus is composed of boulders which exhibit considerable variation in long-axis orientation and which are often inclined at steep angles (Gerrard, 1988).

Second, the clitter is arranged, particularly on the western slopes, into stripes, runs and other patterns (Te Punga, 1957; Green and Gerrard, 1977; Gerrard, 1983, 1988; Figure 4.6). A vast variety of these forms exists around the Staple Tors, including narrow stone stripes, boulder runs and garlands. Narrow stripes (up to 3 m wide) start and finish in mid-slope positions. In places, they coalesce to form wider runs; elsewhere they diverge or coalesce apparently at random (Gerrard, 1983). However, according to Gerrard (1983), there is an order to the arrangement of the individual blocks. Boulders in the centre of runs often stand on-end or with their long-axes pointing downslope. In some stripes, smaller boulders rest against or override larger ones. Some small stripes show a central hollow (Gerrard, 1983). The stripes are present on slopes as gentle as 6° (Green and Gerrard, 1977).

It is significant that many runs and garlands lead directly from the base of tors. On the other hand, stripes often start mid-slope at a great distance from the nearest outcrop. There is little differentiation in the size of material found in the various boulder structures (Gerrard, 1983).

Altiplanation terraces

The flanks of Cox Tor consist of well-defined rock-cut terraces or 'benched hillslopes'. These are particularly well developed on the north and south slopes where the features are most frequent but small; on the eastern slopes they are more regular and extensive and to the west it is not clear whether the breaks of slope are terrace forms or are the result of clitter accumulations (Te Punga, 1956, 1957; Waters, 1962; Green and Gerrard, 1977; Gerrard, 1983, 1988) (Figure 4.7). These terraces were first described by Te Punga (1956, 1957), and were re-mapped in detail by Gerrard (1983). The highest are cut in the diabase of Cox Tor itself, the lower ones in hornfels and Culm Measures. The inclination of the 'treads' varies from 3–9°; the 'risers' from 11–20° (Green and Gerrard, 1977; Gerrard, 1983, 1988). Towards Cox Tor, the risers become small vertical rock cliffs cut in the diabase. Tread widths range from 13–65 m and the features can be as much as 800 m long (Figure 4.7). Local exposures confirm that the terraces are cut in rock: only a very thin veneer of debris, rarely thicker than 1 m, rests upon the treads (Te Punga, 1956; Gerrard, 1983).

Earth hummocks

The Cox Tor area contains one of the most extensive fields of earth hummocks in Britain. Thousands of small sub-hemispherical mounds, up to 2 m in diameter and 0.25 m high, occur on the terraced and adjacent slopes around Cox Tor (Te Punga, 1956; Green and Gerrard, 1977; Gerrard, 1983, 1988; Bennett *et al.*, 1996). They are best developed on the eastern side of the tor and are confined to soils developed on the metamorphic aureole. These mounds form a polygonal network but vary considerably in size and shape: some are elongated downslope, others show degraded profiles on their downslope side (Gerrard, 1983; Bennett *et al.*, 1996). Bennett *et al.* (1996) have classified the hummocks as: 1. 'single hummocks'

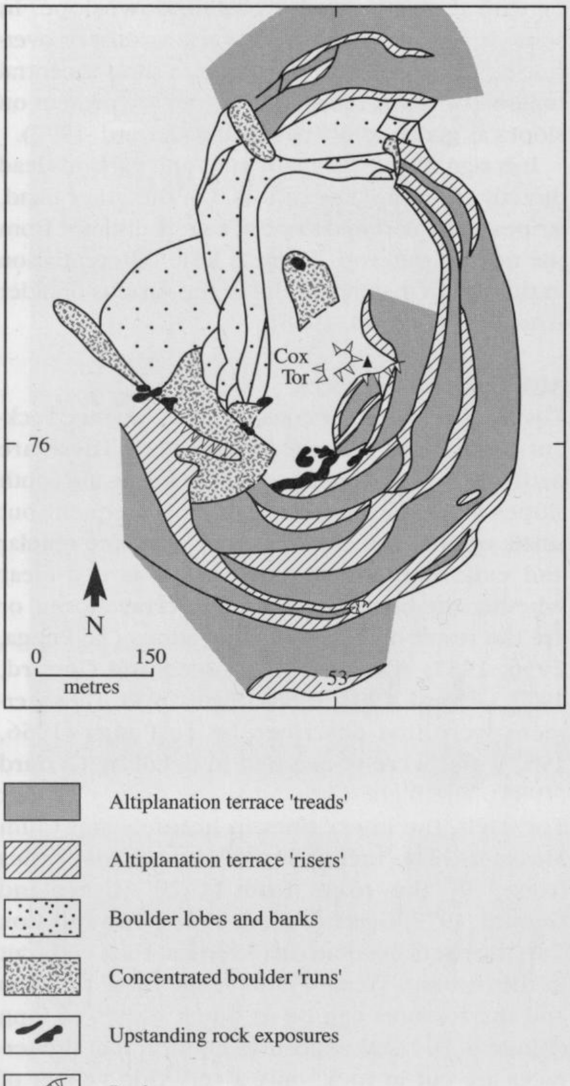

Figure 4.7 The geomorphology of Cox Tor and adjacent areas. (Adapted from Gerrard, 1983.)

(of various shapes, but mostly kite-shaped); 2. 'compound hummocks' (multi-peaked with variable morphology); and 3. 'rock-cored hummocks' (prevalent where clitter reaches the ground surface). The vast majority seem to be composed of a well-drained, fibrous brown loam derived from weathering of the diabase, although some are underlain by large boulders (Green and Gerrard, 1977; Bennett *et al.*, 1996). Whether boulder-cored or not, all exhibit considerable sorting of the soil (Gerrard, 1983).

Weathering products

Two roadside exposures through slope materials occur on the lower slopes of Cox and Staple Tors, respectively (Gerrard, 1983). The exposure adjacent to Staple Tors shows up to 0.4 m of head comprising small weathered granite cobbles and more angular schorl underlain by a light-brown sandy gravel (lower head) with some very large boulders. A similar pattern, that is a coarse head overlain by a finer head, is shown by the Cox Tor exposure, although the materials are different. Here, the finer head exhibits a characteristic downslope orientation of particles (Gerrard, 1983; cf. Figure 4.3).

Interpretation

It has long been accepted that Dartmoor was never glaciated, but that it lay in the periglacial zone beyond the maximum limit of the ice sheets, and was subjected to cryonival processes (e.g. Waters, 1964; Gerrard, 1983). Most workers have therefore argued that significant landform elements and the superficial deposits at Merrivale, and elsewhere on Dartmoor, are primarily the result of periglacial, frost-assisted processes. Although the nature and origin of the decomposed granite (growan) are key factors in understanding the evolution of these landforms and deposits, and have been much disputed (see 'Kaolinization or Tertiary chemical weathering?'; this chapter), it is generally assumed that the tors were exhumed from beneath a weathered or 'softened' mantle mainly by Pleistocene periglacial activity. The close association between the tors, their clitter (blockfields and stone runs), local rock terraces and earth hummocks has been used as evidence that the features were all formed at a comparatively late stage of the Pleistocene by periglacial weathering (Waters, 1964, 1974; Green and Gerrard, 1977; Gerrard, 1983).

Tors

Both of the main models of tor formation explain the 'exhumation' of tors by periglacial stripping. Linton (1955; p. 476) 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 ... '. This two-stage mechanism first involved deep weathering under warm humid conditions (probably during the

Palaeogene) when a thick regolith developed with corestones occurring where the joint planes were most widely spaced. Second, the products of weathering (the regolith) were removed by mass wasting, leaving the corestones as upstanding tors. Linton proposed that the tors were exhumed under periglacial conditions in the Pleistocene when solifluction and meltwater would have been efficient agents in removing the regolith (Figure 4.2).

Alternatively, Palmer and Radley (1961) and Palmer and Neilson (1962) suggested that tors, such as those in the Pennines and on Dartmoor, had formed solely as a result of mechanical weathering under periglacial conditions. Indeed, Palmer and Neilson (1962) doubted the former existence of deep weathering at tor sites, and attributed the known occurrences of deep decomposition (e.g. Two Bridges Quarry) to the effects of pneumatolysis. Waters (1974) went further and suggested that the chronology of tor formation in the Dartmoor area could be related directly to local head sequences. In identifying two head facies (an upper coarse-grained head and a lower finer-grained head), he argued that the principal phase of tor exhumation had occurred during the Wolstonian (Saalian Stage) when a regolith of fine-grained material was stripped from around the tors and redeposited in valley-side and valley-bottom locations as the 'Main Head' (Figure 4.3). A second phase of periglacial activity, during the Devensian Stage, produced the 'Upper Head', much of the clitter now surrounding the tors and reducing the mass of the tors still further. All of these theories, however, involve stripping of weathering or alteration products from around the tors by periglacial mass wasting processes.

Gerrard (1983, 1988) argued that tors, such as those at Merrivale, formed where weathered material (whatever its origin) was removed faster than it was produced. Thus, the tors are found in 'high energy' locations such as steep valley-side slopes, at breaks of slope and on summits where the processes of removal are most efficient (Gerrard, 1983, 1988). He argued that a simple explanation, based on weathering followed by removal, is not adequate to explain the major elements of a granite landscape with tors, and that several possible relationships exist between the rates of accumulation and removal of material. For example, where the ground surface is stable, deepening of the regolith may occur. Where the ground surface is unstable, a gradual removal of regolith is likely. Alternatively, local conditions may promote the renewal and removal of material at similar rates. Thus, these conditions may exist concurrently at different sites and vary in significance through time.

Such thinking is mirrored by Battiau-Queney's (1984, 1987) work in Wales, particularly on tor landscapes in the Preseli and Trefgarn areas (Campbell and Bowen, 1989). Like Linton, she argued that the tors had formed in response to two main factors. First, evidence, particularly from Trefgarn, showed that deep chemical weathering of the land surface had occurred in a hot humid environment (probably during the Palaeogene). Secondly, this weathered mantle had been stripped, but not solely by periglacial processes in the Pleistocene. Rather, the exhumation of the more resistant tors had occurred as the result of protracted uplift along old structural axes throughout the Cenozoic, and not simply because of changing climatic and environmental conditions. Battiau-Queney therefore suggested that the tors were formed in response to slow uplift where subaerial denudation had exceeded (perhaps only locally) the rate of chemical weathering. Consequently, a sharp deterioration of climate was not required to trigger stripping of the weathered regolith. Instead, a closely balanced relationship between persisting local uplift and erosion offered the most conducive conditions for tor formation (Battiau-Queney, 1984, 1987).

Green and Gerrard (1977) suggested that the pattern of vertical and horizontal jointing in the granite of Staple Tors (particularly Great Staple Tor) suggests that some form of 'unloading' mechanism has operated in the past, along a broadly whale-backed ridge of the granite. They argued that the centre of the ridge was probably its weakest part, accounting for the missing portion of the tor.

Clitter

It has been suggested that the Dartmoor clitter (blockfields, stone runs and stripes etc.) was derived from the periglacial demolition of the tors (e.g. Waters, 1964, 1974), and it has long been recognized that frost heaving and thrusting, as well as differential movement downslope, have been involved in its formation. However, the exact origin of the clitter is poorly understood (Gerrard, 1983).

The traditional view that tors and clitter are closely associated is partly borne out by the stone runs and garlands at Merrivale which lead directly from the base of some tors (Gerrard, 1983). However, other boulder accumulations appear to have originated *in situ*. For example, some of the

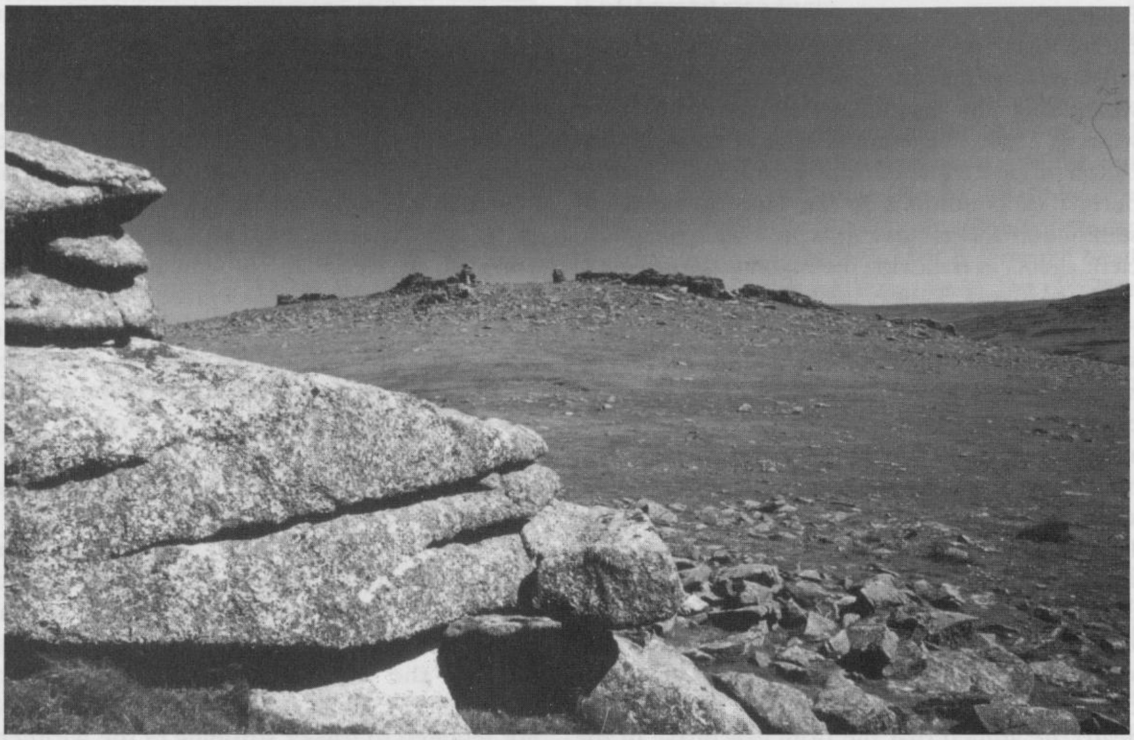

Figure 4.8 Great Staple Tor seen from Middle Staple Tor. The missing central portion or 'avenue' of Great Staple Tor can be seen clearly on the horizon. (Photo: S. Campbell.)

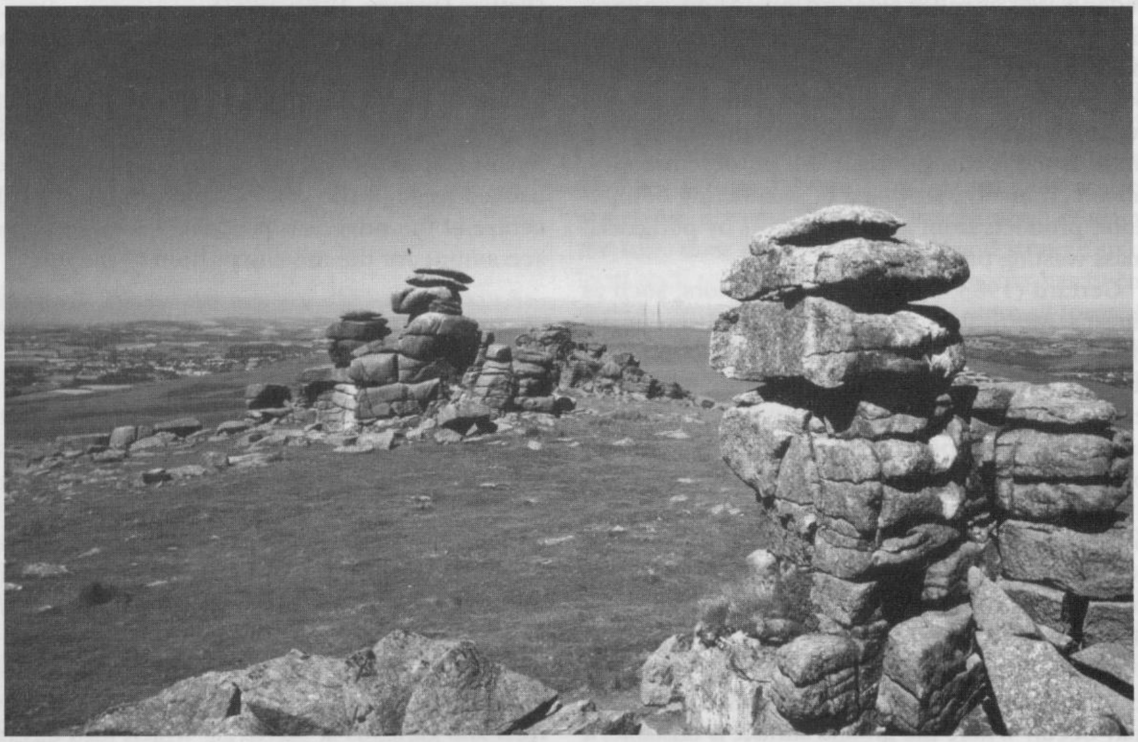

Figure 4.9 Looking west through the 'avenue' of Great Staple Tor. (Photo: S. Campbell.)

