Quaternary of South-West England

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Chapter 3

Pre-Quaternary and long-term landscape evolution

THE PRE-QUATERNARY INHERITANCE

C. P. Green and S. Campbell

Introduction

The main outline of South-West England's landscape owes its origin to a combination of geological and tectonic controls and geomorphological processes in pre-Quaternary time. Together with other areas of southern Britain which escaped the major erosive and depositional effects of Pleistocene ice sheets, South-West England became a focus for numerous studies concerned with establishing the nature, distribution, ages and origins of various perceived erosion surfaces and related drainage networks (e.g. Balchin, 1937, 1946, 1952, 1964; Trueman, 1938; Wooldridge and Linton, 1939; Wooldridge, 1950; Bradshaw, 1961; Weller, 1959, 1960, 1961). These morphological studies mark an important stage in the development of geomorphological thought and technique. However, over much of South-West England there are relatively few on-land pre-Pleistocene deposits, and the great majority of relict features in the landscape are erosional and therefore almost impossible to date precisely. Overwhelmingly, the morphological evidence has proved profoundly unsatisfying, and until recently has lacked any serious confirmation from deposits (Kidson, 1977). However, two sites in particular provide significant evidence for establishing the nature and timing of major pre-Quaternary landshaping events and processes in the South-West, and are the subject of this chapter. St Agnes Beacon provides unique evidence for establishing the relative age(s) of erosion surfaces in the region (Walsh *et al.*, 1987; Jowsey *et al.*, 1992), while Beer Quarry shows a spectacular example of the controversial clay-with-flints, and has a major bearing on the pattern and nature of Palaeogene weathering processes. A brief synopsis of the early work on erosion surfaces and drainage networks, and a more detailed account of pre-Quaternary weathering residues, sediments and landform development are given here, both as an introduction to the subject and to the selected GCR sites. The long-term evolution of the characteristic granite terrains of the South-West merits separate consideration in Chapter 4.

Erosion surfaces and drainage networks: a brief history of research

Erosion surfaces have been recognized at a variety of heights throughout South-West England, up to and including the summits of Exmoor, Dartmoor and Bodmin Moor. The first examples were probably recognized by Reid (1890), who described a narrow shelf around the south and west coasts of Cornwall. The location of fossiliferous marine deposits in a valley cut in this shelf at St Erth, and the presence of what appeared to be a degraded cliffline backing the shelf above *c.* 430 ft (131 m), led Reid (1890) and Reid and Flett (1907) to suggest a marine origin and early Pliocene age for the surface (cf. Milner, 1922; Wooldridge, 1950). A similar coastal plateau was recognized around Torquay by Jukes-Browne (1907), while Barrow (1908) drew attention to possible marine erosion surfaces (Miocene) on Bodmin Moor at 750 and 1000 ft (229 and 305 m, respectively). The first proponents of a subaerial origin for surfaces in the South-West were Davis (1909) and Sawicki (1912).

The 1930s and 1940s saw a proliferation of erosion surface studies in the South-West: Gullick (1936), Balchin (1937, 1946) and Pounds (1939) described further surfaces in Cornwall; Green (1936) extrapolated Barrow's (1908) Bodmin surfaces to east Devon; while Macar (1936) and Hollingworth (1939) provided more general accounts and attempted wider correlations. In 1941, Green described the high platforms of east Devon, distinguishing at least six erosion surfaces between 440 and 920 ft (134 and 280 m): these were believed to range in age from Miocene to Pliocene and to be marine in origin (Green, 1941).

In 1952, Balchin provided details of planation surfaces in the Exmoor region, describing a 'staircase' of eight surfaces ranging in height up to *c.* 1225 ft (373 m) and being separated by bluffs or 'worn-down clifflines'. At this time, the assumption was that the lower six surfaces were marine in origin. The possibility was acknowledged, however, that the summit level and the surface below it could have been formed subaerially in 'sub-Cretaceous' and 'early Tertiary' times, respectively (Balchin, 1952). An acceptance that even the marine-formed surfaces had undergone substantial subaerial modification was by now becoming implicit in the literature (e.g. Balchin, 1952; Stephens, 1952).

The 1960s saw substantial interest in the erosion surfaces and drainage networks of the South-West, with an increasing emphasis on measurement and statistical correlation. Detailed studies were undertaken on Bodmin Moor and in east Cornwall by Weller (1959, 1960, 1961); in north Devon (Arber, 1960); in west Cornwall (Everard, 1960b); in the Lizard Peninsula (Fryer, 1960); and in north-west Devon (Bradshaw, 1961). This work on erosion surfaces was to become intimately related to models concerning the development of drainage networks (e.g. Waters, 1951, 1953, 1960c; Kidson, 1962; Brunsden, 1963; Brunsden *et al.*, 1964). Fryer's (1960) study is notable in that it rejected a marine origin for all surfaces, save the 430 ft (131 m) level (cf. Reid, 1890), and invoked a single extensive surface, formed subaerially as a peneplain from Triassic times onward: this echoes views put forward by Jones (1951) concerning the evolution of the Welsh landscape. This shift in thinking is to some extent mirrored in subsequent studies. Orme (1961, 1964), for example, recognized four high-level planation surfaces around southern Dartmoor (Chapter 4): the upper two belonged to the early and mid-Tertiary respectively, the lower two to the late Tertiary. All were believed to have been formed subaerially. According to Orme (1964), the late Tertiary landscape was then drowned in early Pleistocene times to a height of *c.* 700 ft (213 m): a 'staircase' of forms below this level marked stillstands of the falling Pleistocene sea. Although Wooldridge (1950) noted similar surfaces up to heights of 1200 ft (366 m) (Calabrian), he ascribed the lower levels to retreat stages of the Pliocene sea.

In contrast, Kidson (1962) found no evidence in the South-West to support sea levels or marine planation above the general level of 210 m. The latter level was regarded as the most prominent surface in the region, representing the limit of an early Pleistocene marine transgression (Kidson, 1962, 1977; Brunsden, 1963; Brunsden *et al.*, 1964). Even the latter ascription has not gone unchallenged: Simpson (1964) dismissed this feature as an exhumed shoreline of Upper Cretaceous age (see below). Such datings would seem all the more unconvincing in view of the evidence from St Agnes Beacon, which shows that any geomorphologically significant transgressions of the sea above *c.* 75 m OD in post-Miocene times are highly unlikely (see St Agnes Beacon; Walsh *et al.*, 1987; Jowsey *et al.*, 1992).

Neither have attempts to link drainage development to the erosion surfaces and to general schemes of denudation chronology proved particularly rewarding. While many of the earliest studies on drainage systems were largely incidental to enquiries on the age and origin of the region's erosion surfaces (e.g. Clayden, 1906; Dewey, 1916), several notable attempts at a more holistic approach have been made. These include the work of Waters (1951, 1953, 1960c) in south-west Devon, and Wooldridge (1954), Brunsden (1963) and Brunsden *et al.* (1964). In general, an hypothesis of a falling, albeit oscillatory, base level from late Tertiary through Pleistocene times, producing both erosion surfaces and river rejuvenations, has been upheld (Balchin, 1964, 1981): Brunsden (1963) claimed that up to 17 separate stages in this development could be recognized in the catchment of the River Dart.

Pre-Quaternary weathering residues, sediments and landform development

Introduction

A more precise reconstruction of pre-Quaternary landform development, however, has been based on the nature and distribution of pre-Quaternary weathering residues and sediments and upon structural information. Evidence of weathering and soil formation is particularly useful since it may demonstrate the presence and environmental significance of palaeosurfaces. Datable, unconsolidated deposits found at given locations within the landscape, for example, the Miocene and Oligocene sediments of St Agnes Beacon, provide not only evidence of processes and environments at the time of deposition, but also important constraints on the extent and magnitude of later events and processes: in the context of St Agnes Beacon, it is highly unlikely that the sands and clays there could have survived a significant post-Miocene marine transgression or an incursion of Pleistocene ice. The importance of the age of the relict deposits remaining both as conformable and unconformable outcrops in the landscape is immediately evident. In the subsequent section, a brief outline of the chief surviving sedimentary evidence is given, followed by a possible model for pre-Quaternary landform development: the latter relies heavily on the synthesis given by Green (1985).