Figure 4.10 Great Staple Tor seen from Cox Tor, revealing a diverging anastomosing pattern of boulder runs on the west-facing slopes. (Photo: S. Campbell.)

stone stripes start mid-slope at a great distance from the nearest tor or outcrop. Similarly, many of the blockfields occur towards the base of slopes, suggesting that much of the clitter has not travelled very far, and has therefore originated *in situ* (Green and Eden, 1973; Green and Gerrard, 1977; Gerrard, 1983). The possibility that some of this clitter might resemble protalus ramparts or even rock glaciers must not be discounted (Harrison *et al.*, 1996).

Gerrard (1983) suggested that the size distribution of the boulders was clearly a function of the intensity of jointing in the granite, and therefore that the difference in pattern and arrangement of the boulders was likely to be the result of the relative abundance of blocks: where blocks occur in profusion, blockfields, boulder garlands, lobes and runs might be expected, whereas where fewer blocks are available, stone stripes may be the dominant feature.

Further support for the limited transport of blockfield material comes from the patterns of the constituent boulder long-axes. In the blockfields these show considerable variation, with many boulders being inclined at steep angles often into the slope. In contrast, boulders in the stripes show a dominant long-axis orientation parallel with the steepest local slopes, suggesting greater downslope movement and sorting (Gerrard, 1983). Gerrard tentatively suggested that slope angle was probably not a controlling factor in the distribution of the various boulder (clitter) patterns, since all types occur on slopes of similar angles. Recently, Bennett *et al.* (1996) have re-examined the boulder runs on the west-facing slopes beneath Great Staple and Middle Staple tors (Figure 4.10). Controversially, they have concluded that the runs originated from the erosion of soil in lines, perhaps by ancient springs, to reveal the clitter beneath. In this model, the boulder runs are regarded simply as a function of discontinuous soil cover.

Altiplanation terraces

The benched hillslopes or rock terraces described around Cox Tor (Te Punga, 1956, 1957; Waters, 1962; Brunsden, 1968; Green and Gerrard, 1977; Gerrard, 1983, 1988; Ballantyne and Harris, 1994) closely resemble altiplanation terraces described elsewhere in the world which have been attributed to periglacial conditions (e.g. Demek, 1968; Czudek and Demek, 1970). Altiplanation terraces in the

British landscape were first recognized by Guilcher (1950) who described several examples around the coasts of north Devon. The examples flanking Cox Tor were described in detail by Te Punga (1956) who argued that they closely resembled features currently forming in perennially frozen ground in Alaska (Eakin, 1916; Lewis, 1939). Te Punga suggested that the terraces had formed where snow patches, with their major axes lying transverse to the local pattern of drainage, had eroded backwards and downwards into the hillside by frost-action, leaving a series of pronounced 'treads' and 'risers' (Te Punga, 1956). There could be no doubt, he argued, that the formation of these terraces around Cox Tor (and elsewhere in southern England) was closely associated with perennially frozen ground (permafrost), developed under Pleistocene periglacial conditions. Comparable features were later recognized elsewhere on Dartmoor (Waters, 1962).

The lithological characteristics of the local bedrock were seen as important in the development of the features, particularly for maintaining a sharp shoulder at the margin of the terraces (Te Punga, 1956). Indeed, rock control appears to be crucial, since terraces such as those at Cox Tor and elsewhere on Dartmoor are always found on metamorphic rocks and not on the granite (Green and Gerrard, 1977; Gerrard, 1983): closely spaced joints, and the cleavage and bedding planes found in the former rocks, may have facilitated more effective frost-action. Similarly, Te Punga (1956) noted that variations in hardness of subhorizontally stratified rocks also favoured the development of altiplanation terraces: the features, however, are not restricted to such conditions for they commonly bevel steeply inclined strata and may also be cut in massive homogenous bedrock (Te Punga, 1956).

Te Punga also recorded that the surfaces of the altiplanation terraces in north Devon were closely associated with the occurrence of stone polygons. Indeed, stone polygons were so common on such terraces and adjacent summits elsewhere, that ' ... it may be desirable to regard all areas covered by stone polygons, formed in material derived by periglacial robbing of the underlying bedrock, as altiplanation features' (Te Punga, 1956; p. 337). It was not made clear, however, whether the low earth mounds found on the terraces and flanks of Cox Tor were generically similar (see below).

Earth hummocks

Sharp (1942) first used the term 'earth hummocks' to describe patterned ground characterized by dome-shaped, apparently non-sorted nets or circles. Such features have a circumpolar distribution, and are found in northern Europe, Siberia, Greenland, Iceland and North America (Gerrard, 1983). Comparable features have been described on Ben Wyvis in northern Scotland (Ballantyne, 1986), in the Pennines (Tufnell, 1975) and Cumbria (Pemberton, 1980), and are broadly analogous to the 'thufur' of tundra areas (Ballantyne and Harris, 1994).

Te Punga (1956) likened the small, roughly circular mounds around Cox Tor (Figure 4.11) to the 'high-centred polygons' of high latitudes, and suggested that they had also been formed under periglacial conditions. Gerrard (1983, 1988) argued that there is no evidence to suggest that the features at Cox Tor are forming at the present time, and some are indeed being destroyed. Many of the mounds occur on top of clitter and only formed once the clitter had become stabilized, presumably after the Younger Dryas. Some have been removed by Bronze Age humans during the construction of circular huts in the area. It seems likely, therefore, that the mounds formed at some time between *c.* 9000 and 2000 BP (Gerrard, 1983), although Brunsden (1968) considered that they might be even younger, having formed as the result of spring action dissecting the thick soil cover.

There is considerable doubt, however, as to the mode of formation of the earth hummocks. Although two principal types occur around Cox Tor (boulder-cored and non-boulder-cored, with the latter being dominant), all demonstrate considerable sorting of the soil: the soil of the mounds is consistently finer than that at the same depth in the depressions alongside, and it is thought that frost-heaving is the primary process in their formation (Gerrard, 1983, 1988). Beskow (1935) has shown that frost-heaving is unlikely to occur in soils with less than 30% silt and clay (cf. Williams, 1957; Corte, 1963). Gerrard (1983, 1988) has argued that such requirements may have controlled the distribution of the earth hummocks at Merrivale, restricting the features to the fine silty loam soils derived from the weathering of the Cox Tor diabase, and excluding their development on adjacent granitic soils which are generally deficient in the silt and clay grades. Recent work by Bennett *et al.* (1996) has confirmed this fundamental relationship between soil type and hummock distribution. It is interesting that such hummocks occur all along the western edge of Dartmoor where similar rock types exist.

Most authors seem to agree that earth hum-

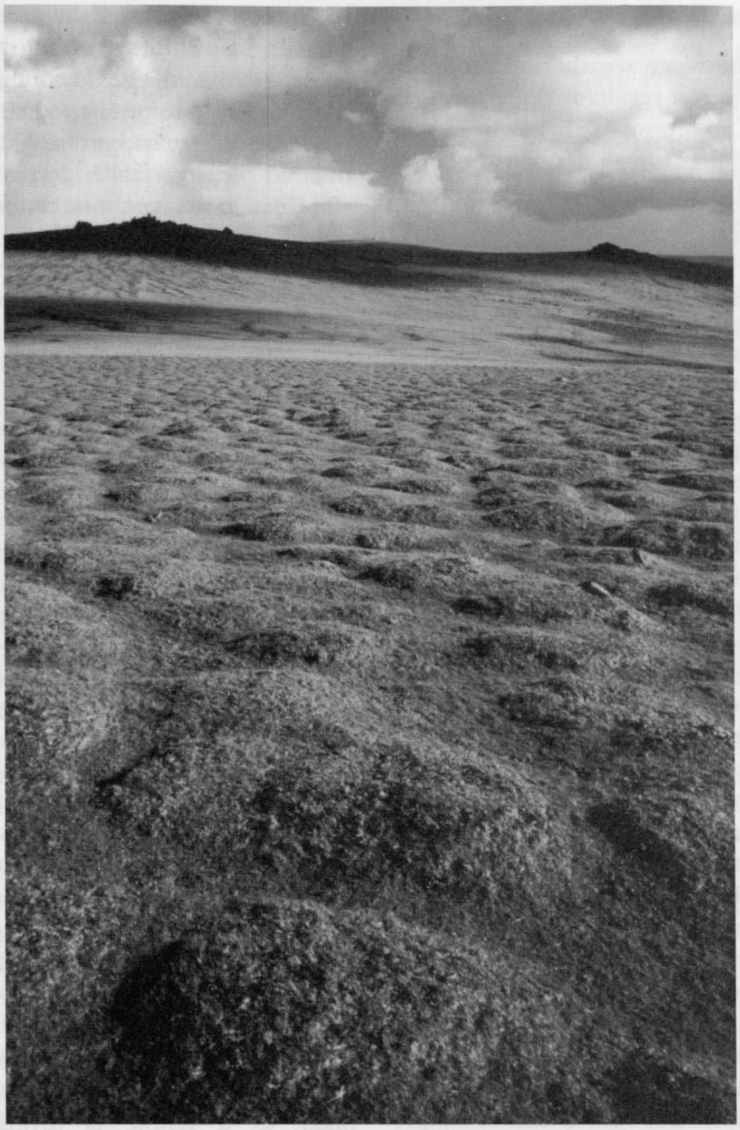

Figure 4.11 A profusion of earth hummocks on the east-facing slopes of Cox Tor, with Great Staple Tor and Middle Staple Tor on the horizon. (Photo: S. Campbell.)

mocks are formed by frost-heaving, caused by uneven ground freezing and thawing, although the specific mechanisms involved are disputed (Ballantyne and Harris, 1994). The main problem in understanding the genesis of these small-scale landforms, however, is establishing how the initial micro-relief forms. Once the mounds are created, their vegetation cover may afford better insulation than the intervening water-soaked areas where freezing is likely to occur first: this differential freezing may set up pressures forcing material inward and upward into the hummocks, causing them to 'grow' (Beskow, 1935; Gerrard, 1983, 1988; Bennett *et al.*, 1996). Although a variety of mechanisms has been suggested which would produce the initial micro-relief, for example, hillwash, soil movement, wind deposition and differential vegetation growth in clumps (Gerrard, 1983; Bennett *et al.*, 1996), the exact mode of formation of the mounds is largely conjectural (Green and Gerrard, 1977; Ballantyne and Harris, 1994; Bennett *et al.*, 1996): all that can be said with any certainty is that the mounds are fossil features which appear unrelated to present conditions (Gerrard, 1983, 1988). Bennett *et al.* (1996) provide a comprehensive review of the earth hummocks at Merrivale, and discuss possible modes of formation.

Weathering products and slopes

The relationships between weathering products, solifluction deposits and resultant slope forms in the Merrivale area are complex. It has been suggested that two different head deposits occur in the Dartmoor area, namely a lower fine-grained deposit and an overlying coarse-grained sediment – both periglacial solifluction deposits (e.g. Waters, 1964, 1974; Mottershead, 1976). Such a sequence of head deposits has been taken to reflect an inversion of a normal granite weathering profile, that is, with finer-grained weathering products removed from upper slopes during an initial periglacial phase, and subsequently redeposited on lower slopes and in valley bottoms; and with a subsequent phase of periglacial activity removing large, sound blocks from tors and other surface exposures, and depositing them on top of the finer-grained head materials (Figure 4.3). Green and Eden (1973) challenged this view and demonstrated that much of the coarse debris actually occurs in the lower parts of the head sequences, and has been derived from proximal basal sources and not from more elevated and distant rock outcrops. It is likely, therefore, that the head deposits are derived from many parts of the slope and that an inversion of weathering profiles will only have occurred in localized situations (Green and Gerrard, 1977; Gerrard, 1983).

Gerrard (1982, 1983, 1989a) has presented detailed evidence from head sequences throughout Dartmoor to show that initial weathering profiles were probably more complex than hitherto thought, and that periglacial processes led to a substantial mixing of materials, rather than to simple re-sorting. Indeed, in 47 exposures across Dartmoor, Gerrard (1982, 1989a) has shown that the relationship between the coarse- and fine-grained facies is complex, with both layers often being intermixed and with large blocks of granite occurring throughout the beds. He argued that significant mixing of materials has therefore occurred, with gullies having been cut and infilled at different times, showing complicated sequences of slope modification rather than simple reworking of weathered granite. The Merrivale exposures may therefore be somewhat atypical in showing 'coarse' head overlain by 'fine' head, and exposures elsewhere show that the distribution and characteristics of solifluction deposits are far more complex.

In conservation terms, Merrivale provides an outstanding assemblage of the landforms characteristically developed on the granite intrusions and adjacent aureole rocks of upland South-West England. While the broad configuration of the area, with its large dome-shaped ridge of granite bordered by valleys, had probably been established by the mid-Tertiary, smaller details of the local slopes, altiplanation terraces, tors, clitter and slope deposits reflect the operation of periglacial processes throughout the Pleistocene. The Pleistocene periglacial legacy to the Dartmoor landscape has been substantial and Merrivale illustrates many of the key features of its periglacial geomorphology. The tors and clitter are some of the very finest examples anywhere in Britain: the Staple Tors and Roos Tor demonstrate, particularly clearly, the relationship between bedrock lithology and structure and tor morphology and development. The clitter shows a remarkable variety of forms (blockfields, stone stripes, stone runs and garlands), and its distribution and characteristics have a considerable bearing on processes of slope development, and on the origin of the tors themselves.

The Cox Tor area of Merrivale shows some of the finest altiplanation terraces in southern Britain and some of the most convincing evidence for cryoplanation: the Cox Tor examples are also of historical significance since they were the subject of the first detailed exposition of altiplanation terraces in the British landscape (Te Punga, 1956). The superb and profusely developed earth hummocks in this area also add significantly to its scientific interest, although their precise age and origin are still far from clear.

While the individual landforms are exceptional and worthy of special note, the landform assemblage as a whole is probably unparalleled elsewhere in Britain. In particular, Merrivale provides an outstanding assemblage of interrelated landforms which illustrate many of the most significant theories of long-term and, especially, periglacial landscape evolution in southern Britain.

Conclusion

Merrivale is one of Britain's most important sites for understanding the development of granite landscapes. When the Dartmoor granite was intruded into the surrounding 'country' rocks about 290 million years ago, it altered them profoundly, and the wide range of landforms now seen at Merrivale in part reflects differences in rock type and local geological structure: the Staple and Roos tors are granite landforms of textbook quality, showing clearly how tors have developed in relation to the pattern and density of jointing in the host rock. In contrast, the more angular outlines of Cox Tor reflect the nature of its constituent rocks, in particular the markedly different reaction of the diabase to protracted weathering. Cox Tor is surrounded by arguably the finest 'altiplanation terraces' in Britain, a 'staircase' of horizontal benches cut back into the rock by freeze-thaw processes at a time when perennial snow patches were present on Dartmoor. The siltier soils of the Cox Tor area have given rise to one of the best British examples of 'earth hummocks', controversial landforms of disputed age and origin, although almost certainly formed by frost-assisted processes in the Late Devensian. Many of the landforms at Merrivale – the large accumulations of loose rock or 'clitter', the altiplanation terraces and earth hummocks – owe their origin to a range of cold-climate processes which operated during the Quaternary. Frost-shattering of local rocks, the repeated contraction and heaving of the ground surface as it alternately froze and thawed, and the downslope movement (solifluction) of weathered materials over frozen ground (permafrost) all gave rise to characteristic landforms now seen in fossil form today. Merrivale is also important because some of the landforms, such as tors, may have begun to form well before the Pleistocene ice ages of the last two million years or so – perhaps as far back as the early and mid-Tertiary, when subtropical or even tropical conditions may have prevailed. Merrivale is unique in showing such a wide range of landforms in a small area, and provides important evidence for understanding how landscapes evolve over timescales of many millions of years.

BELLEVER QUARRY
S. Campbell

Highlights

A reference site demonstrating the relationship between slope deposits and granite weathering products on Dartmoor, Bellever Quarry provides particularly detailed evidence for the origin of 'bedded growan' deposits.

Introduction

Bellever Quarry is of considerable geomorphological interest for its related assemblage of periglacial slope deposits and granite weathering features, which are considered typical of many Dartmoor slopes. The generic relationship between the intact, relatively unaltered, granite here and the overlying weathered granite (growan), 'bedded growan' and periglacial head deposits is graphically illustrated, and has long attracted scientific interest (Waters, 1961; Brunsden, 1964, 1968). A detailed description and interpretation of the sequence at Bellever Quarry by Green and Eden (1973) has major implications for theories of slope development throughout the region (Te Punga, 1957; Waters, 1964; Mottershead, 1971; Green and Gerrard, 1977; Cullingford, 1982; Cresswell, 1983; Gerrard, 1983, 1989a).

Description

Bellever Quarry (SX 658763), sometimes known as Lakemoor or Laughter Quarry, lies on the lower slopes of the East Dart Valley in the Bellever Plantation, approximately midway between Riddon Ridge and Laughter Tor. It exposes granite, weathered granite and overlying slope deposits in one main face and several other less extensive and more overgrown faces. The stratigraphic sequence is as follows:

4. 'Head' consisting of granite clasts set in a coarse matrix of growan (up to 1.5 m)
3. Disturbed weathered granite ('bedded growan') (up to 1.0 m)
2. *In situ*, undisturbed, weathered granite or growan (> 2.0 m)
1. Intact, relatively unaltered granite

The head (bed 4) shows a concentration of clasts in its lower layers, but there is no indication that the bed should be divided on this basis (Green and Eden, 1973). The disturbed weathered granite (bed 3) shows colour bands which are conspicuously overturned in a downslope direction (Figure 4.12). The apparent layering is related to colour as well as textural variations, and can be traced into both beds 1 and 2. It is believed to be related to a zone or vein of tourmalinization (Green and Eden, 1973; Green and Gerrard, 1977). The amount of lateral displacement of individual layers relative to one another is only a few millimetres at *c.* 2 m depth below the top of the bedded growan (bed 3), but increases upwards in the profile (Green and Eden, 1973) The *in situ*, undisturbed, weathered granite or growan (bed 2) both overlies intact granite (bed

Figure 4.12 Granite alteration products and slope deposits at Bellever Quarry being examined during the 1977 INQUA trip to the South-West. (Photo: N. Stephens.)

1) and is juxtaposed between bosses or stacks of the relatively sound rock (cf. Two Bridges Quarry).

Interpretation

The first detailed work at this site is attributable to Brunsden (1968), who used evidence from various sites, including Bellever Quarry, to devise a classification of weathering zones found in the Dartmoor granite (see Kaolinization or Tertiary chemical weathering?; Two Bridges Quarry). The Bellever Quarry section showed most of the different weathering types proposed: from relatively intact granite with corestones, showing only partial decomposition along joints; through well-rotted, incoherent granite still showing details of the original rock structure; to undisturbed, stained, weathered granite containing much quartz, but displaying no detail of any previous structure. In addition, the sections showed evidence for soil creep (bed 3; the 'bedded growan' of later workers) as well as a capping layer of head, Brunsden's 'migratory layer'. Sites like Bellever Quarry were used by Brunsden to demonstrate that pneumatolytic alteration, deep chemical weathering and physical, frost-assisted processes had all affected the Dartmoor granite, and that evidence for all three could be found in individual profiles.

Although disturbed weathered granite (bedded growan) is not always present between the *in situ* weathered granite and the overlying head on Dartmoor, it is common on many slopes and some interfluves (Green and Eden, 1973). Waters (1964) attributed its bedded appearance to downslope wash or creep, hence the term 'bedded growan': he appears to have favoured surface wash as the most likely agent in its formation (Waters, 1971; Green and Eden, 1973).

Green and Eden (1973) re-examined the bedded growan from a number of sections on Dartmoor, including those at Bellever Quarry. They showed that, in composition, the material is similar to the underlying undisturbed and *in situ* growan, despite the frequent colour banding and appearance of downslope bedding. They concluded that its general characteristics are not consistent with an origin as a surface-wash deposit. In studying the relationships of local head sequences and clitter patterns to the bedded and *in situ* growan deposits, Green and Eden surmised that the movement of the bedded growan had been contemporaneous with that of the overlying periglacial head: namely that the bedded growan was not a pre-existing surface deposit derived from upper slope source areas. In support of their claim they cited evidence for superficial layers having passed over and displaced underlying *in situ* material elsewhere (e.g. Penck, 1953; Fitzpatrick, 1963; Jahn, 1969).

The relationship between the periglacial slope deposits and the weathered granite established by Green and Eden (1973) at Bellever Quarry and other sites is significant. Formerly, slope deposits on Dartmoor were considered to have developed under periglacial climatic conditions, when successive layers of the pre-existing weathered profile were removed from the upper parts of slopes and deposited in the reverse order on lower slopes – the 'inversion' theory of Waters (1964) (Figure 4.3). Such a mechanism also found favour with other workers (e.g. Te Punga, 1957; Brunsden, 1964, 1968), and was the basis for a simple model of slope development. It was noted that

'The rapid wasting away of the land surface during periglaciation, due to the transportation of enormous quantities of material to lower levels, has produced a landscape of subdued aspect characterized by slopes that are convex near the top and concave near the bottom. The convex upper slope has been a zone of wastage and the concave lower slope has been a zone of deposition.' (Tricart, 1951; p. 196; Te Punga, 1957; p. 410).

The evidence presented by Green and Eden, derived substantially from Bellever Quarry, is vital for demonstrating that this slope transfer and inversion model is not generally applicable. These workers have argued that such inversions are rarely the norm, and that the processes responsible for the formation of slope deposits have included the erosion of substantial amounts of underlying material (ranging from large granite blocks to fine-grained growan) and its incorporation into the transported layer on all parts of the slope. Even on lower slopes, as at Bellever Quarry, the movement of slope deposits (head) appears to have been accompanied by the erosion of the underlying weathered granite.

On the basis of this evidence, it was possible to dispel two long-held notions: first, that slopes could be divided into simple 'source' and 'accumulation' areas; second, that there had been a widespread inversion of the pre-existing weathering profile (Green and Eden, 1973; Green and Gerrard, 1977). Waters' (1964) suggestion that transfers of material downslope during successive cold phases had led to a typical three-fold succession overlying the weathered granite, namely the bedded growan, the 'main head' and the 'upper head' (Figure 4.3), was therefore shown to be untenable on Dartmoor, and any widespread evidence for two separate layers of head was refuted (Green and Eden, 1973). A comparable study by Mottershead (1971), on head deposits overlying schist in south Devon, similarly failed to confirm the applicability of Waters' model. Recent studies by Gerrard (1982, 1983, 1989a) have further highlighted the complex relationships between the types of slope deposit and weathering products found in the region. He confirmed that considerable mixing of materials had taken place, with gullies being cut and infilled at various times, and he showed that complicated sequences of slope modification rather than a simple reworking of weathered granite had occurred.

Conclusion

Bellever Quarry provides particularly strong evidence to demonstrate that the bedded growan of Dartmoor did not accumulate at the ground surface, but instead formed beneath periglacial head deposits while they accumulated. Such evidence has profound implications for models of slope development in the region. Both Two Bridges and Bellever quarries provide significant evidence for the numerous arguments regarding the origin of the decomposed granite on Dartmoor, and its relevance to landscape evolution, and particularly tor formation. Whereas Two Bridges Quarry has become almost pre-eminent in such debates, Bellever Quarry provides complementary evidence, and is fundamental to understanding mechanisms of slope development, and especially the relationships of slope deposits (principally periglacial head) to the underlying granite weathering/alteration products.

TWO BRIDGES QUARRY
S. Campbell

Highlights

Two Bridges Quarry provides an excellent example of the 'decomposed' Dartmoor granite, and is one of the best sites in Britain for understanding the formation of tors.

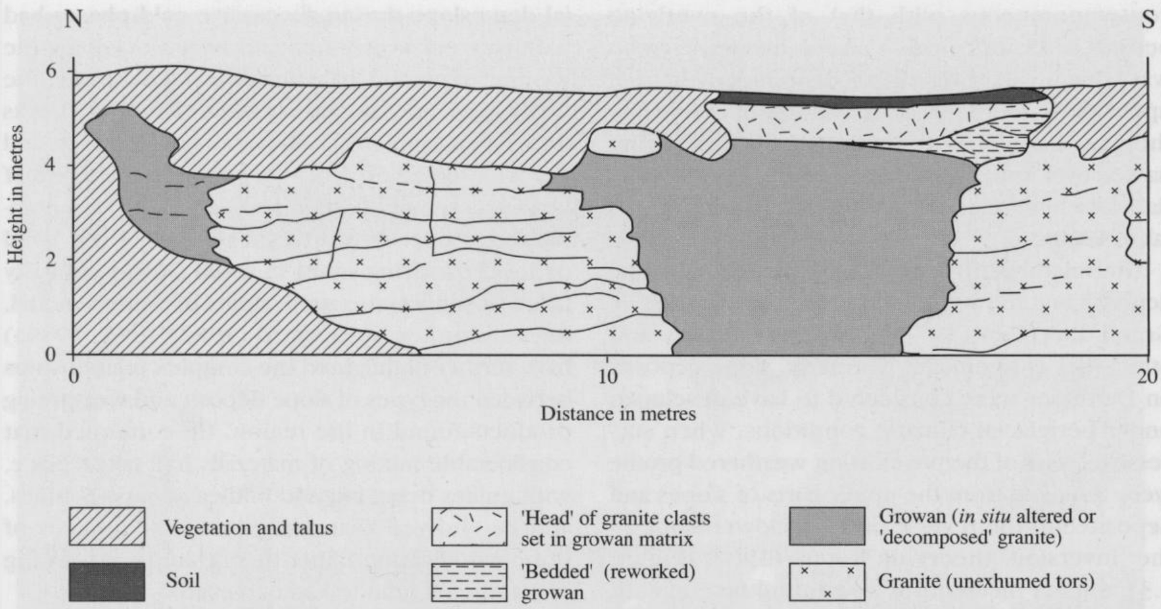

Figure 4.13 A cross-section through the granite and associated alteration products at Two Bridges Quarry, Dartmoor, adapted from Campbell (1991).

Introduction

Two Bridges Quarry is one of the most important geomorphological sites in South-West England, and is particularly noted for its association with D.L. Linton's classic theory of tor formation (Linton, 1955). The site shows heavily decomposed granite juxtaposed with masses of harder, less altered granite, and was used as a field model by Linton to illustrate the first stage of tor formation by differential weathering. The site has also featured widely in subsequent studies supporting, challenging or modifying Linton's model (e.g. Palmer and Neilson, 1962; Brunsden, 1964, 1968; Gregory, 1969; Green and Eden, 1971, 1973; Eden and Green, 1971; Green and Gerrard, 1977), and the roles of pneumatolysis (alteration of the granite by mineralizing fluids from deep within the Earth), subsurface chemical weathering and physical weathering by frost-action, in the formation of the altered granite (growan) have all been examined using evidence from this site (e.g. Doornkamp, 1974; Dearman and Baynes, 1978; Cullingford, 1982; Durrance and Laming, 1982). A summary of the site's scientific importance and conservation value was given by Campbell (1991).

Description

Two Bridges Quarry (SX 609751) lies near Princetown on Dartmoor, and *c.* 6 km east of Merrivale. The floor of this small disused quarry is now occupied by a car park, but the curved working face (*c.* 20 m long by 6 m deep) still provides an excellent section through the granite and associated weathering products (Figure 4.13). Both ends of the exposure are occupied by relatively solid and intact masses of grey, coarse-grained granite, including intrusions of fine-grained aplite (Green and Gerrard, 1977; Dearman and Baynes, 1978). The largest of these masses (to the north) measures some 6 m wide by 4 m deep: it shows both vertical joints (at *c.* 1–2 m intervals) as well as subhorizontal sheet jointing or 'pseudo-bedding' (at *c.* 0.5 m intervals).

Growan or decomposed granite, up to 6 m in thickness, occurs between the more coherent granite masses (Figures 4.13 and 4.14). Thin quartz-tourmaline veins are present in this material: the structure of the original granite is undisturbed and the primary rock-forming minerals are readily identifiable (Green and Gerrard, 1977). This pattern, however, breaks down within *c.* 1 m of the ground surface. Here, the growan is

Figure 4.14 The section at Two Bridges Quarry, showing large intact granite masses, the unexhumed tors and adjacent deeply altered granite. (Photo: S. Campbell.)

commonly mixed with large angular granite clasts (head) and, in one or two places, the growan shows colour banding which indicates downslope bedding.

Interpretation

Linton (1955) regarded the growan at this pit as the product of subaerial chemical weathering, and the masses of more solid rock as unexhumed tors. Indeed, he considered that the field evidence from Two Bridges Quarry showed that the Dartmoor tors, in general, had formed in response to differential sub-surface weathering, with the decomposed granite (growan) having formed as the result of deep weathering by percolating groundwaters under warm conditions in the late Tertiary (the Neogene). This, he argued, developed a thick regolith with corestones occurring only where joint planes were widely spaced and where the granite was least susceptible to chemical alteration (Figure 4.2). The products of this weathering (the regolith or growan) were subsequently stripped by mass-wasting, probably by periglacial processes in the Pleistocene. Two Bridges Quarry was therefore fundamental for demonstrating an *in situ* example of the selective, deep chemical weathering necessary in Linton's model of tor formation: in most of the more exposed locations the weathering products had subsequently been removed, destroying the critical association of weathered and non-weathered rock.

Palmer and Neilson (1962) disagreed, and related the breakdown of the granite at Two Bridges Quarry (and elsewhere) to pneumatolytic processes, arguing that the decomposition was not a prerequisite for tor formation. They argued that the tors had evolved in response to Pleistocene periglacial processes, and that granite had been removed from around the tors by physical frost-shattering and solifluction. A principal line of reasoning was that the altered granite material was found in valley bottoms and not around the tors themselves.

Alternatively, Brunsden (1964, 1968), also using evidence from Two Bridges Quarry, argued that characteristics of all three forms of rock alteration and breakdown (subaerial chemical weathering, pneumatolytic alteration and physical breakdown) could be found together at individual sites on Dartmoor. He argued that the bulk of evidence from Two Bridges Quarry showed that the decomposed granite there had originated from chemical weathering, most of the weathered deposits belonging to the 'pallid zone' in his classification (see Kaolinization or Tertiary chemical weathering?). He cited, in particular, the pronounced eluviation of clay minerals (found coating joint faces lower in the profile) and the progressive stages of physical disintegration shown by the deposits, and the spheroidal weathering and grus formation found in the lowest parts of the section adjacent to the corestones and 'solid' rock (Brunsden, 1964). Since some of the joint faces are marked by thin veins of tourmaline (cf. Green and Gerrard, 1977), the sections at Two Bridges also probably show evidence for pneumatolytic alteration. However, Brunsden suggested that tourmalinization could only be confirmed if the zone of decayed granite increased and widened with depth, if a widespread cover of solid unaltered granite could be proven and if there was an upward decrease in the frequency of alteration products. Since the depth and extent of alteration at Two Bridges Quarry (and elsewhere) cannot be seen, the role of pneumatolysis remains uncertain in this instance.

The evidence for physical processes in the profile at Two Bridges Quarry, however, was believed to be more sound (Brunsden, 1964): the weathering profile was capped by a thin, 'migratory' layer of head (Brunsden, 1968), and the observed leaching of minerals in solution and the eluviation of clays was also seen as consistent with frost-assisted physical weathering (Brunsden, 1964).

Eden and Green (1971) undertook a detailed mineralogical and grain-size study of the growan at Two Bridges Quarry and from comparable sites elsewhere on Dartmoor. They concluded that the growan was in fact characterized by a relatively low silt and clay content and by a high feldspar residue. These findings were not in keeping with those of Brunsden (1964) who had argued, partly on the basis of the evidence from Two Bridges Quarry, that the granite was 'well rotted' and 'incoherent' and consisted of as much as 90% quartz residue. Neither was there evidence, according to Eden and Green, for the leaching and eluviation of weathering products claimed by Brunsden. Instead, they argued that the high feldspar content and persisting rock texture of the growan showed that there had been only slight chemical weathering and a limited removal of weathering products: the low clay content of the growan was attributed to limited weathering rather than to leaching and eluviation. Although some translocated clay could be found in the profile near the ground surface and along joint planes, they argued that this had originated from the pedogenic zone since there was little evidence for its translocation deeper within the growan profile (Eden and Green, 1971). In conclusion, Eden and Green suggested that the growan at Two Bridges Quarry was only moderately decomposed, contrasting markedly with the alteration products caused by pneumatolysis (kaolinization) found elsewhere in the region. As such, they argued that it was unlikely that the growan had formed in the hot, humid environment perhaps implied by Linton (1955). Rather, it may have originated under conditions somewhat warmer than at present, perhaps akin to a 'meso-humid subtropical climate'.