Pre-Quaternary sedimentary evidence in South-West England

In situ and reworked clay-with-flints

The oldest outcrops of post-Cretaceous/pre-Quaternary sediments in the South-West are found in east Devon, south Somerset and west Dorset. Here, relatively large areas of clay-with-flints and -chert cap the Chalk and Upper Greensand. Where *in situ*, these deposits have been classified as the Combpyne Soil (e.g. Isaac, 1979, 1981, 1983a, 1983b) and the Tower Wood Gravel (Hamblin, 1973a, 1973b) (Figure 3.1). Residual flint gravels also occur in solution pipes formed in Devonian limestone near Kingsteignton (Figure 3.3; Brunsden *et al.*, 1976). A Palaeocene age for these residual deposits has been established from several lines of evidence (see Beer Quarry), but not least because locally they underlie Upper Eocene–Lower Oligocene beds of the Bovey Formation (Edwards, 1976; Isaac, 1981). In many areas, these residual deposits were reworked by Palaeocene and Eocene fluvial processes, giving rise to a series of deposits which include the Peak Hill, Mutters Moor, Buller's Hill and Aller gravels (Edwards, 1973; Hamblin, 1973a, 1973b; Brunsden *et al.*, 1976; Isaac, 1981). Although evidence for dissolution of the Chalk and the redistribution of weathering residues is fragmentary and dispersed, Beer Quarry has been chosen by the GCR to demonstrate both an excellent example of *in situ* clay-with-flints and a spectacular series of solution-formed, clay-filled chalk pipes.

The Bovey Tracey and Petrockstow basins

Significant outcrops of post-Cretaceous/pre-Quaternary sediments are found in the Bovey Tracey and Petrockstow basins (Figure 3.1). These freshwater Eocene gravels and Oligocene sand, clay and lignite deposits, lie in fault-guided basins which were tectonically active at various times in the Tertiary: in places, these sediments overlie residual gravels of proposed Palaeocene age. They contain weathering products which have a bearing on the development of adjacent landmasses, especially the granite terrain of Dartmoor.

St Agnes Beacon

Mid-Oligocene and Miocene sands and clays occupy an area of some 1.6 km^2 around St Agnes Beacon in west Cornwall. Although the age and origin of these sediments have long been disputed, recent work has established the presence of two distinct Mid-Oligocene and Miocene outliers, the sediments in which were formed by a variety of lacustrine, aeolian and colluvial processes (Walsh *et al.*, 1987; Jowsey *et al.*, 1992). The site, described in detail in this chapter, is of great significance for constraining the age of landforms and erosional surfaces in the region.

St Erth

The St Erth Beds consist of sands and clays located in a valley at a height of *c.* 30 m OD in west Cornwall (Figure 3.1). The clays contain a rich marine fauna with strong Mediterranean affinities and many extinct species. Reid (1890) argued that the fauna indicated water depths of around 90 m, and postulated that the sediments had been laid down in a sea which was also responsible for cutting an extensive platform at about 430 ft (131 m) OD (Reid, 1890; Reid and Flett, 1907; see above). Reid correlated the St Erth Beds with the Lenham Beds of south-east England and ascribed both to the Pliocene.

Reid made no reference to earlier suggestions that the clay at St Erth was a 'boulder clay' containing marine shells. However, this possibility was revived by Mitchell (1965) who argued that the fauna had been deposited during the Cromerian and had been reworked by an ice sheet of Anglian age. Subsequently, Mitchell *et al.* (1973a) re-examined molluscs, foraminifera and ostracods from the clay and concluded, like Reid, that the deposits were marine in origin and Pliocene in age: a water depth of only 10 m, however, was suggested, giving a projected sea level some 45 m above present OD (Kidson, 1977).

Although a glacial origin for any part of the St Erth sequence is no longer considered likely, considerable controversy still surrounds the chronostratigraphic classification of the beds. In this context, the site is particularly significant in providing evidence for arguments over the position of the Pliocene/Pleistocene boundary which, in the United Kingdom succession, has a particularly controversial history. Currently, the boundary is based on a stratotype section at Vrica in southern Italy, which establishes an age of *c.* 1.6 Ma BP, more or less coincident with the end of the Olduvai magnetic event (Aguirre and Pasini, 1985). In the North Sea region, however, there is much evidence to suggest that the boundary should be older: exact definitions vary, but the base of the Praetiglian Stage (2.3 Ma) (Zagwijn, 1989; Gibbard *et al.*, 1991) or the transition between the Matuyama and Gauss magnetic polarity chronozones at 2.45 Ma

BP (Harland *et al.*, 1982) have been suggested (Balson, 1995).

Recent work on planktonic foraminifera indicates an age for part of the Red Crag between 3.2 and 2.4 Ma BP, that is Late Pliocene by either definition (Funnell, 1987, 1988). Foraminifera from the St Erth Beds indicate an age of *c.* 2.1–1.9 Ma BP (Jenkins *et al.*, 1986) – Pliocene according to the international definition of the boundary, but Pleistocene by most current United Kingdom practice. The St Erth site has been selected as part of the Pliocene GCR site network and will be described in the *Tertiary of Great Britain* stratigraphic volume of the GCR Series. The St Erth deposits, however, have been described widely in Quaternary and geomorphological literature pertaining to the region, and further consideration of their relevance is given below.

Crousa Common and Polcrebo Downs

There are other localities in South-West England where high-level deposits of post-Cretaceous/pre-Quaternary age are found. The most notable, perhaps, are found on Crousa Common and Polcrebo Downs in west Cornwall. The deposits on Crousa Common were described as early as 1843 by Budge, and consist of yellow clay with copious quantities of water-worn quartz pebbles (Stephens, 1980; Campbell, 1984), and occur at a height of about 110 m OD. Unlike the Polcrebo deposits (*c.* 152 m OD), they contain fossils (spores and pollen) but their age and origin are also unknown (Scourse, 1996b). Correlations, however, have been made between the Crousa/Polcrebo deposits and those at St Erth; a Pliocene age has often been alluded to (Hill and MacAlister, 1906; Reid and Scrivenor, 1906; Milner, 1922; Hendricks, 1923). Both marine and fluvial agencies have been suggested to account for the deposits, and although recent Scanning Electron Microscopy (SEM) work upholds a waterlain origin for those at Crousa Common (Campbell, 1984), precise environmental and age inferences cannot yet be made. Bowen (1994b) speculated that the deposits on Crousa Common could be glacial in origin, formed during an Early Pleistocene (Oxygen Isotope Stage 16) ice advance.

Similar gravels above 82 m OD in the Bristol district have been described by Palmer (1931). Mitchell (1960) correlated gravels at Hele near Barnstaple (56 m OD) with the St Erth Beds (Pliocene) and argued that neither ice nor sea level had attained this height since their emplacement. Kidson and Wood (1974), however, have argued that the Hele gravels are not marine but glacio-fluvial in origin, and have ascribed them to the glacial sequence which includes the Fremington Clay (see Chapter 7).

A controversial sandy flint gravel has also been described at Orleigh Court near Bideford in north Devon. This small outcrop, some 1.2 km long by 0.4 km wide, was regarded by Ussher (1879b) as re-sorted Cretaceous material of Tertiary age; by Boswell (1923) as Eocene; and by Rogers and Simpson (1937) as a derived deposit of at least post-Eocene age. Although the age and origin of these deposits are poorly understood, it is possible that they can be correlated with residual flint gravels of proposed Palaeocene age in the Haldon Hills (Tower Wood Gravel) and Beer/Sidmouth area (Combpyne Soil) (Edwards and Freshney, 1982; Green, 1985).