Further detailed work was carried out at Two Bridges Quarry by Doornkamp (1974) and by Dearman and Baynes (1978). Doornkamp studied the micro-morphological characteristics of detrital quartz grains taken from head deposits, bedded growan and *in situ* growan at the site, and from other locations on Dartmoor. He demonstrated that only the growan material at Two Bridges Quarry showed significant evidence for chemical alteration, most of the deposits elsewhere were strongly affected by the processes of mechanical weathering. Indeed, the various facies of head deposits could not be distinguished on the basis of quartz grain micro-morphology, and even the bedded growan and *in situ* growan at most sites showed similar quartz grain surface features dominated by mechanical weathering. Quartz grains from the growan at Two Bridges Quarry, however, showed quite different characteristics, with solutional and etch features highly indicative of chemical weathering in a more humid and hotter environment than that found on Dartmoor today (Doornkamp, 1974).

He concluded that the evidence of chemically decomposed granite in Two Bridges Quarry alone could be construed to support Linton's hypothesis that a climate of a 'more tropical' nature had occurred on Dartmoor, and that it effectively produced a sub-surface differential weathering of the granite (Doornkamp, 1974; p. 81). Such evidence also supported Eden and Green (1971) who had concluded that there were only relatively few present-day remnants of any pre-existing widespread cover of a chemically weathered mantle. Either, most of this regolith had been removed during the Pleistocene or, more likely, the deep weathering described by Linton had been much more localized in the first place (Eden and Green, 1971; Doornkamp, 1974). A cautionary note should, however, be added: Doornkamp admitted that the evidence from Scanning Electron Microscopy (SEM) was probably insufficient to differentiate between the products of chemical weathering under a hot humid climate, and the effects of metasomatic (hydrothermal/pneumatolytic) alteration.

Dearman and Baynes (1978) further attempted to distinguish the relative effects of hydrothermal alteration, chemical weathering and frost-shattering on the formation of the rotten granite on Dartmoor, and also used evidence from Two Bridges Quarry. By mapping the distribution of equal intensities of granite decomposition at a number of sites, Dearman and Baynes constructed a model to allow differentiation between chemical weathering (characterized by an overall increase in intensity upwards to the ground surface) and hydrothermal alteration (characterized by an even distribution of alteration products with depth) at any given outcrop.

At Two Bridges Quarry, they demonstrated that only small proportions of the granite had been weathered to grade D in their engineering classification, most of the *in situ* growan belonging to their grade C. Since decomposition of the granite could therefore be demonstrated to increase in intensity upwards, they argued that the origin of the growan was attributable, at least partly, to chemical weathering. However, the precise structural controls on the extent and distribution of chemical weathering, like veins and joints, were also those which had controlled the original distribution of the hydrothermal alteration. Thus, although a dominant set of characteristics (chemical weathering or hydrothermal alteration) could be determined for any given profile, the precise contribution of each in exposures like those at Two Bridges Quarry, where both were believed to be present, was very difficult to ascertain (Dearman and Baynes, 1978). These workers also noted that nearly all of the granite weathering products (head, bedded growan and *in situ* growan) at the site had been substantially affected by frost-action, tending to support Brunsden's earlier argument.

Evidence from Two Bridges Quarry has important implications for landscape evolution in the Dartmoor region and, particularly, a major bearing on the genesis of granite landforms including tors. According to Eden and Green (1971) and Green and Gerrard (1977), it is clear that the growan at Two Bridges closely resembles, and is indeed typical of, weathered granite found elsewhere on Dartmoor and in other parts of Europe. The material is quite unlike the products of pneumatolytic alteration also present on Dartmoor and which are quarried from the southern part of the moor as china clay (Green and Gerrard, 1977). It is significant that substantial depths of the growan are confined, apparently, to the present-day valleys: they are not found on interfluve summits, and this condition may be the principal determinant in the distribution and formation of the tors themselves which are also found in similar locations and not on plateaux surfaces or the higher interfluves (Eden and Green, 1971; Green and Gerrard, 1977).

Although the general principle of a two-stage mechanism in the formation of tors was accepted by Eden and Green, they argued that the weathering process on Dartmoor was likely to have been much less effective and widespread than previously envisaged. Linton (1955), for example, implied the previous existence of weathered granite (growan) up to 20–30 ft (6–9 m) in thickness on Dartmoor, from which the tors were subsequently exhumed. Since the extensive plateaux surfaces of the region are largely devoid of tors and growan, it would appear likely that the weathering process was indeed more localized. Eden and Green (1971) argued that the tors had been exhumed from a sandy and not clayey weathering zone located principally in or adjacent to the main river valleys. These authors also recognized that many of the Dartmoor tors had been exhumed and modified by periglacial processes.

Two Bridges Quarry has furnished evidence for all the theories put forward to explain the altered or decomposed granite or growan of Dartmoor. As such, it is a key site for the understanding of long-term landscape evolution in the region, and holds one of the principal keys to explaining the origin, long-debated, of local and other British tors. There is no doubt that the origin of the decomposed granite on Dartmoor is critical to understanding how tors, such as those at Merrivale, formed. Two Bridges Quarry shows a profile considered by some to be typical of the Dartmoor growan, and one which has been used by many workers to demonstrate proposed mechanisms for granitic decomposition including chemical weathering, pneumatolytic alteration as well as physical disintegration and weathering. Since the weathering products at Two Bridges Quarry are closely juxtaposed with more intact granite masses, which strikingly resemble unexhumed tors, the site has become a reference locality in theories of tor formation and granite landscape evolution. However, it must be stressed that the quarry does not provide a three-dimensional picture. The latest evidence from the site is probably the most convincing and suggests that weathering of the Dartmoor granite was selective and that it probably occurred under a warm and mildly humid climate. Major difficulties still remain, however, in assessing the relative effects of hydrothermal alteration and chemical weathering where they occur together in one section. Although the granite alteration scheme recently proposed by Floyd *et al.* (1993) for the St Austell Granite does not aid in this discrimination, it does provide an appropriate model and time-frame for geomorphologists working on the evolution of granite terrains and landforms.

Whereas nearby Merrivale exhibits one of the finest assemblages of tors (and associated periglacial landforms) anywhere in Britain, it does not provide the detailed juxtaposition of sedimentary evidence necessary to elaborate and test theories of the longer-term aspects of tor formation: this is provided at Two Bridges and Bellever quarries. Although these quarries share some common characteristics, the evidence is complementary, and Bellever Quarry provides an altogether different insight into the geomorphological evolution of Dartmoor, showing particularly detailed evidence for periglacial slope processes and head formation. Together, these sites form a network indispensable to any detailed reconstruction of long-term geomorphological evolution.

Conclusion

Two Bridges Quarry is one of the most important sites in Britain for understanding processes of granite alteration. The site shows relatively sound, unaltered masses of granite surrounded by softer, decomposed granite or growan. This association of rock and alteration products was central to D.L. Linton's proposal that many British tors had formed by differential chemical weathering of the granite in the Tertiary, followed by a stripping of the weathering products by periglacial processes in the Pleistocene. Many of the subsequent studies which have either challenged or modified Linton's classic theory, have also used Two Bridges Quarry as critical field evidence. In particular, the site has been central in establishing the relative rôles played in alteration of the granite by pneumatolysis (alteration by mineralizing fluids from deep within the Earth) and chemical and physical weathering processes. The importance of Two Bridges Quarry, in conservation terms, can be summed up simply: its 'embryonic' tors juxtaposed with granitic alteration products will remain central to debates on the origin of British granite terrains and landforms.

DEVENSIAN LATE-GLACIAL AND HOLOCENE ENVIRONMENTAL HISTORY

J. D. Scourse

Introduction

This section introduces GCR sites located on the granite moorlands of Bodmin Moor (Hawks Tor and Dozmary Pool) and Dartmoor (Blacklane Brook and Black Ridge Brook). These four sites were selected because they demonstrate the most complete and detailed records of Devensian late-glacial and Holocene environmental history in these areas. They are effectively regional representatives in a national GCR site network designed to illustrate the most salient features of British Devensian late-glacial and Holocene environmental change.

With the exception of the Somerset Levels (Chapter 2), the environmental history of South-West England during the Devensian late-glacial and Holocene is perhaps less well understood than that of other areas in the British Isles. This partly reflects a lack of suitable depositional basins in which sediments from this time interval could accumulate. This is especially true of the granite moorlands, and is at least partly because large areas were never glaciated. In contrast, other areas of the British Isles north of the Devensian maximum glacial limit (Figure 2.3) are characterized by more profuse erosional (e.g. cirque) and depositional (e.g. kettle hole) basins in which both Devensian late-glacial and Holocene sedimentation occurred. Depositional basins yielding palaeoenvironmental data from this part of the Quaternary in South-West England, by contrast, consist generally of topogenous or soligenous mires, or are the sites where lakes developed in hollows on granitic bedrock. The most critical sites of this age in the region are, as a result, mostly confined to areas of granite bedrock on Bodmin Moor, Dartmoor and the Isles of Scilly. It should be noted that these areas are characterized by acidic soils, with Bodmin Moor and Dartmoor providing the highest relief of the region. The palaeoenvironmental records from sites in these areas should therefore be interpreted in the light of local edaphic and physical controls, and should not necessarily be regarded as being indicative of typical regional conditions.

Despite the uneven distribution and context of the most important localities, the GCR sites across South-West England together provide a comprehensive coverage of Devensian late-glacial and Holocene environmental history. These mire and lake sediments have yielded pollen and plant macrofossil data critical in vegetational reconstruction, and some have yielded diatom data which have enabled assessments of temporal changes in water chemistry. All the selected sites have been calibrated by the radiocarbon method. These data together enable a continuous record of climate, vegetational and environmental change to be reconstructed for the past 13 000 years.

No organic deposits are known in the region which date from between 21 000 to 13 000 BP, the full-glacial phase of the Late Devensian. The earliest record for the Devensian late-glacial is provided by Hawks Tor on Bodmin Moor (Conolly *et al.*, 1950; Brown, 1977, 1980) where the classic tripartite stratigraphy of the Devensian late-glacial was first identified in Britain. The study published by Conolly *et al.* (1950) was actually undertaken during the late 1930s and early 1940s prior to the identification of the Allerød event (Windermere Interstadial) at Windermere (Pennington, 1947) and at Flitwick (Mitchell, 1948): their study allowed correlation with better-established Devensian (Weichselian) late-glacial sequences in Ireland, Germany and southern Scandinavia, and made Hawks Tor a 'landmark' in the development of pollen biostratigraphy in Britain.

Although the Holocene record at Hawks Tor is incomplete, the Devensian late-glacial sequence there is undoubtedly the finest known in the region. Pollen and plant macrofossil evidence from the site indicates the presence of arctic-montane species prior to 13 000 BP (Older Dryas) at a time of active solifluction. The climatic amelioration of the Allerød (Windermere Interstadial) led to the development of birch woodland in sheltered valleys. The succeeding Younger Dryas (Loch Lomond Stadial) saw a reversion to active solifluction with arctic-montane species flourishing in an open, treeless environment. This record is important in demonstrating the relative paucity of the interstadial vegetation here in comparison with other sites in southern Britain at lower altitudes and on more base-rich soils, and in registering the severity of periglacial processes during the Younger Dryas: this implies a degree of continentality in marked contrast to the present oceanic climate.

More complete Holocene records are preserved in sediments at nearby Dozmary Pool (Conolly *et al.*, 1950; Brown, 1977) and at Blacklane Brook (Simmons, 1964a; Simmons *et al.*, 1983; Maguire and Caseldine, 1985) on Dartmoor. Both sites occur on upland granite characterized by acidic soils, but Blacklane Brook (457 m OD) lies at a considerably higher elevation than Dozmary Pool (265 m OD). In common with many other sites across southern England, these two localities demonstrate the major features of vegetational and environmental change characteristic of the Holocene: early Holocene open-grassland vegetation, gradual immigration of thermophilous arboreal species, a mid-Holocene forest stage, and then gradual clearance of woodland as a result of anthropogenic activity. There are, however, some important vegetational differences between the two sites. There is some evidence to suggest that Blacklane Brook lay close to the regional treeline during the phase of maximum forest cover during the mid-Holocene while the lower-lying environs of Dozmary Pool were dominated by open oak forest. This is in marked contrast to other areas of Britain which apparently demonstrate a much higher treeline at this time, and also contrasts with other sites in southern England which were dominated by other tree species (Bennett, 1989). The dominance of oak in the Holocene forest of South-West England is thought to be related to the dominantly acidic character of the soils. However, as indicated above, this may not hold true for the entire region and may simply reflect the acidic substrate of these particular sites. Whatever their spatial extent, these differences illustrate the significance of climatic and edaphic factors in determining the pattern of Holocene vegetational development.

Both Dozmary Pool and Blacklane Brook are extremely important in providing evidence of woodland clearance by fire as early as the Mesolithic. At Blacklane Brook, the evidence is based on changes in pollen assemblages at around 7500 BP, and at Dozmary Pool such changes are complemented by charcoal within the peat profile at around 7000 BP, and by a profusion of archaeological material close to the site. Both sites continue to be important in discussions regarding the relative significance of climatic and anthropogenic factors in disrupting woodland from the mid-Holocene onwards.

At around 6500 BP, many sites in the region indicate a change to a wetter climate. This is indicated by the development of raised and blanket bogs, and the rapid spread of alder at sites on Bodmin Moor and Dartmoor. It is perhaps significant that this coincides with the onset of peat accumulation at Higher Moors (St Mary's) on the Isles of Scilly (Chapter 8). Peat from the base of this mire has been dated to 6000 BP (Scaife, 1984), the oldest Holocene organic sediments yet reported from the islands. This site is important because its pollen evidence indicates that indigenous woodland was able to generate on the Isles of Scilly during the mid-Holocene: this has implications for studies of tree migration and dispersal given that the islands lie 45 km from the mainland against the direction of the prevailing south-westerly winds.

The Higher Moors site on Scilly, and the Bodmin Moor and Dartmoor sites, all demonstrate the progressive clearance of woodland by humans during the Neolithic and later. The Mesolithic clearance episodes were relatively minor and limited to the mainland, and most sites show evidence of post-clearance forest regeneration. The mainland Neolithic clearances, however, were more long-lasting, and pollen evidence, including pollen grains of cereals, weeds and ruderals, indicates active cultivation from this time onwards. On Scilly, regeneration occurred after an initial phase of Neolithic clearance, woodland only being irreversibly removed from the middle Bronze Age onwards.

HAWKS TOR
S. Campbell and N. D. W. Davey

Highlights

The most complete record of Devensian late-glacial vegetational and climatic changes in South-West England comes from Hawks Tor on Bodmin Moor. This site was central to the development of pollen biostratigraphy in Britain in the 1930s/1940s and still provides the regional 'standard' with which sequences elsewhere in Britain, Eire and continental Europe are compared.

Introduction

Hawks Tor provides the most detailed and extensive record of Devensian late-glacial conditions in upland South-West England, as well as a partial record of Holocene environmental changes. Pollen, plant macrofossils, diatoms and radiocarbon dates from the site show unique evidence in the area for the Allerød Interstadial of the Late Weichselian (= Late Devensian). The kaolinized granite at Hawks Tor was discussed by Reid *et al.* (1910), and its origin and importance in landscape evolution were also mentioned in studies by Barton (1964) and Clayden (1964). The pollen biostratigraphy of the site has been studied in detail by Conolly *et al.* (1950) and Brown (1972, 1977, 1980), and radiocarbon dates for selected horizons were provided by Libby (1952) and Brown (1977, 1980). The site's importance is highlighted by its use as the reference locality for the Allerød Interstadial in the Geological Society's Quaternary correlation charts for South-West England (Stephens, 1973; Campbell *et al.*, in prep.), and by its continuing citation in both regional and national syntheses of Quaternary evidence (Te Punga, 1957; Pennington, 1974; Kidson, 1977; Caseldine, 1980; Bell *et al.*, 1984).

Description

Hawks Tor GCR site (SX 150749) lies at *c.* 220 m OD on Bodmin Moor, and consists of a small peat bog situated at the northern end of the lake which now occupies the disused pit of the Hawks Tor China Clay Works (Figure 4.15). The bog lies in a depression flanked to the east by the Warleggan River and to the west and north by the rising slopes of Menacrin Downs and Hawks Tor itself. Up to 2.5 m of organic sediment is exposed in the valley bottom, thinning to less than 0.5 m on the surrounding hillslopes. The upper layers of peat, however, have been reduced by cutting, and the bog surface is much disturbed by spoil, trackways, embankments and ditches. The Devensian late-glacial and Holocene deposits are exposed in sections along the lake edge, at the margin of the former kaolin workings. These sections also expose the underlying growan or grus (the kaolinized granite). Similar stratigraphic relationships occur to the south of the GCR site and were exposed, temporarily, during widening of the A30(T) in 1987.