Pre-Quaternary landform development in South-West England: a synthesis

The pre-Quaternary origin of significant elements in the relief of the British Isles is now widely accepted. Historically, there have been two main schools of thought regarding the shaping of the pre-Quaternary landscape, and debate has centred on the key question of whether the bulk of denudation took place in the Palaeogene (e.g. Pinchemel, 1954) or in the Neogene (e.g. Wooldridge and Linton, 1955). On the Palaeozoic rocks of South-West England, there is clearly the added possibility that some landforms could be of Mesozoic age (Guilcher, 1949; Linton, 1951; Green, 1985). Recent work throughout southern England has certainly raised considerable doubts concerning the reality and age-range of the various geomorphological 'staircases' which have been proposed (see above; Jones, 1980; Green, 1985), and sedimentary and landform evidence from South-West England, in particular, has been fundamental in shifting opinion towards the Pinchemel school of thought. Although it is beyond the scope of the present work, which is overwhelmingly concerned with reviewing the Quaternary evidence, to examine all aspects of work and field evidence concerning pre-Quaternary landscape evolution, the following synthesis highlights the most important aspects with respect to the landforms and deposits of the South-West.

Pre-Tertiary geomorphological development

There is significant evidence that Permian–Triassic erosion effected the primary shaping of the present relief of the Palaeozoic rocks of western Britain:

massive denudation of the rocks of South-West England occurred at this time. The granites of Dartmoor (Chapter 4) range in age from Late Carboniferous to Early Permian (Hawkes, 1982) and are believed to have been intruded at depths of between five and nine kilometres below the surface. Despite this depth of intrusion, debris from the Dartmoor igneous complex occurs in Early Permian sediments, indicating substantial erosion and exposure of parts of the pluton within a surprisingly narrow time interval (Laming, 1982; Green, 1985). Material from the Dartmoor igneous complex is also present within Triassic conglomerates, and both Permian and Triassic sedimentary rocks locally provide excellent and familiar evidence of geomorphological and climatic conditions at the time of their deposition: breccias, aeolian and fluvial sands, conglomerates and mudstones indicate deposition under semi-arid conditions around the margins of a dissected upland (Green, 1985). Certainly, by the end of Triassic times, the rocks of South-West England appear to have been reduced to a surface of very low relief: progressive denudation is reflected in the passage upward in the thick (> 1000 m) Permian succession in Devon from basal breccias through sandstones to mudstones (Green, 1985).

Only relatively minor modifications to the Permian–Triassic landscape of South-West England are believed to have occurred during Jurassic and Lower Cretaceous times. Hart (1982) argued that South-West England remained a land area for much of the Jurassic: most of the Jurassic rocks of the Wessex Basin are marine shelf/shallow water sediments, and any terriginous inputs, such as clay minerals, appear to have originated from a landmass of low relief (Cosgrove, 1975). Certainly, no surfaces of Jurassic age can be recognized on the Palaeozoic rocks of the South-West, and evidence of Jurassic terrestrial weathering in southern England is confined to the Lulworth Beds of the uppermost Portlandian in south Dorset (Green, 1985).

The culmination of the Upper Cretaceous marine transgressions (Hancock, 1969) was a turning point of far-reaching significance in the long-term development of landforms in southern Britain (Green, 1985). The most elevated parts of the South-West Peninsula may have escaped submergence (Hancock, 1969), but over the rest of southern Britain a continuous cover of chalk was deposited. Towards the end of the Lower Cretaceous, the intensity of erosion appears to have increased in South-West England, presumably as a result of uplift: arenaceous sediments in the Lower and Upper Greensands reflect this intensification. In many areas of the South-West, the only evidence of a former chalk cover is the preservation of flint in residual deposits (clay-with-flints) or in later sediments derived from them (Isaac, 1981). Whatever the character of the relief across which the Cenomanian transgression extended, details of the subchalk surface must have been shaped by marine agencies. Although unconformities between the Upper Cretaceous rocks and older Mesozoic sediments are effectively planar, the planation effected by the transgression on the harder rocks of the Peninsula was less complete: some benches on the flanks of Dartmoor, however, have been explained as the product of the transgressive Upper Cretaceous seas (Simpson, 1964). The surviving evidence, however, fails to show whether the submergence of Cornubia was complete (Green, 1985).

Notwithstanding, it is highly unlikely that terrestrial surfaces and associated features of pre-chalk age in South-West England survived without some modification. However, the gross morphology of the region could well pre-date deposition of the Chalk and be the product of earlier Cretaceous or Mesozoic denudation (Green, 1985). It is also possible for rocks deeply weathered in pre-chalk times to have survived, and a pre-chalk age for the kaolinized granites of the South-West has been proposed (cf. Millot, 1970; Lidmar-Bergström, 1982; Esteoule-Choux, 1983; Chapter 4).

Chalk sedimentation in South-West England appears to have ended in mid-Campanian times (Figure 3.1). Since this is also likely to reflect the termination of marine conditions, removal of chalk by subaerial agencies could have begun as early as the Upper Cretaceous (late Campanian to Maastrichtian) (Green, 1985). Maastrichtian (Upper Cretaceous) and Danian (Lower Palaeocene) sediments are absent in southern England, but offshore they consist of pure limestones, consistent with denudation of chalk from contemporary land areas such as parts of South-West England.

Palaeogene geomorphological development

The uplands of east Devon, south Somerset and west Dorset furnish some of the most compelling evidence in Britain for Palaeocene denudation of the Chalk cover under tropical climatic conditions (Green, 1985; see Beer Quarry). This weathering reduced the Chalk over the Palaeozoic basement to a mantle of weathering residues, essentially the widespread clay-with-flints, the Tower Wood Gravel found on the summits of the Haldon Hills (Hamblin, 1973a) and the Combpyne Soil of the

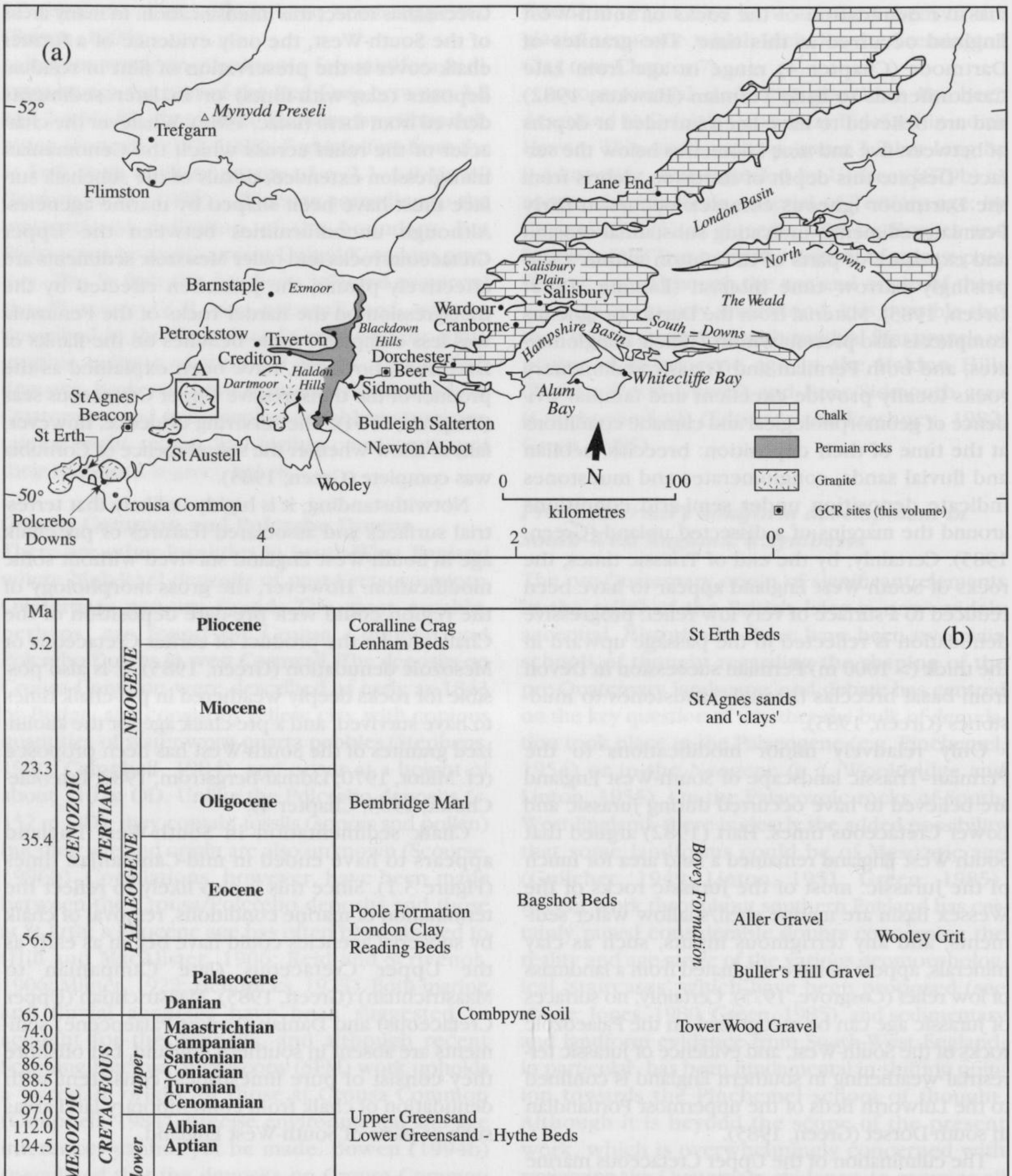

Figure 3.1 (a) Southern and South-West England, showing localities referred to in the text, and selected geological outcrops. (b) Significant deposits and events in the geomorphological evolution of southern Britain. (Adapted from Green, 1985, with timescale based on Harland *et al.*, 1982.)

Sidmouth and Beer area (Isaac, 1981, 1983b). Isaac (1983b) places the formation of the Combpyne Soil and Tower Wood Gravel in the Danian (Lower Palaeocene), and regards this as a time of intense lateritic weathering, when any former chalk cover was reduced to a mantle of weathering residues: in a few places, he identified *in situ* lateritic weathering characteristics such as pallid and mottled zones overlying red earth horizons. A Danian age is inferred by analogy with lateritic weathering of that age in the Interbasaltic Formation of Northern Ireland (Isaac, 1983b), although there appears to be no good reason why weathering of the Chalk could not have begun earlier, in the Upper Cretaceous (Green, 1985).

Late Palaeocene and Eocene erosion then occurred under subtropical climatic conditions. Evidence for this comes from the Tertiary gravel deposits of south and east Devon. Resting on the Tower Wood Gravel of the Haldon Hills, and directly on the Upper Greensand in the Kingsteignton pipes (Brunsden *et al.*, 1976) and around the margin of the Bovey Basin, are flint-rich gravels, the Buller's Hill Gravel of Hamblin (1973b) (see Figure 3.5). These gravels, and their lateral equivalents, the Peak Hill Gravels, are thought to have been reworked by fluvial processes from the residual Tower Wood Gravels and Combpyne Soil, respectively. In the Kingsteignton pipes, the Buller's Hill Gravels are overlain by the Aller Gravels (Edwards, 1973; Brunsden *et al.*, 1976): these gravels appear to be overlain by the main part of the Bovey Formation (Figure 3.5; Green, 1985).

Small amounts of Palaeozoic debris present in the Buller's Hill Gravel may indicate a renewed exposure of the basement at this time, and there are clear indications that the Late Palaeocene and Early Eocene saw repeated reworking of a thin veneer of sediments and weathering residues over substantial areas of the South-West. Isaac (1983b) has shown that kaolinite in deposits of the Bovey Formation, including the Buller's Hill Gravel, is less well ordered than in the *in situ* Tower Wood Gravel (residual). This has been taken to indicate a weathering phase separate from and shorter (or of lesser intensity) than the phase responsible for the Tower Wood Gravel and Combpyne Soil. Similar indications of *in situ* deep weathering profiles have been described beneath Oligocene Bovey Formation sediments in the Petrockstow Basin (Bristow, 1969), confirming the existence of a deeply weathered terrain in South-West England during the Palaeogene (Green, 1985). Silicified deposits (often termed Sarsens) are widespread in southern Britain, and most workers have proposed a Palaeogene age for their formation (see Beer Quarry; Clark *et al.*, 1967; Isaac, 1979, 1981, 1983a, 1983b).

Deposition of the bulk of the Bovey Formation appears to have occurred during the Eocene and part or all of the Oligocene: throughout this period, sediment was derived from erosion of deep but relatively immature weathering profiles developed on both granite and Upper Palaeozoic metasediments under subtropical or warm temperate climatic conditions (Green, 1985). It is likely that the erosional morphology of the summit relief on these rocks was acquired during this interval. An extensive erosional surface in the region between Salisbury Plain in the east and Dartmoor in the west appears to have developed, becoming refined by Early Eocene (London Clay) times by marine and fluvial agencies (Green, 1985). In south-east England, the Chalk inherited its present summit morphology before the end of the Palaeocene, prior to quite deep burial beneath later Tertiary sediments. Areas of Palaeozoic rocks in the west were drained by rivers running into the Early Eocene sea of southern England: there is no evidence that this sea, even at its maximum extent in London Clay times, extended farther west than the basin of the upper Otter (Green, 1974b, 1985). Faulting contributed significantly to relief development at this time, and also later in the Tertiary (Green, 1985).

Throughout southern Britain, there are consistent indications that denudation of the Chalk was largely effected under tropical or subtropical conditions before the end of the Palaeocene. In the Late Palaeocene and Early Eocene, the Chalk around the western fringe of the Hampshire Basin, and the rocks exposed by the removal of the Chalk both to the west and north of the surviving chalk outcrop in southern England, formed an erosional province in which a surface of low relief was widely developed (Cope, 1994). During the same interval, the area occupied by the Chalk outcrop in south-east England became an essentially depositional province and was buried beneath the Thanet Sands, the Reading Beds and a substantial thickness of Eocene sediments, derived largely from the northern part of the aforementioned erosional province (Morton, 1982). Towards the end of the Palaeogene (mid-Eocene onwards), the area of marine sedimentation in southern Britain became progressively smaller (Murray and Wright, 1974), although there is no evidence for the substantial production of terrigenous sediment. In fact, in the offshore record of Palaeogene sedimentation in the English Channel (Curry *et al.*, 1970), carbonate rocks predominate throughout and form the whole recorded sequence for the Middle and Late Eocene. The volume of Oligocene sediments is small, comprising in addition to the onshore outcrops, only one offshore record – of freshwater limestone. This scarcity of terrigenous sediment when most of southern England formed a land area strongly suggests a Late Palaeogene terrain of low relief close to base level (Green, 1985).

Neogene geomorphological development

The record of Neogene landform development in southern Britain is extremely difficult to interpret. This arises both from the deficiencies of the sedimentary record and the possibility that the Neogene consisted of a prolonged morphostatic phase – a time in which geomorphological activity was limited through one mechanism or another. Certainly, Neogene deposits in Britain are limited and scattered (e.g. the Coralline Crag and the St Erth Beds), and until recently, Miocene sediments were only known offshore around southern Britain (Curry *et al.*, 1970; Evans and Hughes, 1984): St Agnes Beacon, west Cornwall, however, is one of five known sites in the British Isles where fossiliferous non-marine sediments (in the case of St Agnes Beacon, sands and 'clays') of possible Miocene age have been preserved (Walsh *et al.*, 1987; Jowsey *et al.*, 1992; Walsh *et al.*, 1996), while the St Erth Beds provide the only sedimentary evidence for the incursion of the Pliocene sea in south-west Britain.