Figure 4.16 shows the stratigraphic sequence exposed at the north-east end of the lake. This representation, based on the work of Brown (1977, 1980), is highly generalized: considerable lithological variations occur in the beds, the pattern of which is frequently disrupted by complex unconformities and cryoturbation structures. The sequence of vegetational development and inferred climatic changes given here is based principally on pollen analyses carried out on three separate

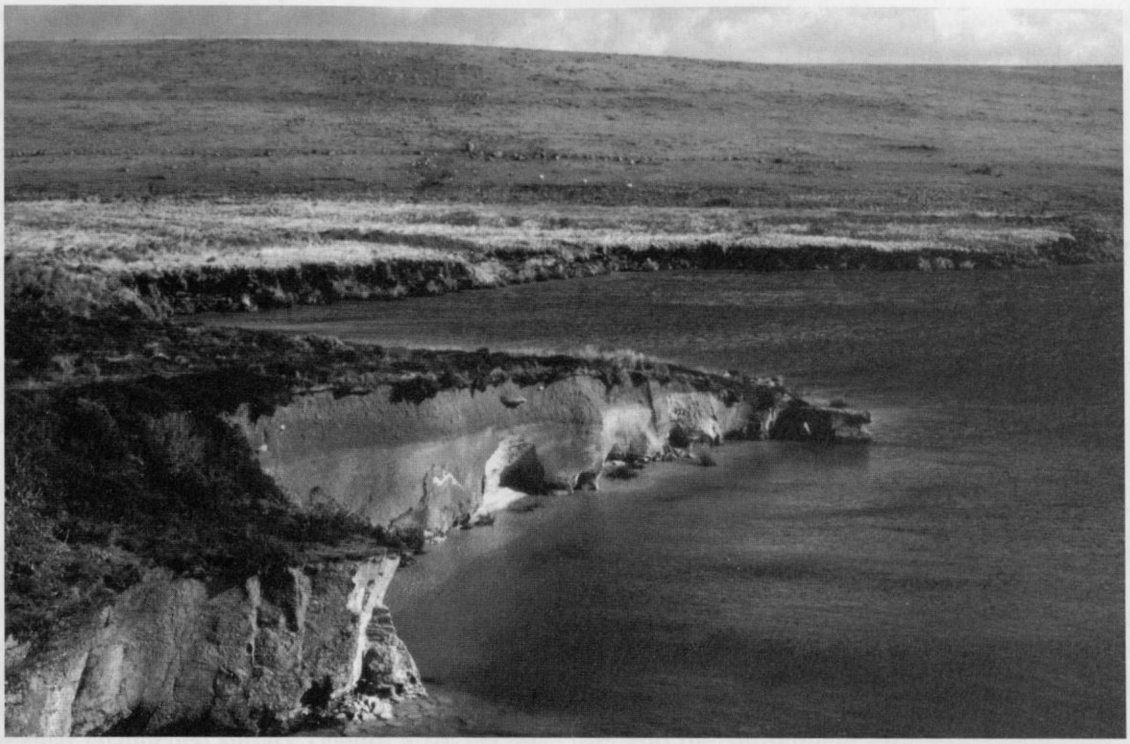

Figure 4.15 The disused china clay workings at Hawks Tor, Bodmin Moor. The altered granite or growan is seen in the foreground faces, with the cliffed, but somewhat degraded, Devensian late-glacial and Holocene sequence along the lake edge behind. (Photo: S. Campbell.)

monoliths by Brown (1977, 1980) (Figure 4.16) although a brief appraisal of the earlier work by Conolly *et al.* (1950) is also given.

Interpretation

Conolly *et al.* (1950) presented the results of pollen analyses carried out on the peat beds (beds 3, 5 and 6). Their 'upper peat' (beds 5 and 6) showed characteristic tree pollen assemblages from Pollen Zones V–VIII of the 'post-glacial' (Holocene), although there was some doubt as to whether deposits with a Pollen Zone IV flora (Pre-Boreal) were present at the site. With this exception, the 'upper peat' showed a pollen zonation similar to many other British tree pollen diagrams for the period.

The Pollen Zone V assemblage, found at the base of bed 5 in the wood peat, showed a preponderance of birch and hazel pollen with small amounts of pine, oak and willow. Such a pattern also characterizes the succeeding zone (also in bed 5), but with a decline in birch and hazel, and a corresponding increase in oak and alder. Pollen Zone VII (bed 5) was characterized by a significant reduction in tree birch pollen and by the continued rise of oak. Alder and hazel pollen values are maintained at a steady level throughout this zone. The Pollen Zone VIII assemblage, found in the non-humified peats of bed 6, showed a renewed peak in birch, a sudden expansion in oak and a corresponding decline in alder. Beech makes its first significant appearance in this zone.

Conolly *et al.* (1950) noted that Pollen Zone IV (Pre-Boreal) pollen might be present in the upper layers of the underlying silty peats, sands and gravels (bed 4). However, these dominantly minerogenic beds had lithological and stratigraphical characteristics suggesting a Younger Dryas (Pollen Zone III) age (Conolly *et al.*, 1950).

These workers also identified pollen, fruits and seeds from the organic sediments in bed 3 which was sandwiched between two dominantly inorganic layers (beds 2 and 4). The fossil flora from bed 3 was characterized by plants now restricted to more northern parts of Britain – for example, *Betula nana*, *Salix herbacea* and *Thalictrum alpinum*. Pollen from this bed revealed an open-tundra or 'park-tundra' vegetation and, although

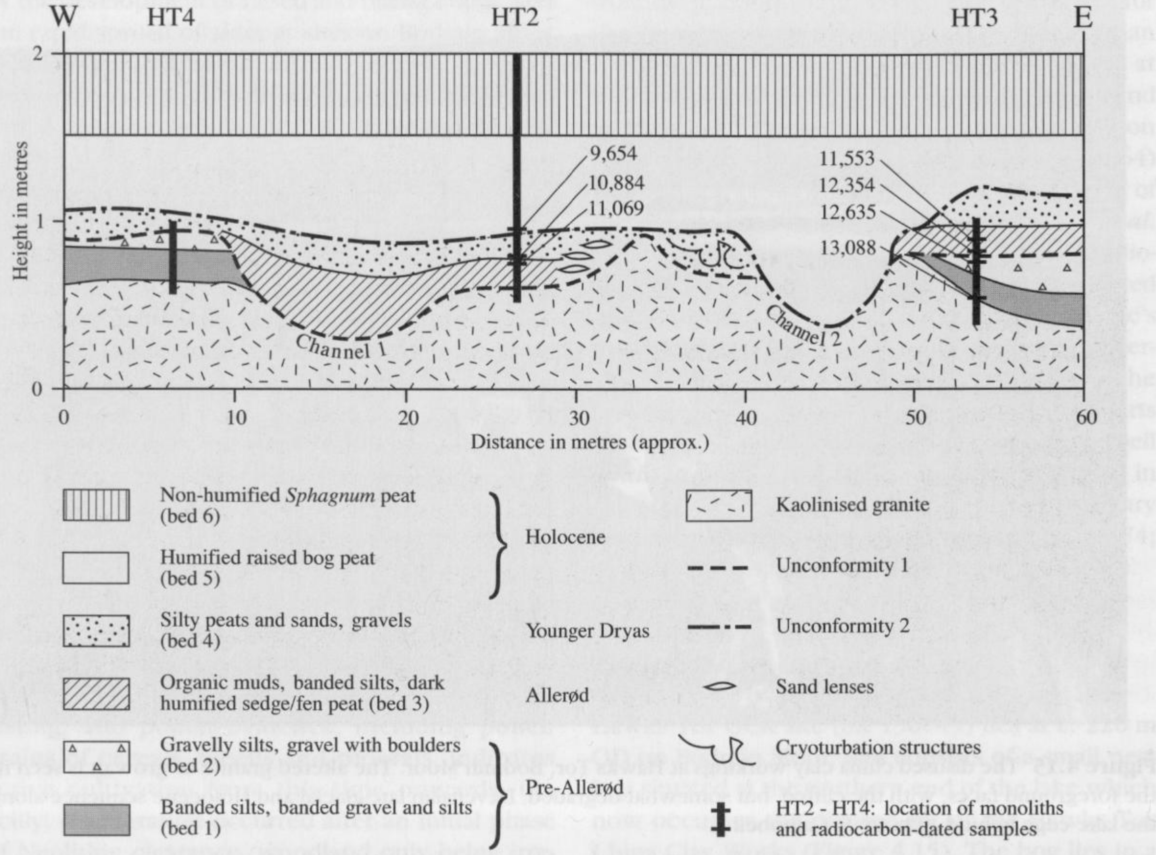

Figure 4.16 A simplified composite section of the north-east face of the exposures at Hawks Tor as exposed in 1970–1971. Adapted from Brown (1977, 1980).

there was no clear evidence for tree growth (but see below; Brown (1977, 1980)), conditions were clearly warmer than when the underlying and overlying, dominantly minerogenic, beds were deposited. Organic lake muds at the base of bed 3 yielded a diatom flora indicative of cool-temperate, moderately eutrophic conditions. On the basis of this evidence, Conolly *et al.* (1950) confidently ascribed bed 3 to the Allerød oscillation (= Pollen Zone II) of the classic Danish sequence.

The gravelly silt, which contains some large granitic boulders up to 1 m across (bed 2), was interpreted as a solifluction deposit, probably ascribable to cold conditions in Pollen Zone I times (Conolly *et al.*, 1950). Likewise, the dominantly minerogenic deposits of bed 4 were considered to have accumulated by solifluction during a deterioration of climate represented by Pollen Zone III (Younger Dryas): Conolly *et al.* argued that the disturbance, cracking and contortions found in the underlying peats and lake muds (bed 3) had been caused by frost-action and cryoturbation at this time. The Hawks Tor sequence therefore provided a record showing the threefold subdivision of the Scandinavian Late Weichselian (= Late Devensian late-glacial), in addition to a comprehensive record of Holocene vegetation changes with the exception of detailed evidence in the earliest Holocene (the Pre-Boreal/Pollen Zone IV) (Conolly *et al.*, 1950). An early attempt by Libby (1952) to calibrate the Devensian late-glacial and Holocene sequence at Hawks Tor, using radiocarbon dating methods, provided ambiguous results (Libby, 1952; p. 75).

Brown (1977, 1980) re-investigated the pollen biostratigraphy of the Hawks Tor site, and provided radiocarbon dates from critical lithological and pollen assemblage boundaries (Figure 4.16). The oldest Quaternary sediments (bed 1) overlie kaolinized granite. These banded silts and alternations of silt and gravel appear to have resulted from cyclic sedimentation in still water. The pollen record shows that deposition occurred in a treeless, sparsely vegetated landscape, probably with hill-side snowbeds. The occurrence of pollen in these beds from the arctic-montane species *Artemisia norvegica* and *Astragalus alpinus* indicates low mean annual temperatures and a degree of base-element enrichment caused by local solifluction (Brown, 1980). The oldest radiocarbon-dated organic sediment (13 088 ± 300 BP (Q-979)) comes from banded silt in bed 1, near its junction with the underlying kaolinized granite. These sediments may have accumulated in a clear, shallow water, mud-bottomed channel. In places, they are succeeded by gravel which contains some large boulders (bed 2) reflecting continued slope instability and solifluction.

This cold channel environment with local solifluction gave way to warmer conditions by about 12 600 BP, when organic muds and a sedge mire (bed 3) started to accumulate. These dominantly organic sediments accumulated on an irregular channelled surface (Figure 4.16; unconformity 1) after a change in drainage had effected local removal of parts of beds 1 and 2 and, in places, the underlying bedrock. The pollen record from bed 3 shows that a tall herb fen and birch carr had developed by about 11 500 BP: these warmer conditions are correlated with the Allerød Interstadial (Brown, 1977, 1980). The Allerød deposits are succeeded unconformably in places by solifluction gravels (bed 4). Elsewhere, the peat is overlain by dominantly inorganic gravels, sands and silts, which contain bands of peat presumably reworked from bed 3. Radiocarbon dates show that this change from organic to dominantly minerogenic sedimentation occurred at around 11 000 BP. Pollen from these sediments (bed 4) shows a return to an open treeless vegetation with several cold-climate species. This climatic deterioration is correlated with the Younger Dryas event (Pollen Zone III), and was characterized by a return to solifluction, possibly wet-soil creep, in a cold, oceanic regime (Brown, 1977, 1980). Two notable botanic records occur in the Younger Dryas sediments: *Luzula arcuata* and *Epilobium alsinifolium* are arctic-montane species found now only at higher latitudes in northern England, Scotland and Scandinavia (Brown, 1980).

There is no pollen evidence for an unconformity between the solifluction/sheet-wash deposits of the Younger Dryas (bed 4) and the overlying Holocene peat (beds 5 and 6). The radiocarbon date of 9654 ± 190 BP (Q-1017) (Figure 4.16) from the base of the Holocene peat, however, does suggest an unconformity, much as Conolly *et al.* (1950) had suspected, since the date is too young to mark the start of the Holocene. The fact that the peat of bed 5 also directly overlies sediments of bed 3, and even granite in places (Figure 4.16; unconformity 2), shows that some erosion took place between deposition of beds 4 and 5.

The Holocene sediments consist of highly humified *Sphagnum* and sedge peats (bed 5) which grade into *Sphagnum/Eriophorum* peats (bed 6) of decreasing humification. This shows that the Late Devensian sediments were covered by a wet *Sphagnum* mire which dried out progressively to fen carr. This part of the Hawks Tor pollen sequence (covered by Pollen Zone V; Conolly *et al.* (1950)) is, however, discontinuous and there has been some erosion of the bed (Brown, 1977, 1980). The development of the fen carr was followed by a return to wetter conditions, impeded drainage and the development of raised bog (bed 6); blanket bog developed at the site by about 3100 BP, and the subsequent effects of pastoral and, later, arable agriculture are also clearly evident in the pollen record (Brown, 1977, 1980).

The Hawks Tor deposits are of considerable significance as they have yielded the most complete record of Devensian late-glacial conditions known from upland South-West England. Although incomplete, the Holocene pollen record from the site complements that from nearby Dozmary Pool, collectively providing some of the best evidence for the vegetation history and climate of this period on Bodmin Moor. (The Holocene pollen record for Bodmin Moor has been supplemented recently by data from nearby Rough Tor (Gearey and Charman (1996).)

Hawks Tor is also important in the historical development of pollen biostratigraphy in Great Britain. Conolly, Godwin and Megaw's (1950) study was undertaken at a time, in the late 1930s/early 1940s, when little evidence for Devensian late-glacial conditions in Britain was known. Although strong evidence for recognizing the Allerød Interstadial had been made at Windermere in the Lake District (Pennington, 1947) and at Flitwick in Berwickshire (Mitchell, 1948), other British sites with comparable sequences had only been described and interpreted more speculatively (Godwin, 1947). The study by Conolly *et al.* (1950) at Hawks Tor is therefore a significant 'landmark' in correlating the British Devensian late-glacial record with more comprehensively studied sequences in Ireland, Germany and southern Scandinavia.

The pollen and stratigraphic evidence, including periglacial structures in the beds, is also of importance for demonstrating the considerable severity of Devensian late-glacial climate at latitudes well south of the Late Devensian maximum ice limit (Pennington, 1974).

Conclusion

The sequence of Quaternary deposits at Hawks Tor includes frost-weathered, reworked granitic deposits, peats, lake muds and silts. It has yielded pollen, plant macrofossils and radiocarbon dates which have enabled one of the most detailed reconstructions of vegetational and climatic changes in South-West England during the Devensian late-glacial to be made. Particularly significant is its unambiguous evidence for the Allerød oscillation of the Late Devensian – a discrete interlude of relative warmth, lasting some 1500 years, sandwiched between periglacial phases (equivalent to the Older and Younger Dryas) when the local landscape resembled tundra. In conservation terms, Hawks Tor is important because it provides the most complete record in the South-West for the climatic and environmental conditions of this time interval and shows, uniquely, that trees were established on the Peninsula during the Allerød at high elevation. Although its record of Holocene environmental changes is incomplete, it complements the fuller record at nearby Dozmary Pool: both can be regarded as reference sites for understanding changing climatic and environmental conditions in the latest Quaternary. Hawks Tor has the further distinction of being a significant 'landmark' in the development of British pollen biostratigraphy.

DOZMARY POOL
S. Campbell

Highlights

Dozmary Pool is a key pollen site with a radiocarbon-dated record spanning almost the entire Holocene. Changes in the relative proportions of tree-shrub-herb pollen, in association with occurrences of charcoal in the peat layers, are central to the controversy surrounding the extent of human activity on Bodmin Moor during the Mesolithic.

Introduction

Organic deposits at Dozmary Pool preserve the most complete Holocene pollen sequence yet known from Bodmin Moor, and provide a key record of the vegetational history of South-West England for this period. Dozmary Pool is a reference site for interpreting more discontinuous Holocene pollen sequences found elsewhere in the region, for example, at Parsons Park, Stannon Clay Pit and Hawks Tor. The site was first referred to in an archaeological context by Whitley (1866), Brent (1886) and later by Robson (1944). The pollen biostratigraphy has been studied by Conolly *et al.* (1950), Brown (1972, 1977, 1980) and Simmons *et al.* (1987). Evidence from the site was also discussed by Caseldine (1980) and Bell *et al.* (1984) in reviews of environmental change in Cornwall during the last 13 000 years.

Description

Dozmary (Dozemare) Pool GCR site (SX 192743) lies on Bodmin Moor at *c.* 265 m OD, some 4.5 km east of Hawks Tor (Figure 4.1). The pool occupies a peaty depression to the north-east of Gillhouse Downs between the Fowey and St Neots rivers: the GCR site consists of a rectangular bog (*c.* 300 m × 150 m) situated at the south-west end of the lake where there is a small outlet stream (Figure 4.17). This raised mire has a vegetation community of *Eriophorum vaginatum*, *Rhynchospora alba*, *Erica tetralix*, *Calluna vulgaris*, *Molinia caerulea*, *Juncus effusus* and *Narthecium ossifragum*. The sediment sequence comprises *c.* 2.5 m of lake muds, sedge and fen peats topped by decreasingly humified raised bog peats. Conolly *et al.* (1950) recorded the following stratigraphy from a core of the deposits:

7 Non-humified fresh peat (0.72 m)
6. *Sphagnum–Eriophorum* peat with lake mud at base (0.23 m)
5. Moderately humified *Sphagnum–Calluna* peat with layers of ash and charcoal (0.90 m)
4. *Sphagnum–Eriophorum* peat and some organic mud (0.23 m)
3. Brown and black organic lake muds (0.23 m)
2. White lake mud (0.30 m)
1. Dark brown lake mud with *Phragmites* (0.10 m)

Brown (1977) recorded a deeper profile, with the following stratigraphy:

Figure 4.17 The peat bog at the south-west end of Dozmary Pool, Bodmin Moor. (Photo: S. Campbell.)

9. Coarse, non-humified *Sphagnum/Eriophorum vaginatum* peat (0–64 cm)
8. Slightly humified *Sphagnum/Eriophorum vaginatum* peat (64–77 cm)
7. Coarse, non-humified *Sphagnum/Eriophorum vaginatum* peat with angular quartz gravel (< 1 cm diameter) at 80–85 cm (77–93 cm)
6. Blackish, well-humified *Sphagnum/Eriophorum vaginatum/Calluna* (raised bog) peat with carbonized material throughout, and charcoal fragments in distinct bands at 146, 154, 170 and 175–180 cm; large chunks of burnt peat at 145–150 cm. *Calluna* flowers, leaves and twigs frequent throughout (93–188 cm)
5. Highly humified monocotyledonous peat with fresh wood fragments at 190, 193 and 197 cm; thin black band at 198 cm; frequent minute carbonized fragments throughout, fungal perithecia frequent in the upper half of the bed (188–207 cm)
4. Highly humified sedge peat with abundant fresh *Salix* wood; *Carex* nutlets are frequent at the top and *Juncus* seeds at the base (207–215 cm)
3. Medium and fine muds with a fibrous layer at 220 cm and dark band at 223 cm; *Juncus* seeds frequent throughout. *Carex* nutlets, *Littorella uniflora* and *Hydrocotyle vulgaris* fruits, *Menyanthes trifoliata* seeds occasional towards the base (215–224 cm)
2. Fine, very silty mud; megaspores of *Isoëtes lacustris* and *Isoëtes echinospora* abundant; oospores of *Nitella* type, *Elatine hexandra*, *Luronium natans*, and *Juncus* seeds occasional; *Potamogeton natans* fruits rare; *Sphagnum* leaves present (224–235 cm)
1. Kaolin clay (below 235 cm)

Although Simmons *et al*. (1987) recorded a slightly deeper profile, their stratigraphy is essentially similar to that given by Brown (1977) (see above), although they do not record the highly humified sedge peat with abundant *Salix* wood (bed 4). Brown's stratigraphic sequence is given here in preference because his reconstructed pollen assemblage zones cover most of beds 2–6. Simmons *et al*. (1987), on the other hand, concentrated their pollen analyses on beds 5 and 6 only: the muds (beds 2 and 3), the sedge peat (bed 4) and the upper peats (beds 7–9) were not analysed. Brown's pollen analyses were supported by five radiocarbon dates (Q-1021 to Q-1025). Five additional radiocarbon dates (HAR-5077 to HAR-5080 and HAR-5083) for the profile were provided by Simmons *et al.* (1987).

Interpretation

Artefacts

First mentioned in the scientific literature by Whitley (1866), Dozmary Pool attracted archaeological attention: over 100 'very perfect flint-flakes' were recovered from around the site, mainly from the uppermost soil layers. Brent (1886; pp. 60–61) remarked that

'Although no traces of Lake Dwellings could be observed when Dosmare Pool was entirely dry in the summer of 1866, yet the presence of hut-circles, barrows, &c., on the surrounding moor; the five 'Kings' Graves', one since destroyed, on Bron Gilly; and the vast quantity of flakes, pieces, and some arrow-heads from the peat; would indicate that there was once a large population in this interesting district.'

Robson (1944) noted that 'Neolithic' flints occurred beneath the peat at Dozmary Pool, thereby proving the 'recent formation of the peat'. More up-to-date accounts of the microlith assemblages were given by Wainwright (1960) and Jacobi (1979). Wainwright described the microliths found at Dozmary (mostly during the nineteenth century) which have now been dispersed to various museum collections, including 2500 flints to Plymouth Museum alone: their original stratigraphic provenance is unknown. Brown (1977) recorded burnt peat within the sequence (his bed 6) immediately prior to the 'elm decline' (see below). He therefore argued that the microliths might be late Mesolithic in age. Jacobi (1979), on the other hand, has linked the microliths from Dozmary with an assemblage from Thatcham in the Kennet Valley, suggesting an early eighth millennium date, namely very early Mesolithic. Such an age would place the Dozmary flints in a period when pollen shows that *Empetrum* heath and juniper scrub grew on the gentle local hillslopes, and before the spread of birch woodlands. Such a view implies that the microliths either come from, or can be correlated with, a very much earlier deposit in the sequence than suggested by Brown (1977) (Simmons *et al.*, 1987).

Pollen biostratigraphy and radiocarbon dating

Conolly *et al.* (1950) provided an arboreal pollen diagram based on analyses in their beds 3–5 and from the lower layers of bed 6. The diagram follows the standard zonation with full detail for Pollen Zones VI–VII, and parts of Zones V and VIII. They noted that it was likely that the top metre of peat (beds 6 and 7) was formed in Pollen Zone VIII: there was also an ample depth of mud (beds 1 and 2) beneath the lowest counted sample to record the vegetation history in Pollen Zone IV and the earlier part of Zone V. The incompletely analysed record for Pollen Zone V (in bed 3) shows birch and hazel to be dominant: the latter, however, declines rapidly towards the end of the zone. The upper part of bed 3 (lake mud) and most of bed 4 (peat and lake mud) contain an arboreal pollen assemblage characteristic of Pollen Zone VI – with a rapid decrease in birch and the progressive invasion of oak. Alder first becomes continuously represented in this zone while hazel maintains steady values. A Pollen Zone VII assemblage occurs in the very lowest part of bed 4 and throughout bed 5 (moderately humified peat). This shows the progressive decline of birch to low but stable levels, the continued increase of oak and the steady maintenance of alder and hazel in the developing mixed deciduous forest. Conolly *et al.* (1950) further noted that the layer of ash and charcoal in bed 5 (Pollen Zone VIII) probably reflected the activities of prehistoric humans in clearing the local forests.

Brown (1972, 1977) reinvestigated the pollen biostratigraphy of the site, providing detailed evidence (absolute pollen frequencies) for the vegetation history of the beds which had previously yielded Pollen Zone VI and VII assemblages (Conolly *et al.*, 1950): a summary of this work was given by Brown (1980). His work covers an important gap in the existing site record – namely the early Holocene.

According to Brown (1977), the basal silty muds (his bed 2) started to accumulate at *c.* 9053 ± 120 BP (Q-1021), and are characterized by a local pollen assemblage zone dominated by grasses. Pollen and plant macrofossil evidence confirms that deposition took place in a shallow, clear-water, base-poor lake with a gravelly bed. The high grass and low tree pollen values, together with a rich herb flora, show that the early Holocene landscape was open, dominated by a short-turf grassland, with trees limited to only small areas or more continuously distributed at some distance (Brown, 1977).

A second pollen assemblage zone (DP2), found in beds 2 and 3, consists of an early *Corylus*-Gramineae zone with a subsequent Cyperaceae subzone (Brown, 1977). The first stage of a hydroseral succession is shown by increasing Cyperaceae values, the occurrence of *Carex* nutlets in the mud, the appearance of abundant *Sphagnum* spores and the disappearance of most aquatic pollen. This indicates that open-water conditions were gradually replaced by a *Carex/Sphagnum* mire which formed above the local water-table, and that Dozmary Pool itself was reduced in area shortly after 9000 BP in response to drier conditions (Brown, 1977). Elm pollen appears in the profile for the first time at a level dated by radiocarbon methods to 8829 ± 100 BP (Q-1022). A persistence of herb and grass pollen was taken to indicate the limited extent of the local woodland, which was perhaps restricted to sheltered valleys (Brown, 1977).

Local pollen assemblage zone DP3 (bed 4; humified sedge peat with *Salix* wood) is broadly similar to the preceding subzone, although *Salix* pollen reaches high values in the lower part of the wood peat: together with higher levels of birch pollen, and the occurrence of *Salix* wood itself, the evidence points to a mixed tree layer forming fen carr in the immediate vicinity (Brown, 1977).

The succeeding pollen biozone (DP4) is marked by high *Corylus*, with a *Calluna* subzone (DP4a): it spans the upper part of the wood peat laid down in a fen carr (bed 4) and the majority of bed 5. Following an initial persistence of birch/willow-dominated fen carr, dated to *c.* 7925 ± 100 BP (Q-1023), the carr was swamped by active mire growth as shown by high *Sphagnum* frequencies and the appearance of *Calluna* pollen (Brown, 1977). This zone is also characterized by a sparse but varied herb flora, fern spores and increasing Gramineae values. Oak and elm values are also higher and are taken as showing the continued spread of open woodland to well-drained hillside locations.

Zone DP5 and its subzone DP5a span the upper part of bed 5 (highly humified peat) and the base of the dark *Sphagnum/Eriophorum/Calluna* peat (bed 6). A radiocarbon date of 6793 ± 70 BP (Q-1024) from the upper layers of bed 5, provides a maximum age for the sediments covered by pollen assemblage zone DP5. This characteristic hazel/fern biozone sees a peak in grass and birch pollen early in the zone (DP5). Fluctuations in the pollen curve in this zone, and the appearance of ferns, may indicate the restriction of the woodland on better soils by fire (Brown, 1977). Pollen assemblage zone DP5 may well cover the driest period in a climatic regime which had improved continuously since the opening of the Holocene some 3000 years earlier.

Calluna/Alnus subzone DP5a commences at 6451 ± 65 BP (Q-1025): the lower boundary of the zone corresponds with the base of the raised bog peat (bed 7). The appearance of alder for the first time in this zone reflects the development of alder carr around the mire, together with *Fraxinus* and *Tilia cordata*. Brown has argued that the presence of these trees shows the onset of a mild, but wetter, climate as does the ensuing development of the raised bog itself. Indeed, a general recession of woodland is indicated as waterlogging of local sites progressed (Brown, 1977).

Brown did not provide a detailed analysis of pollen present in the remainder of the beds (upper bed 6 and beds 7–9): the likely biozonation of these beds is, however, thought to conform with analyses carried out on comparable beds at nearby sites (e.g. Hawks Tor and Parson's Park) (Brown, 1977). Radiocarbon dates were not attempted from the upper peats at any of these sites due to the likely effects of modern rootlet contamination (Brown, 1977). It is assumed, on the basis of preliminary pollen work and on inter-site correlation, that the 'elm decline' is manifest in bed 6 in the Dozmary Pool record somewhere between 120–160 cm (Brown, 1977).

From the pollen and plant macrofossil evidence given by Brown (1972, 1977, 1980), the course of vegetation development and hydroseral succession, right up to and including the climatic optimum of the Boreal period, is clear. Initially, the Dozmary area was occupied by a base-poor clear lake. This was partially replaced by a sedge and *Sphagnum* mire, then by birch and willow carr and finally by raised bog. The latter may have been caused by the local development of fen carr near the present lake outlet. This would have impeded drainage from the lake (Thurston, 1930; Brown, 1977) which may indeed have been present continuously in the vicinity, albeit in varying size, since the Late Devensian (Brown, 1977).

Other salient features of Brown's pollen diagram, which covers the early and middle Mesolithic periods only (between *c.* 9000 and 6500 BP), include the maintenance of some open ground at this altitude throughout the period, and a tendency towards treelessness in the later part covered by the diagram. The latter coincides with increases in bracken spores and the pollen of grasses and *Potentilla*. He has argued that fluctuations in the pollen record at *c.* 6541 ± 75 BP (Q–1025) may indicate the restriction by fire of oak and elm, with a corresponding rapid spread of birch, ferns and grasses. He has correlated these changes with evidence from Dartmoor (see Blacklane Brook) where a record of forest recession, similar rises in fern spores and grass pollen, have been taken to indicate forest clearance by Mesolithic inhabitants (Simmons, 1964a). Brown has suggested, however, that such deliberate woodland clearance would have been unnecessary on Bodmin Moor where, at this time, the pollen evidence reveals an already open landscape.

It is against the background of Brown's work that Simmons *et al.* (1987) subsequently concentrated their pollen analyses on beds 5 and 6, where they judged the fluctuating conditions associated with Mesolithic activities to be present. All the vegetational changes recorded within this part of the sequence fall within a single local pollen assemblage zone (Simmons *et al.*, 1987).

Generally low total tree pollen percentages, together with sporadic occurrences of a range of herbs and open-land indicators, point to the persistence of some unwooded land in the vicinity of the site throughout the period (Simmons *et al.*, 1987). Some large fluctuations in the relative pollen contributions of trees, shrubs, small (ericaceous) shrubs and herbs do occur, with a major fluctuation between 209 and 203 cm in an equivalent of Brown's bed 6, coincident with much charcoal and mineral matter. Oak is dominant in the tree pollen record throughout: *Alnus* is lacking in the lowest samples (bed 5) but rises steadily before fluctuating and finally rising again to reach similar values. Pine is not judged to have been a constituent of the woods on Bodmin Moor during the period covered by the diagram constructed by Simmons *et al.* (1987). Elm pollen is generally low and is probably absent where charcoal is found in bed 4 at 205 cm (Simmons *et al.*, 1987).

Although the oldest radiocarbon date of 7590 ± 100 BP (HAR–5083) falls between Brown's (1977) dates of 7925 ± 100 BP (Q–1023) and 6793 ± 70 BP (Q–1024) derived from similar monocotyledonous peat (bed 5), covered by an equivalent pollen assemblage zone (Brown's DP4), the other radiocarbon dates given by Simmons *et al.* pose considerable problems of interpretation: these dates are not arranged in the expected chronological order in the profile. Since sample contamination is considered unlikely, the radiocarbon dates probably show that the site here was not disturbed by fire alone, but by the physical removal of peat and the inversion of the profile: this may have been on two separate occasions – at least as recently as *c.* 2740 BP in the case of the lower disturbance, and 510 BP for the upper. Alternatively, and more likely, both apparent disturbances may have happened simultaneously after the latter date. Considerable fluctuations in the pollen, charcoal and mineral contents at the 201–209 cm-levels lend much support to the latter view (Simmons *et al.*, 1987).

Dozmary Pool is a reference site for upland vegetation history in South-West England with one of the most extensive Holocene pollen records in the region. It is a member of a network of pollen sites in Britain which shows regional and altitudinal variations in the course of vegetation succession, and is particularly important for demonstrating the effect of oceanicity – that is, a local climate dominated by exposure to wind and rain – on vegetation development. In this respect, the vegetation record from Dozmary Pool shows strong similarities with sites on the western fringes of Britain and indeed areas on the seaboard of continental Europe, but contrasts with other inland and montane sites (Brown, 1977). In particular, the strong record of birch throughout the Holocene, as shown in part from the evidence at Dozmary Pool, contrasts markedly with other parts of southern England and even Dartmoor: its persistence here may be ascribed to its survival in a very open landscape, one maintained by exposure to the elements rather than by human activity (Brown, 1977).