However, the recognition of a supposed Neogene erosional surface on the Chalk of south-east England (the Miocene–Pliocene peneplain) was central to the work of Wooldridge and Linton (1955) and their belief that the bulk of post-Cretaceous denudation had occurred in the Neogene. The reality of this peneplain has often been challenged (Pinchemel, 1954; Clark *et al.*, 1967; Green, 1985), and most indications are that the bulk of chalk denudation occurred much earlier in the Tertiary (see above; Jones, 1980; Green, 1985).

Certainly in the South-West, the disposition of Cretaceous and Early Tertiary sediments and weathering residues in relation to the broad pattern of relief on the Palaeozoic rocks, seems inconsistent with the production of a significant part of that relief by Neogene erosion: indeed, relief elements which can be referred confidently to the Neogene are virtually absent throughout southern Britain, and in the South-West, the late Palaeogene surface survives without convincing evidence of either Neogene erosion or significant solutional lowering. However, in other areas of southern Britain, such as parts of the Weald, erosional surfaces do appear to have developed, and have removed evidence of older Palaeogene surfaces and deposits (Jones, 1980). Such erosional areas now form the summit relief and clearly pre-date the Quaternary terrace sequences found in many river valleys: a Neogene age is therefore indicated. The summit relief of southern Britain is evidently not everywhere of the same age: substantial areas of the South-West appear to have escaped significant Neogene modification, while the latter's effects elsewhere are more clearly demonstrable. The lack of Neogene landform development over large areas of the South-West is best explained by a generally low level of relief in relation to base level, while differential development of relief is most readily explained by localized structural activity (Green, 1985).

The evidence from St Agnes Beacon demonstrates very clearly that, excepting unexplained local structural activity, there can have been no significant regional marine incursions above the general level of *c.* 75 m OD since the Miocene: the largely unconsolidated Miocene sands there are unlikely to have survived such an incursion. Evidence for a subsequent marine transgression on to the Peninsula in Pliocene times is witnessed by the deposits at St Erth (and possibly by those at Crousa Common and Polcrebo Downs), but the wider geomorphological effects of this incursion are unknown. Although, through amino-acid geochronology, the raised beach deposits of southern Britain have started to provide a framework for determining the changing pattern of Pleistocene land and sea levels (e.g. Bowen, 1994b), the overwhelmingly erosional nature of the evidence lends vast uncertainty to determining the nature and timing of geomorphological conditions and events in later Tertiary and early Pleistocene times. The low-level erosion surfaces, shore platforms and raised beach deposits with a major bearing on these issues are the subject of Chapters 6, 7 and 8.

BEER QUARRY

S. Campbell

Highlights

One of the best exposures of clay-filled chalk 'pipes' in Britain, Beer Quarry provides important evidence for interpreting solutional processes oper-

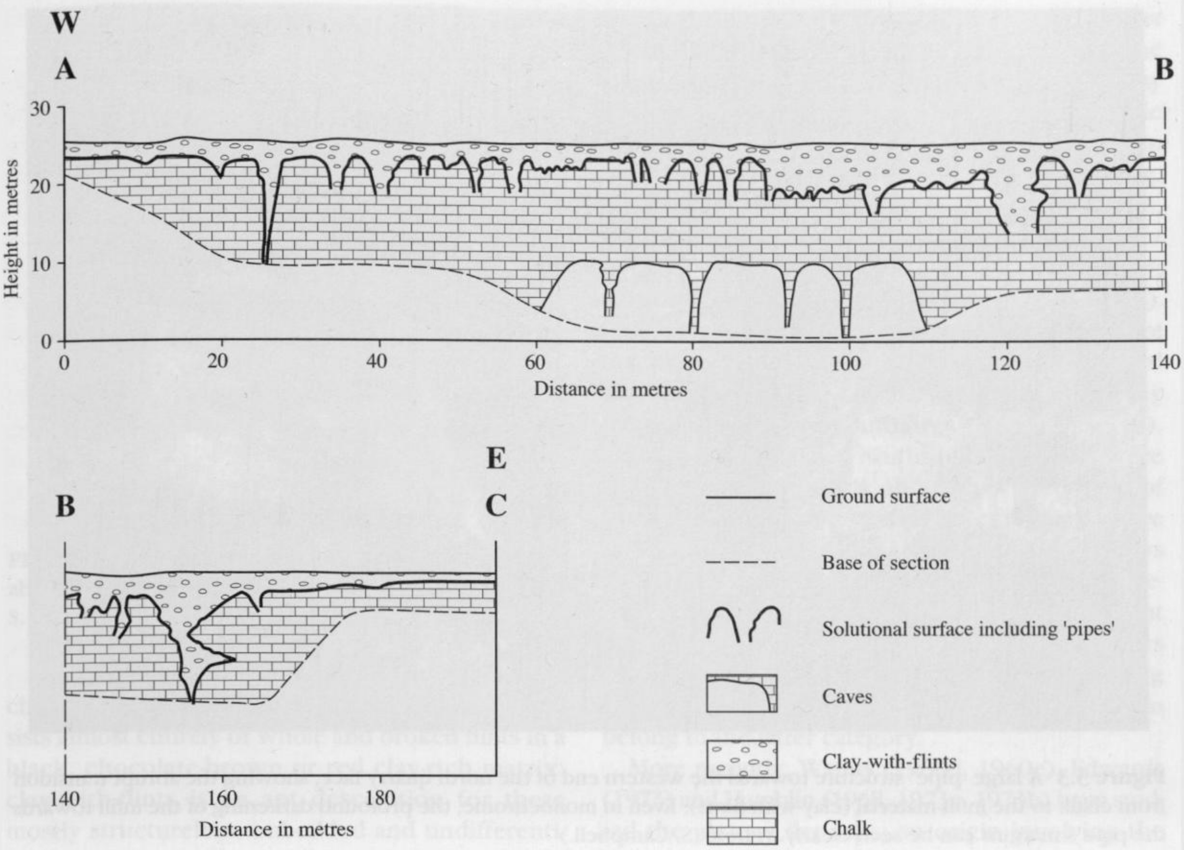

Figure 3.2 Clay-filled chalk 'pipes' exposed along the northern working face of Beer Quarry in 1990.

ating in chalk landscapes, and shows a classic example of the controversial 'clay-with-flints'. Recent evidence suggests that the pipes may have formed largely as the result of solutional processes which accompanied lateritic (tropical) weathering in the Palaeocene.

Introduction

Beer Quarry exposes important evidence for long-term, including pre-Pleistocene, landscape evolution in South-West England. A superb series of 'pipes' here was probably formed by chalk solution in the Tertiary: an infill of 'clay-with-flints' may be the product of dissolution of Upper Cretaceous rocks. Described in detail for the first time here, the features at Beer Quarry have a major bearing on reconstructions of the Tertiary palaeoenvironment of east Devon: these have formerly been adduced from weathering profiles and lithostratigraphic evidence found elsewhere in the plateau deposits of the region (e.g. Woodward and Ussher, 1911; Green, 1974a; Isaac, 1979, 1981, 1983a, 1983b). Little agreement exists as to the origins of solutional cavities and associated infill materials in general: Beer Quarry provides important evidence for both, and adds to the growing belief that these features are probably polygenetic and have formed at different times.

Description

Beer Quarry (SY 215895), one mile west of Beer in Devon, is noted for the famous Beer Freestone, worked here for centuries, and for an extensive network of caves cut into the Chalk during its extraction. The main area of caves, excavated as early as Roman times (Perkins, 1971), lies to the south of Quarry Lane, and is now a visitors' centre. The current workings, including the GCR site, lie to the north of Quarry Lane and consist of a large disused face between *c.* SY 213896 and 215896. Present freestone workings are restricted to a small area at the extreme eastern end of the face, and

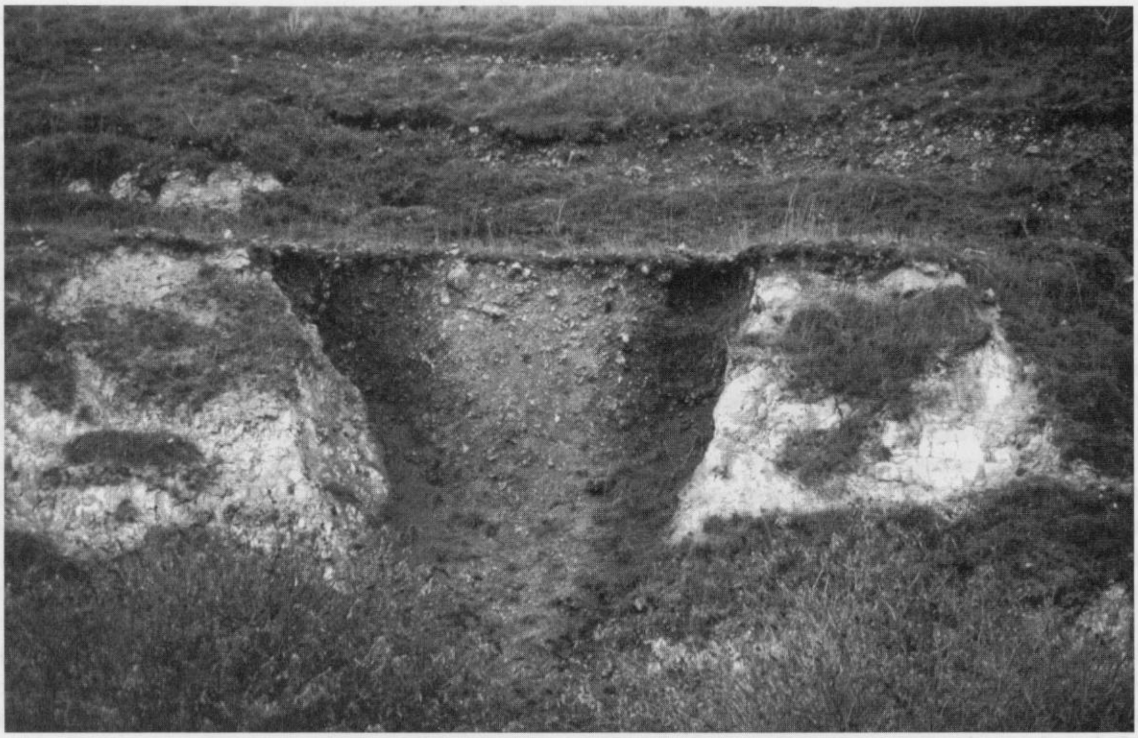

Figure 3.3 A large 'pipe' structure towards the western end of the north quarry face, showing the abrupt transition from chalk to the infill material (clay-with-flints). Even in monochrome, the profound darkening of the infill towards the pipe's margins can be seen clearly. (Photo: S. Campbell.)

other beds in the Middle Chalk are now worked for agricultural lime in the south-eastern part of the quarry. The quarry floor is occupied by plant and buildings and, in its deepest part, excavated caverns run north for about a quarter of a mile into a large chamber supported by chalk pillars (De la Beche, 1826; Ager and Smith, 1965). These adits underlie the main disused face (Figure 3.2) and were used as ammunition stores during the Second World War.

Jukes-Browne (1903) recorded a succession of Middle Chalk up to 24 m thick overlying Cenomanian limestone at Beer Quarry. The Beer Freestone, some 4 m thick, is the basal part of the Middle Chalk and is itself overlain by a series of more highly jointed, flinty, nodular and brecciated chalk beds (Jukes-Browne, 1903). These less coherent beds are penetrated from the top by solution cavities, here conveniently referred to as 'pipes'. Details of the pipe structures found in the northern quarry face are shown in Figure 3.2. These sediment-filled pipes are well exposed along the entire 200 m-long section (Figure 3.2; section A–C), and merge upwards into an extremely poorly sorted, flinty gravel which forms a continuous layer, some 2 m thick, at the top of the sections. Individual pipes are commonly 2–3 m deep by 2–3 m wide at the top; most, although not all, taper with depth. The pattern of piping, however, is extremely irregular. Many small pipes (< 1 m wide by 1 m deep) occur, in addition to several much larger examples (at 25, 120 and 155 m along the section; Figure 3.2). Features at 25 m and 155 m extend beneath the base of the exposed face and therefore exceed 15 m in depth. Some pipes are narrow, others much wider (e.g. those at *c.* 120 m and 155 m); between *c.* 90 and 115 m along the section, the Chalk has been replaced/dissolved over a broad area now occupied by flinty gravel at least 3.5 m in depth.

Similar pipes also occur elsewhere in the quarry, but are generally less frequent and less well developed. An extremely large, clay- and gravel-filled pipe occurs, however, at the easternmost end of the quarry. One example (Figure 3.2; section B–C) shows the infill material to occur beneath an *in situ* 'shelf' of unaltered chalk. In several pipes, the clay-with-flints is completely surrounded by unaltered chalk.

Most of the pipes show a rapid transition from

Figure 3.4 Detail of a typical pipe margin, showing the abrupt transition from chalk to clay-with-flints. (Photo: S. Campbell.)

chalk to infill (Figures 3.3 and 3.4). The latter consists almost entirely of whole and broken flints in a black, chocolate-brown or red clay-rich matrix: clay-with-flints is an apt description for these mostly structureless, unbedded and undifferentiated deposits. Material infilling the pipes is visually strongly similar to the capping layer: there is some suggestion that flints are more densely packed towards the base of pipes where, as a result, the deposit is almost clast-supported. Variations in the colour of the infill material do, however, occur. Generally it is reddest towards the top of the sections and dark chocolate-brown or black towards the base. Along pipe margins, the infill is frequently colour-zoned with a blackened band, almost 0.5 m wide, occurring next to the Chalk (Figures 3.3 and 3.4). Elsewhere, the different colours are abruptly juxtaposed without apparent pattern, perhaps having been disrupted by frost.

Interpretation

Details of the petrography and sedimentology of the deposits filling the pipe structures at Beer are not available, although the pipe structures were recorded by Ager and Smith (1965) and Perkins (1971). However, much information regarding the nature and origin of the infill can be gleaned from published studies of adjacent plateau deposits in east Devon (e.g. Woodward and Ussher, 1911; Waters, 1960d, 1960e; Hamblin, 1968, 1973a, 1973b, 1974a, 1974b; Edwards, 1973; Brunsden *et al.*, 1976; Isaac, 1979, 1981, 1983a, 1983b). The formation of the solutional cavities or 'pipes' may also be related to work on comparable karstic structures and associated infills found elsewhere in southern England and northern France (e.g. Osborne White, 1903; Kirkaldy, 1950; Avery *et al.*, 1959; Hodgson *et al.*, 1967; Mathieu, 1971; Thorez *et al.*, 1971; Pepper, 1973; Walsh *et al.*, 1973; Chartres and Whalley, 1975; Brunsden *et al.*, 1976).

The Tertiary plateau deposits of east Devon were first mapped and described in detail by Woodward and Ussher (1911), in the Geological Survey Memoir for the Sidmouth area (Sheet 326/340). Large areas of clay-with-flints and -chert were shown to cap the Chalk and Upper Greensand of the east Devon tableland. These deposits were divided into two groups (both Eocene): 1. clays and gravels with quartz, quartzite and other materials in addition to flint and chert; 2. clay with flint and chert – at least, in part, true clay-with-flints (Woodward and Ussher, 1911). Material infilling the pipes at Beer would appear, albeit visually, to belong to the latter category.