Similarly, both on Bodmin Moor and on Dartmoor, oak is believed to have invaded rapidly, and although it never completely covered the uplands, being restricted by the lack of shelter, it soon reached its maximum extent to become the dominant tree species (Brown, 1977). Its rapid domination of the landscape may have been facilitated by the extensive areas of grasslands, open birch woods (see above) and immature hazel scrub which covered the uplands and which offered little competition for the advancing oak populations (Brown, 1977). Again, the open landscape is believed to have been strongly influenced by the oceanicity of the climate.

On the other hand, *Pinus* does not seem to have been a major constituent of the early forests of the South-West. Evidence from Dozmary Pool (and elsewhere) shows that it was absent on the moorlands of the South-West (Brown, 1977), although it may have been present at lower altitudes and in more sheltered southern coastal locations (Ussher, 1879c; Clarke, 1970). In this respect, the evidence from Dozmary Pool shows strong similarities with sites in Brittany (van Zeist, 1963; Brown, 1977). Elsewhere in the British Isles, *Pinus* spread rapidly north-westwards in response to the improving climate of the early Holocene. Where *Pinus* was not established, as in South-West England, hazel and oak expanded rapidly (cf. south-west Ireland and Northern Ireland). Brown (1977) has argued that the oceanicity of the Atlantic seaboard in these parts of Europe put *Pinus* at a disadvantage when in direct competition with *Quercus* as the climate improved. It is possible that light-demanding pine seedlings were quickly shaded-out when birch arrived (Brown, 1977), although the precise requirements of different genera are still poorly understood and must be established before definitive statements can be made about regional variations in forest composition (for discussion of these problems see Jessen, 1949; Iversen, 1954; Jones, 1959; Planchais, 1967; Carlisle and Brown, 1968; Bennett, 1989; Bennett and Birks, 1990).

Another important regional contrast exhibited by the pollen evidence from Dozmary Pool concerns the relative expansions of oak and elm in Britain during the early Holocene. Mitchell (1951) has shown that elm tended to expand in calcareous areas first, and this is clearly shown by pollen records from the calcareous areas of southern England where *Ulmus* either expanded before or simultaneously with *Quercus* (e.g. Seagrief, 1959, 1960; Seagrief and Godwin, 1960). Farther west in South-West England, on the other hand, oak expanded before elm, and this was clearly a result of the acidic upland soils, particularly those on Dartmoor and Bodmin Moor (Brown, 1977). The unbroken record of vegetation succession in Pollen Zone VII at Dozmary Pool is particularly important: it is almost certainly due to the continuously adequate water supply at the site, allowing anaerobic preservation throughout the climatic optimum of the Holocene (*c.* 7900–6500 BP). This contrasts with Hawks Tor and Parsons Park where the mires dried out at this time, fossil (pollen) preservation ceased, and where erosion probably occurred (Brown, 1980). Retention of water sufficient to form a lake and support the growth of a mire at Dozmary Pool during the driest (Boreal) period, may have been promoted by the restricted drainage outlet (see above), and may also have been a function of the greater annual rainfall which would have been received at these higher altitudes (Shorter *et al.*, 1969). In any event, Dozmary Pool contains arguably the most complete Holocene pollen sequence on Bodmin Moor with an unbroken pollen/sediment sequence through Pollen Zones V and VI, although this evidence has been supplemented recently by archaeological and palynological data from Rough Tor on Bodmin Moor (Gearey and Charman, 1996). The evidence from Dozmary Pool has been instrumental in revealing the existence of unconformities in other regional profiles which date approximately from this time (see Hawks Tor and Blacklane Brook). The pollen stratigraphic record from Dozmary Pool is therefore a key to the interpretation of more abbreviated sequences found elsewhere in upland South-West England.

The potential of the site for assessing the extent of Mesolithic activities in the area has not, unfortunately, been realized from the pollen evidence, although it will remain central to resolving the controversy, and may provide complementary evidence to the Rough Tor site in this respect (Gearey and Charman, 1996). The apparently continuous pollen record from a peat sequence containing Mesolithic flints and charcoal, provides great scope for elaborating the patterns and timings of various postulated Mesolithic clearances in the area. The most recent study of these phenomena was severely hampered by unforeseen disturbances to the peat profile at the chosen sample point. Although positive evidence of Mesolithic clearance, as interpreted from pollen sequences on Dartmoor (Blacklane Brook and Black Ridge Brook), cannot yet be demonstrated at Dozmary Pool, the evidence afforded from the most recent study here has wide implications. The evidence from Dozmary Pool suggests that stratigraphical and pollen data from cores alone, especially where no peat faces are available, may provide misleading results: the disturbances and inversion of parts of the Dozmary profile were not visible in the sample core. Only the radiocarbon evidence reveals the scope of the problem and highlights the need for detailed radiocarbon calibration for all pollen biostratigraphic studies carried out on core material. It is possible that the disturbances noted at Dozmary Pool are localized: further pollen work with additional radiocarbon dates may well prove the extent of disturbance and reveal the true importance of anthropogenic factors on the regional vegetation history.

Conclusion

Peat and lake muds at Dozmary Pool preserve the fullest record of changing Holocene environmental conditions on Bodmin Moor. This radiocarbon-dated sequence, and that of Blacklane Brook on Dartmoor, together provide some of the best available Holocene vegetational and inferred climatic records for upland South-West England. The conservation value of this GCR site stems not only from the unusual combination of archaeological and stratigraphic evidence, but from the apparently continuous sedimentary record which spans the driest (Boreal) part of the Holocene, a time when water supplies at other sites were inadequate to allow continued peat growth and pollen preservation. The pollen record demonstrates very clearly that the vegetation of Bodmin Moor developed throughout the Holocene in response to exposure to the elements, and a generally open, sparsely wooded landscape is indicated. Although there is clear archaeological evidence for anthropogenic activities at the site, the relative rôles of climatic change and human interference in vegetational development are not entirely clear from the site evidence. Recent studies here, using radiocarbon dating methods, demonstrate very clearly the potential pitfalls of interpreting pollen data from borehole cores without the use of such calibration.

BLACKLANE BROOK

S. Campbell

Highlights

A reference site for Holocene vegetational history on Dartmoor, Blacklane Brook provides exceptionally detailed evidence for a pre-*Ulmus* (elm) decline in forest cover, attributed to the activities of Mesolithic people.

Introduction

Relatively few detailed studies have been carried out on the peats of South-West England, and Blacklane Brook preserves one of the most extensive Holocene vegetational records yet known from the region. First studied in detail by Simmons (1964a), the site has become a cornerstone for studies of Holocene vegetational and environmental history (e.g. Simmons, 1962, 1964b; Smith, 1970; Stephens, 1973; Caseldine and Maguire, 1981, 1986; Cullingford, 1982; Simmons *et al.*, 1987; Caseldine and Hatton, 1996; West *et al.*, 1996). Recent accounts of the site's pollen stratigraphy and plant macrofossils were given by Simmons *et al.* (1983) and Maguire and Caseldine (1985), respectively.

Description

The Blacklane Brook pollen site (SX 627686) lies on southern Dartmoor at *c.* 457 m OD, and consists of a series of shallow peat sections exposed along this tributary of the southward-flowing River Erme (Figure 4.18). The site lies in an area covered mostly by blanket peat. Simmons (1964a) originally described a peat section some 1.2 m deep, but a more complete 2.2 m-deep section was later described by Simmons *et al.* (1983). The following stratigraphy is reconstructed here using data from two separate, but overlapping, monoliths (Simmons *et al.*, 1983).

7. Red-brown, fibrous *Eriophorum* peat, becoming increasingly humified towards base (0–110 cm)
6. Dark brown, well-humified amorphous peat (110–174 cm) with wood fragments at 142 cm and 169 cm
5. Wood layer of *Salix* and *Betula* (174–182 cm)
4. Dark brown amorphous peat with scattered wood fragments (182–202 cm)
3. Dark brown, pseudo-fibrous laminated peat with occasional lighter bands of more fibrous peat (202–217 cm)
2. Dark well-humified peat with increasing mineral matter with depth (217–222 cm)
1. Grey-brown silty clay with granite gravel (below 222 cm)

Three radiocarbon age determinations (HAR–4460 to HAR–4462) were obtained from materials within the section (Simmons *et al.*, 1983).

Interpretation

The original pollen spectrum (Simmons, 1964a) was thought to cover the period from the end of the Devensian late-glacial to the opening of the Sub-Boreal or Pollen Zone VIIb of Godwin's scheme. A phase of open-country conditions dominated by shrubs, birch and pine (corresponding to Godwin Pollen Zone IV) gave way to a phase characterized by the immigration of trees, particularly *Corylus*, which displaced the open-ground species (= Pollen Zone V and early and mid-Zone VI). Finally, the pollen record showed a rapid 'clear-

Figure 4.18 Blacklane Brook pollen site, southern Dartmoor. (Photo: S. Campbell.)

ance' phase followed by the stabilization but not regeneration of many taxa (= late Zone VI and early Zone VIIb; Simmons, 1964a; Simmons *et al.*, 1983). The main characteristics of the clearance phase were: 1. a slight reduction in the frequency of *Quercus* pollen; 2. the appearance of *Fraxinus* and *Prunus-Sorbus* type pollen; 3. a fall in *Corylus/Myrica* pollen; followed by 4. a peak in grass pollen and fern spores. This clearance was judged to have taken place late in Pollen Zone VI, well before the Neolithic, leading to the speculation, now more widely accepted, that woodland clearance had been initiated in this area by Mesolithic people.

From the evidence presented by Simmons (1964a), Simmons *et al.* (1983) and Maguire and Caseldine (1985), the following updated sequence of vegetational, climatic and environmental changes can be interpreted from the peat sections at Blacklane Brook. The pollen record here commences in the early Holocene at an estimated 10 200 BP: it has been divided into six local pollen assemblage zones (BLB1–BLB6) from which the mire's history and local forest development can be reconstructed (Simmons *et al.*, 1983). From the pollen contained in beds 1 and 2, the initial vegetation of the site and local area (pollen assemblage zone BLB1) appears to have been predominantly dry grassland or meadowland, with perhaps some localized willow and birch, *Empetrum* heath and juniper scrub. The succeeding pollen assemblage zone BLB2 (occurring in most of bed 3) indicates the continuation of fairly open vegetation, but with a persistence of local birch and willow stands and juniper scrub. The site itself consisted of a sedge and *Sphagnum* mire at this time. Local pollen zone BLB3 (upper bed 3; lower bed 4), dominated by birch and grasses, shows a distinct shift with the mire changing from sedge- to grass-dominated. At the same time, birch and oak woodlands also became established within the pollen catchment, perhaps at lower elevations, on drier sites or even on the hillsides around the mire. Simmons *et al.* interpreted this evidence as indicating a change to more acid conditions prior to the development of blanket peat.

Pollen zone BLB4 (upper bed 4; bed 5; lower bed 6) indicates vegetation succession to the deciduous forest stage (mid-Holocene). Although dominated by shrub pollen, this *Quercus-Corylus/Myrica* zone suggests that forest covered much of the local area, perhaps encroaching locally on the site. However, pollen suggestive of open communities persists throughout the zone, and it is possible that the immediate environs remained as a bog, with perhaps some willow carr (Simmons *et al.*, 1983). A radiocarbon date of 7660 ± 140 BP (HAR-4462) from the lowest part of bed 6 gives a minimum age for the layer of *Salix* and *Betula* wood beneath (bed 5).

Although not radically different to its predecessor in its tree pollen content, it is within the same context of deciduous forest cover in zone BLB5 (bed 6) that human modification to the vegetation can first be detected. The distinguishing feature of this zone is the onset at *c.* 7660 radiocarbon years of higher pollen and spore frequencies usually associated with the opening of the forest: *Pteridium* spores, and the pollen of Rosaceae and that of a number of herbaceous types are all found within the early part of this zone. These floral changes are also accompanied by increased amounts of charcoal within the sediment profile. A radiocarbon date of 6010 ± 90 BP (HAR-4461) within zone BLB5 marks the rise of *Alnus*. The evidence from this pollen zone was interpreted by Simmons *et al.* as indicating the activities of Mesolithic people, and their use of fire to create grassy clearings (see below).

Local pollen assemblage zone BLB6 (upper bed 6; bed 7) (*Quercus-Alnus-Corylus* and *Myrica-Calluna*) reveals a decline in human pressure upon the local forest cover, although the maintenance of a weak herbaceous flora indicates some contemporary human activity. There is no direct evidence for agriculture and no prehistoric remains have yet been discovered from the site or its immediate environs (Simmons *et al.*, 1983). An important feature in this part of the Blacklane pollen record is the 'elm decline' dated to *c.* 4260 ± 90 BP (HAR-4460), and occurring right at the beginning of local pollen assemblage BLB6. Another is the development of a distinctive weed flora including *Plantago lanceolata*, interpreted as evidence for Neolithic activity (Simmons *et al.*, 1983): as in the previous zones, there is no direct evidence for agricultural activity, for example, cereal growing. During this biozone, soil acidity rose and bog growth probably continued.

Relatively few sites have yet been studied in this region for their Holocene (and Devensian late-glacial) pollen biostratigraphy. Blacklane Brook not only provides a key record of Holocene vegetation changes on Dartmoor but, in addition, forms a vital element in a national network of pollen sites which shows major regional variations in the vegetational history of the British Isles. In common with other sites in southern Britain, Blacklane Brook reveals that the periglacial conditions of the Younger Dryas (= Loch Lomond Stadial) were replaced at *c.* 10 000 BP by the gradually ameliorating climate which marks the onset of the Holocene and the progressive development of vegetation to mixed deciduous forest by mid-Holocene times. The record from this site provides important details of this succession, from the colonization of open heathland to the deciduous forest stage, and gives important insights regarding the composition of the forest and the height of the regional tree line. There seems little doubt that *Quercus* sp. was the dominant tree in the forest: its early arrival relative to other trees is a characteristic feature of pollen diagrams from South-West and south-central England (Conolly *et al.*, 1950; Seagrief, 1959, 1960; Simmons, 1964a).

The occurrence of wood remains (*Salix*, *Betula* and *Sorbus aucuparia* (rowan)) in the peat of bed 5 at Blacklane Brook is significant (Simmons, 1964a; Simmons *et al.*, 1983; Maguire and Caseldine, 1985). This, together with pollen evidence from elsewhere on Dartmoor, enabled Simmons (1962, 1964a, 1969) to estimate that the tree-line lay in the range between 427–457 m. This led him to argue that all of upland Dartmoor had been wooded during the so-called 'forest maximum' (Simmons, 1964a), a possible exception being the very exposed summits which may have remained bare, with waterlogged hollows and only thinly dotted with birch or oak-hazel scrub (Simmons, 1969). With the exception of some sites in Wales (Taylor, 1980) and on Bodmin Moor (Brown, 1977), this is one of the lowest published tree-line estimates in Britain for the period. Nowhere else is the tree-line fixed below 650 m; even in the Cairngorms and the Lake District it is reputed to have exceeded 760 m (Maguire and Caseldine, 1985). This has led to the suggestion that all of Dartmoor was in fact wooded at the time of maximum forest development, although, from macrofossil evidence alone, it is only certain that trees actually grew up to altitudes between *c.* 497 and 547 m OD (Maguire and Caseldine, 1985).

Equally significant is the record from Blacklane Brook of the rôle of prehistoric people in modifying the regional vegetation cover. Although many examples of forest clearance by Mesolithic people in the British Isles have now been reported (e.g. Dimbleby, 1962, 1963; Smith, 1970; Jacobi *et al.*, 1976; Mellars, 1976; Simmons, 1979; Simmons and Innes, 1981), and the evidence from Blacklane Brook shown to be by no means unique even on Dartmoor (Caseldine and Maguire, 1981; Hatton, 1991; Caseldine and Hatton, 1993), the sections here are important for they provided the first firm scientific basis for connecting small-scale fluctuations in the local pollen record with the activities of Mesolithic people: this was at a time when little such evidence had been adduced elsewhere (e.g. Dimbleby, 1962). The importance of the early pollen biostratigraphical work at Blacklane Brook (Simmons, 1964a) in this context has been enhanced by additional and more detailed pollen and macrofossil work and by the application of radiocarbon dating methods (Simmons *et al.*, 1983; Maguire and Caseldine, 1985).

The relative responsibility of climatic change and Mesolithic humans to account for these small-scale fluctuations in the pollen record has not been unequivocally determined (Cullingford, 1982). However, it is now widely accepted that Mesolithic alterations did occur to the woodland fringe areas (Caseldine and Maguire, 1986; Hatton, 1991; Caseldine and Hatton, 1993, 1996). There is no evidence at Blacklane Brook to support repeated burning of the area, as occurred in the southern Pennines and the North York Moors (cf. Jacobi *et al.*, 1976; Simmons and Innes, 1981). However, there is no reason why such local clearances were not effected by the use of fire to maintain open ground and scrub in a predominantly mature forest landscape: there is evidence (see above) that some areas of Dartmoor remained unwooded even at the peak of forest development. Alternatively, the Blacklane Brook evidence may suggest clearance as a reaction to the rapid encroachment of forest – which perhaps was less rich in necessary animal food resources than the more open and ecotonal systems which it replaced (Simmons *et al.*, 1983).

The appearance of a 'weed flora' subsequent to the 'elm decline' at *c.* 4260 BP, and perhaps after a temporary cessation of pressure on the local forests, was taken by Simmons (1964a) to be consistent with the archaeological picture of a very sparse Neolithic occupation of Dartmoor. However, the quality of evidence for the elm decline on Dartmoor is very poor (Caseldine and Hatton, 1996) and the interactions between early Neolithic activity and climatic/vegetational change are still poorly understood (Fleming, 1988; Caseldine and Hatton, 1996).

Conclusion

Blacklane Brook provides an important radiocarbon-dated record of vegetational and climatic changes on Dartmoor during the Holocene. This record charts the development of vegetation from the early Holocene colonization by open grassland and heathland through until the attainment of a mixed deciduous woodland dominated by oak in mid-Holocene times: the latter forest may indeed have spread to all but the most exposed summits of Dartmoor, and the wood remains from Blacklane Brook have long centred in a controversy regarding the height of the regional tree-line. Fluctuations in the pollen record thereafter provide crucial evidence for determining the relative effects of climatic change and anthropogenic activities on regional vegetation development: from the Blacklane Brook evidence, there seems little doubt that Mesolithic inhabitants were having an important impact on the forest cover, perhaps even as early as the eighth millennium BP. The details and precise durations of these anthropogenic activities have yet to be determined, and Blacklane Brook will undoubtedly play a key rôle in resolving many of the outstanding questions. Although elsewhere there is much evidence to suggest that Neolithic people had a much greater impact on the forest cover, Blacklane Brook shows no direct evidence of cereal cultivation or other agricultural practices at this time. This has been used to support the view that Dartmoor may have been only sparsely populated by Neolithic people. The pollen biostratigraphic evidence from this site complements that from Black Ridge Brook on northern

Figure 4.19 Shallow peat sections exposed along Black Ridge Brook, northern Dartmoor. (Photo: C.J. Caseldine.)

Dartmoor, where an extensively radiocarbon-calibrated profile provides particularly detailed evidence of changing conditions at the Devensian/Holocene transition.

BLACK RIDGE BROOK
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Highlights

Black Ridge Brook GCR site provides an important record of Devensian late-glacial and early Holocene environmental conditions on northern Dartmoor. It shows that human modification of the natural mid-Holocene forest cover occurred as early as Mesolithic times. The site has also yielded important information regarding the extent of woodland on Dartmoor during the 'forest maximum'.

Introduction

Black Ridge Brook has yielded one of the most extensive records of Holocene environmental change in South-West England. The human rôle in modifying the natural vegetation cover can be shown, on the basis of radiocarbon-dated pollen evidence from this site, to have begun as early as the Mesolithic. The pollen record has also been seen as central to establishing the extent of tree cover ('tree-lines') on Dartmoor during the forest climax in the mid-Holocene. Referred to by Caseldine and Maguire (1981), the site has since been studied in detail by Maguire (1983), Maguire and Caseldine (1985) and Caseldine and Maguire (1986). Pollen studies at this and adjacent sites have allowed a comprehensive picture of vegetational and environmental changes to be reconstructed for the area (Simmons, 1964a; Simmons *et al.*, 1983; Hatton, 1991; Caseldine and Hatton, 1993, 1996).

Description

Black Ridge Brook rises in the northern part of Dartmoor on the south-west-facing slopes of Black Ridge (573 m OD), an interfluve between the northerly draining West Okement river and the south-west-flowing Amicombe Brook. The Black Ridge Brook pollen site (SX 579842) is located

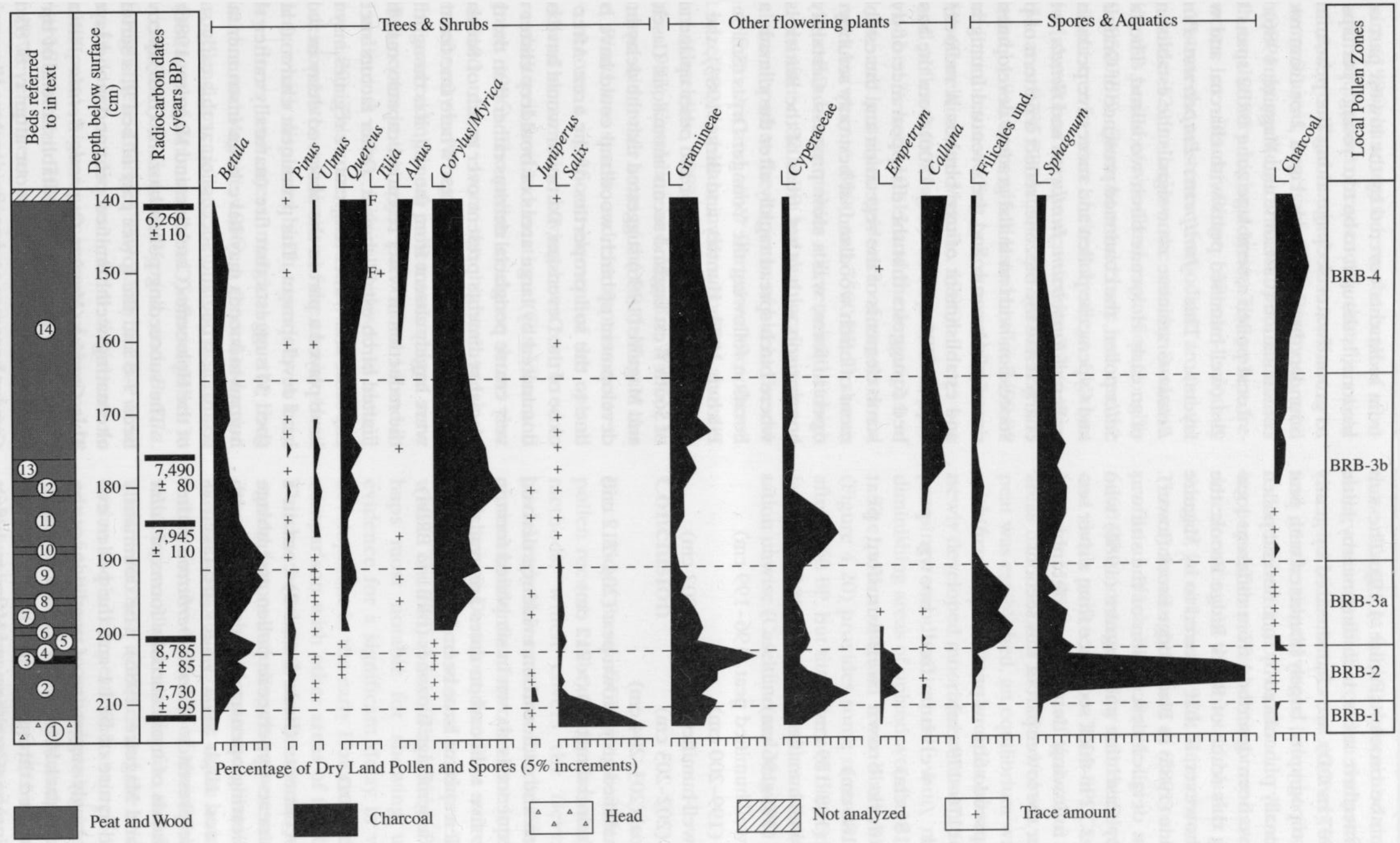

Figure 4.20 Simplified pollen diagram for Black Ridge Brook, adapted from Caseldine and Maguire (1986).

approximately at the confluence of the Black Ridge and Amicombe brooks (Figure 4.19). The surrounding interfluve areas, including nearby Little Kneeset (507 m OD), are characterized by gently undulating topography, largely blanketed with peat and occasionally punctuated by tors. Several pollen profiles have been described from different locations along this reach of Black Ridge Brook: the main site, however, is that referred to by Maguire and Caseldine (1985) as Black Ridge Brook (lower).

The most detailed description of the site was provided by Caseldine and Maguire (1986) who recorded a 2.12 m-thick sequence from a river section. The following detailed stratigraphy was provided for the lower part of this section:

14. Black pseudo-fibrous peat (140–176 cm)
13. Wood (176–179 cm)
12. Wood / well-humified brown peat (179–181 cm)
11. Grey/dark brown well-humified peat (181–188 cm)
10. Wood (188–189 cm)
9. Black well-humified peat (189–195 cm)
8. Wood (195–196 cm)
7. Black well-humified peat (196–199 cm)
6. Wood (199–200 cm)
5. Black well-humified peat (200–202 cm)
4. Wood (202–203 cm)
3. Charcoal (203–204 cm)
2. Well-humified grey/brown peat (204–212 cm)
1. Head (mineral matter) (> 212 cm)

The pollen and radiocarbon evidence derived from this sequence is shown in simplified form in Figure 4.20: five radiocarbon dates are available, and the pollen spectra have been divided into five local pollen assemblage biozones (BRB1 to BRB4).

Interpretation

The basal sediments (beds 1 and 2) contain a *Salix*-Gramineae-Cyperaceae pollen assemblage (BRB1), indicating open-ground conditions with very few trees. High *Salix* values are taken as denoting the presence of *Salix herbacea* rather than local stands of more shrubby forms of *Salix* (Caseldine and Maguire, 1986). The dominantly minerogenic nature of bed 1 and the pollen evidence are strongly suggestive of conditions at the Devensian late-glacial/Holocene transition, similar to those described throughout the British Isles and north-west Europe (Caseldine and Maguire, 1986). The radiocarbon date of 7730 ± 95 BP (GU-1606), from sediments covered by the lowest part of the biozone, is thought to be too 'young', perhaps due to groundwater seepage along the peat/mineral boundary between beds 1 and 2 or from rootlet contamination (Caseldine and Maguire, 1986).

Local pollen assemblage zone BRB2 spans beds 2–4 (well-humified peats with charcoal and wood layers). This *Juniperus-Empetrum-Pinus-Betula*-Gramineae zone signals the establishment of an early Holocene birch woodland. The fall in *Salix* pollen, the continued presence of Gramineae and Cyperaceae pollen and successive peaks in the pollen of *Empetrum*, *Juniperus* and *Betula*, which characterize the biozone, reflect a pattern of plant succession with an initial gradual development of dwarf birch scrub and the eventual immigration and establishment of tree birches. A radiocarbon date of 8785 ± 85 BP (GU-1700) from the base of bed 5 suggests that the disappearance of dwarf scrub elements of the vegetation and the establishment of birch woodland, at best only scrubby and open in form, was a slow process. Certainly, in comparison with other areas of the British Isles, where birch spread rapidly after the climatic amelioration following the Younger Dryas (Smith and Pilcher, 1973; Huntley and Birks, 1983), the late spread of birch to Dartmoor and other upland areas of South-West England seems anomalous. Caseldine and Maguire (1986) suggested that the delay in the development of birch woodland could have been due to the soil properties of the area. After the close of the Devensian, Dartmoor would have been dominated by large areas of bouldery clitter and very coarse periglacial detritus rather than the thick glacial sediments present over much of Scotland, northern England and Wales. Where fine fractions were largely absent from the soil, it is thought that the reduction in water retention capacity may have limited birch establishment. Other factors such as exposure and winter temperature regimes may also have played a part in the observed delay in woodland development. The prominent charcoal layer (bed 3) suggests that fire (naturally rather than human-induced) may have been instrumental in retarding woodland succession at this early stage of the Holocene (Caseldine and Maguire, 1986).

The succeeding pollen biozone (BRB3a) covers beds 5–8 and the lower part of bed 9, a series of alternating well-humified peat and wood layers. This *Corylus/Myrica-Quercus-Betula*-Filicales assemblage denotes the establishment of birch-hazel woodland on Dartmoor after *c*. 8785 BP. *Corylus* becomes co-dominant in the pollen record by *c.* 8500 BP, a relatively late date. Caseldine and Maguire (1986) have argued, on the basis of arboreal and shrub pollen frequencies, that for a time birch-hazel woodland reached close to, if not over, the summit areas, largely clothing Dartmoor, with perhaps only pockets of more open ericaceous heath on the very highest areas. The pollen frequencies at Black Ridge Brook certainly demonstrate the existence of woodland around the site, some 120 m below the nearby summits. During this period of woodland expansion (roughly 8700–8500 BP), *Quercus* would have become the dominant tree in more sheltered valleys. Changes in local conditions are also denoted by pollen zone BRB3a: at *c.* 8785 BP shallow *Sphagnum* bog was replaced by *Salix* carr which lasted until *c.* 7490 BP – well into the succeeding pollen assemblage zone BRB3b (Caseldine and Maguire, 1986).

Local pollen assemblage BRB3b spans the upper part of bed 9, beds 10–13 and the lower part of bed 14, and provides evidence of vegetational changes between *c.* 8000 and 7500 BP. It shows that woodland communities still remained at high altitudes after *c.* 8000 BP, but that locally, oak and hazel developed at the expense of birch; the evidence from this and other Dartmoor sites shows that hazel was dominant in the woodland above *c.* 400 m (Caseldine, 1983; Maguire, 1983; Simmons *et al.*, 1983; Caseldine and Maguire, 1986). In common with other areas of the South-West at this time, *Pinus* was sparse, and elm appears never to have become a significant element of the upland woodland community, having been restricted to more sheltered lowland locations (Caseldine and Maguire, 1986). The pollen evidence shows that woodland retreat from the highest areas of Dartmoor may have begun at *c.* 7700–7600 BP.

The succeeding local pollen assemblage zone (BRB4) occurs in the upper part of bed 14 and in the sediments above it (not analysed in detail; Figure 4.20). This zone opens at *c.* 7490 ± 80 BP, and demonstrates colonization of the area by *Alnus* (alder), which displaced birch especially in local valley floors and areas marginal to the bog (Caseldine and Maguire, 1986). A general reduction in woodland cover is indicated by increases in the percentages of Gramineae and *Calluna* pollen at the expense of *Corylus/Myrica* and *Betula*. Although these changes may partly reflect variations in local conditions – from *Salix* carr to blanket peat – higher percentages of charcoal in the profile after *c.* 7000 BP suggest that vegetational development was being governed by widespread external influences.

Caseldine and Maguire (1986) have argued that these changes (a fall in arboreal and shrub pollen, rising amounts of charcoal in the profile and the extension of blanket peat on relatively level ground and gentle slopes) were brought about by the recurrent burning of woodland by Mesolithic hunting populations. This burning may have led to soil deterioration and the onset of blanket peat formation (cf. Jacobi *et al.*, 1976; Simmons *et al.*, 1983). The continuous presence of charcoal in the peat profile at Black Ridge Brook up to and after *c.* 6260 BP is not matched by a further decline in tree and shrub pollen after *c.* 7000 BP. Caseldine and Maguire (1986) suggested that once the higher areas had lost their woodland cover, and blanket peat was established, an equilibrium was achieved with fire maintaining the open character of the newly developed moorland communities, and suppressing woodland there, but not further diminishing areas of upland woodland.

The pollen diagram from Black Ridge Brook (Figure 4.20) provides some measure of changes after 6260 BP, but the nature of the record and the lack of radiocarbon dates makes detailed interpretation unwise (Caseldine and Maguire, 1986).

Conclusion

Black Ridge Brook GCR site provides a detailed pollen record, calibrated by radiocarbon dating methods, which covers the Devensian late-glacial/early Holocene time interval. Sites providing environmental data from this time interval are not only rare on Dartmoor, but there are relatively few in South-West and central southern England as a whole. The record from Black Ridge Brook is perhaps most notable for showing unequivocal evidence for a significant delay in vegetational development in the early Holocene, especially in comparison with other areas of the British Isles. This has been attributed to a variety of environmental factors including the coarse nature of local parent materials and extreme climatic exposure. The site also provides some of the best evidence in Britain for the influence of Mesolithic people in reducing woodland cover by fire, and for providing a link with these activities and the widespread initiation of blanket peat. The site's pollen record is one of the most comprehensive in South-West England and is central to reconstructions of regional vegetation history. It is intimately linked to human influence on the natural landscape.