More recently, Waters (1960d, 1960e), Edwards (1973) and Hamblin (1968, 1973a, 1973b) have studied the plateau deposits: an origin involving the dissolution of the Chalk beneath a cover of Tertiary deposits has generally been invoked. The broad twofold division of deposits (Woodward and Ussher, 1911) has been upheld and, in the Haldon Hills, a lower residual unit and an upper fluvial unit have been identified (Hamblin, 1968, 1973a, 1973b).

Similarly, Isaac (1979) originally divided Tertiary plateau sediments in the Sidmouth area into two lithostratigraphic formations: 1. the Peak Hill Gravels (composed of unabraded flints in a matrix of kaolinite, and formed by the removal of calcium carbonate from the Chalk under lateritic weathering conditions); and 2. the Mutters Moor Gravels (derived from the Peak Hill Gravels by aeolian and fluvial processes). These formations are separated by an unconformity and, locally, silcretes are present.

Subsequently, Isaac revised this scheme and termed the *in situ* stony clays the Combpyne Soil, and their reworked equivalents the Peak Hill Gravels (Isaac, 1981). The former, he argued, originated as a Palaeocene lateritic weathering profile (with pallid and mottled zones), formed as the Chalk underwent dissolution beneath Tertiary overburden. This led to the development of kaolinitic residual flint gravels up to 10 m in thickness over much of the east Devon tableland: well-differentiated lateritic weathering profiles were preserved in irregular deep pockets in the Chalk, and it seems likely that the material infilling the pipes at Beer can be assigned, at least in part, to the Combpyne Soil lithostratigraphic formation.

Tertiary history in south and east Devon: a synthesis

Isaac (1981, 1983b) has argued that the Tertiary plateau deposits of east Devon are characterized by a complex of superposed weathering profiles which reflect a protracted pedological, diagenetic and geomorphological history, beginning with the emergence of the post-chalk land surface at the end of the Cretaceous. In essence, the plateau deposits represent a series of Tertiary palaeosols in part reworked during the Tertiary and disturbed by subsequent frost-action in the Pleistocene.

The oldest, and principal, Tertiary stratigraphic unit recognized in the Beer/Sidmouth area is the Combpyne Soil, developed as the Chalk underwent dissolution in a tropical (Palaeocene) climate on a relatively stable land surface (Isaac, 1981, 1983b). The depth of chalk dissolved and removed is unknown, but likely to have been substantial. Residual deposits (initially the Combpyne Soil) are mainly kaolinitic, non-indurated, lateritic weathering products. They include, however, a range of silcretes and siliceous indurated deposits reflecting protracted soil formation and diagenesis: the silcretes may indicate several separate periods of desiccation in an arid environment (Kerr, 1955; Isaac, 1979, 1981, 1983a, 1983b). A cycle, beginning with decalcification of the Chalk (and Greensand), followed by kaolinization accompanied by dissolution of residual quartz, and ending with localized silicification at various depths in the weathering profile, can thus be identified (Isaac, 1983b).

Subsequent reworking of the Combpyne Soil altered the structure of the original profile and led to the formation of the Peak Hill Gravels (Isaac, 1979, 1981, 1983b). West and north of Sidmouth, the Combpyne Soil was eroded differentially: where it was removed completely, Pleistocene gravels rest directly on deeply weathered Upper Greensand (Isaac, 1981). The Peak Hill Gravels (themselves reworked Combpyne Soil) have been correlated by Isaac (1979) with plateau deposits on the Haldon Hills to the east of the Bovey Basin. The residual flint gravel there, the Tower Wood Gravel, rests on decalcified Upper Greensand and is overlain by fluvial gravels (Hamblin, 1973a, 1973b). It has a similar clay mineralogy and lithological content to the Peak Hill Gravels, and is thus regarded as a westward continuation of the Sidmouth/Beer kaolinitic residual deposits (Isaac, 1979, 1981).

A Palaeocene age for the residual Tertiary sediments is based on several lines of evidence (Isaac, 1983b). First, the residual gravels underlie Upper Eocene to Lower Oligocene beds of the Bovey Formation (Edwards, 1976; Isaac, 1981), and are cut by faults thought to be of late Middle Eocene or early Upper Oligocene age (Isaac, 1981). Second, these lateritic weathering products have been correlated with the Interbasaltic Formation of Northern Ireland (Eyles, 1952), where clay-with-flints rests on chalk and is overlain by basalt. Radiometric dates (Evans *et al.*, 1973) show the Irish residual gravels to span 65–66 Ma BP, and thus a lowest Danian to Maastrichtian age has been proposed (Figure 3.1). A Palaeocene age for the Tower Wood Gravels of the Haldon Hills, with which the Peak Hill Gravels are correlated (Isaac, 1981, 1983b), was proposed independently by Hamblin (1973a, 1973b). A Palaeocene age thus seems appropriate for the Combpyne Soil, Peak Hill Gravels and associated silcretes (Isaac, 1979).

Following deposition of the Peak Hill Gravels and before the Mutters Moor Gravels were emplaced, a second deep weathering profile was established in the Sidmouth area – the Seven Stones Soil (Isaac, 1981). This zone of weathering, again characterized by mottled and pallid zones, occurs at some localities beneath Mutters Moor Gravels, and elsewhere affects the surfaces of the Peak Hill Gravels, Combpyne Soil and even the Upper Greensand where the former sediments are absent (Isaac, 1981) (Figure 3.5).

In addition to the residual flint gravels and associated pedogenic and diagenetic horizons, the plateau deposits of east Devon include the Buller's Hill Gravel (Hamblin, 1973a, 1973b) and the Aller Gravel (Edwards, 1973), both thought to be fluvial in origin (Figure 3.5). The former is believed to have originated from erosion and subsequent redeposition of the Tower Wood Gravel and, in addition, contains material from deeply weathered Upper Palaeozoic sediments (Isaac, 1983b). The Aller Gravel consists of up to 20 m of rounded quartz and flint gravels and sands with subordinate bodies of white to pale-grey silt and sandy clay (Isaac, 1983b). Although Hamblin (1974a) and Edwards (1973) have differed as to the origin of the Buller's Hill and Aller gravels, Isaac (1983b) is of the opinion that they are 'spatially and temporally closely related'. However, differences in lithological content could indicate that the two deposits are separated from one another perhaps by a fairly substantial time interval – in fact the time

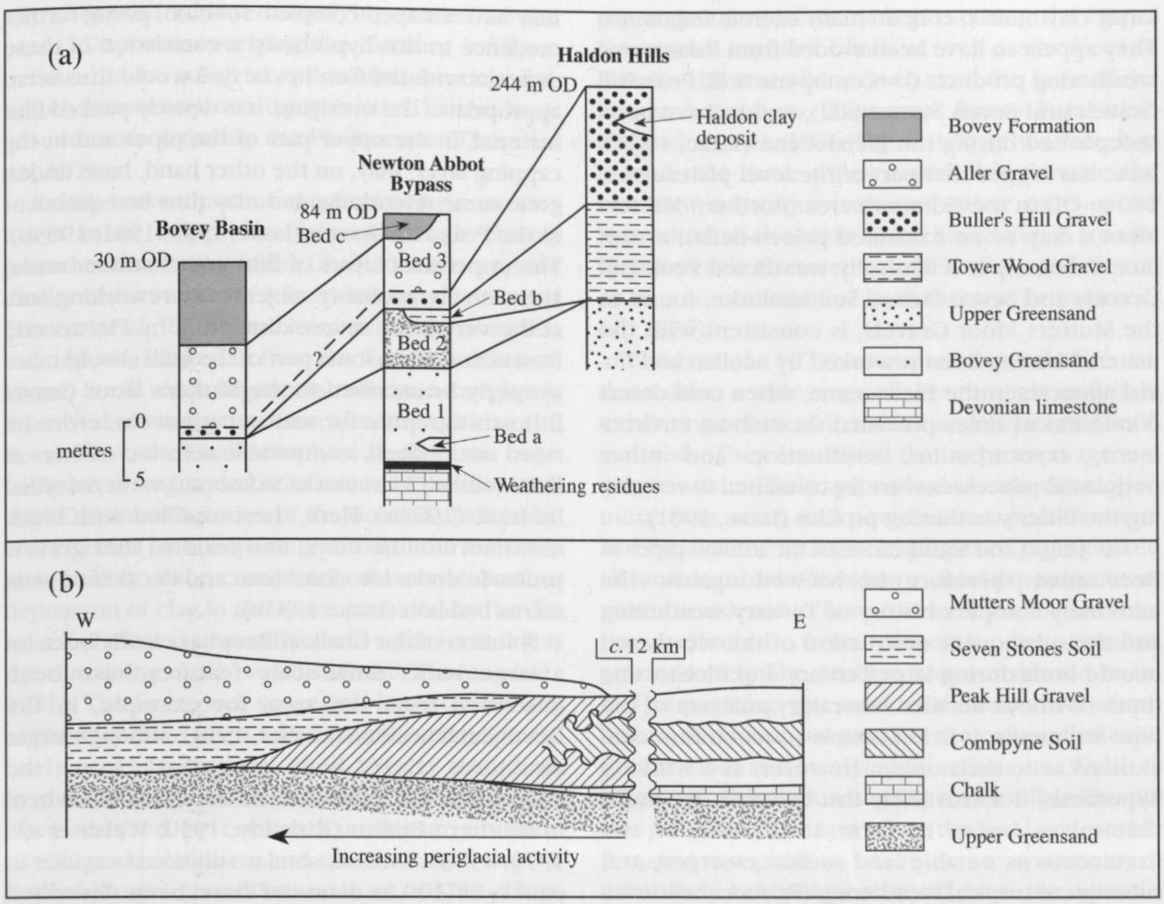

Figure 3.5 (a) Stratigraphic correlations of successions in the Bovey Basin, Newton Abbot bypass and Haldon Hills. (Adapted from Edwards, 1973, Hamblin, 1973b and Brunsden *et al.*, 1976.) (b) Schematic representation (not to scale) of field relations of major lithostratigraphic units in the Sidmouth area. (Adapted from Isaac, 1981.)

necessary to remove the Chalk cover from most, if not all, of South-West England. The Buller's Hill Gravel could therefore be Palaeocene, the Aller Gravel possibly mid-Eocene. Important evidence for the stratigraphic relationships of these deposits comes from solution cavities in Devonian limestone exposed along the margins of the Newton Abbot bypass (Brunsden *et al.*, 1976). Here, Aller Gravel overlies Buller's Hill Gravel which in turn overlies Tower Wood Gravel resting on Upper Greensand (Brunsden *et al.*, 1976; Isaac, 1983b; Figure 3.5). Since all four units are overlain by beds of the Bovey Formation (Upper Eocene to Oligocene), it is likely that the fluvial flint-rich gravels represent a phase of erosion and destruction of the flint-rich Palaeocene weathering profiles (residual sediments) before Bovey Formation sedimentation began: this must have occurred before Upper Eocene times (Isaac, 1983b).

Isaac (1983b) has argued that intra-Eocene tectonism played a key role in the destruction of the residual mantle formed by the deep weathering (Palaeocene) of Cretaceous sediments, and culminated in the initial downwarping of deep tectonic basins along wrench-fault zones: the Bovey Basin, for example, saw subsequent redeposition of the weathered Cretaceous mantle together with weathering products from the adjacent Dartmoor granite (Bristow, 1968) as well as more recently weathered (during the Eocene) Upper Palaeozoic meta-sediments which became exposed as the downwarping progressed.

In the Sidmouth area (Figure 3.5), a further flint-rich gravel, the Mutters Moor Gravel, has been identified (Isaac, 1981, 1983b). Unlike the Tower Wood and Buller's Hill gravels, which are offset by faulting associated with downwarping of the Bovey Basin (Hamblin, 1973a, 1973b), the Mutters Moor Gravels were not so affected (Isaac, 1981). These flinty gravels, with profuse angular chalk-flints in a sandy clay matrix, contain many silcrete fragments. They appear to have been eroded from Palaeocene weathering products (= Combpyne Soil, Peak Hill Gravels and Seven Stones Soil), and to have been redeposited during the Pleistocene (Isaac, 1981). Isaac has argued that part of the level plateau at *c.* 180 m OD in the Sidmouth area (northern Mutters Moor), may be an exhumed palaeo-deflation surface. Intensely mechanically weathered Peak Hill Gravels and Seven Stones Soil kaolinite, found in the Mutters Moor Gravels, is consistent with the material having been reworked by aeolian and fluvial agencies in the Pleistocene, when cold desert conditions at times prevailed. In such an environment, cryoturbation, solifluction and other periglacial processes were instrumental in reworking the older weathering profiles (Isaac, 1981).

The origin and significance of the infilled pipes at Beer must therefore be viewed against the extremely complex history of Tertiary weathering and the subsequent destruction of the weathered mantle both during later Tertiary and Pleistocene times. Without detailed laboratory analyses of the pipe-sediments, it is impossible to reach firm conclusions as to their origin. However, as a working hypothesis, it seems likely that the pipe structures themselves began to form at the end of the Cretaceous as a stable land surface emerged, and subsequent tropical weathering (Palaeocene) developed a thick mantle (flint-rich residual gravels) from beneath a covering of clay-rich Tertiary sediment. From Isaac's descriptions, it is not entirely clear whether the clay-with-flints contained in the pipes at Beer would represent the earliest *in situ* Palaeocene lateritic weathering products, the Combpyne Soil, or material reworked from these beds (Peak Hill Gravels). Certainly, two main fabrics can be discerned within the Beer pipe infill; the first, which occurs near the base of the pipes, shows a dense packing of tightly interlocking flints with little matrix. The second occurs towards the top of the pipes and in the continuous gravel capping. Here, the flints are less profuse, being supported in a red clay matrix. It seems reasonable to assume that the developing pipe structures, with steep sides and restricted lateral extent, would have prevented erosion and downslope reworking of the residual gravels, under almost any but the most severe conditions. The lower, densely packed flint material in the pipes may therefore have formed as lines of tabular and nodular flints were gradually let down, passively, from above as the Chalk was removed by solution (cf. Isaac, 1979). Small 'rafts' of chalk found towards the bottom of some pipes may have escaped complete solution, giving further credence to this hypothesis: a correlation of these deposits with the Combpyne Soil would thus seem appropriate. The overlying, less densely packed flint material, in the upper part of the pipes and in the capping layer, may, on the other hand, have undergone some reworking, and may thus be equivalent to the Peak Hill Gravels (Isaac, 1979, 1981, 1983b). The uppermost layers of flint gravel at Beer were, alternatively, probably subjected to reworking and, at the very least, severe disruption by Pleistocene frost-action. That some part of the infill should more properly be ascribed to the Mutters Moor Gravel lithostratigraphic formation cannot therefore be ruled out. Indeed, comparable solution cavities at Dunscombe (2 km east of Sidmouth) were recorded by Isaac (1983b). Here, they are filled with black montmorillonitic clays, and residual flint gravels protrude down into limestone and decalcified sediments beneath (Isaac, 1983b).

Solution of the Chalk at Beer has clearly been on a large scale. Small-scale features have been described from the area, for example, in the Devonian limestone (Ussher, 1913), although larger structures have been described from the Carboniferous Limestone and the Chalk elsewhere in southern Britain (Kirkaldy, 1950; Walsh *et al.*, 1972, 1973). Indeed, similar solutional cavities in excess of 100 m diameter have been described from Dorset (Arkell, 1947), Wiltshire (Jukes-Browne, 1905) and Kent (Worssam, 1963). Large-scale solution pipes were more recently described from Devonian limestone exposed during construction of the Newton Abbot bypass (Brunsden *et al.*, 1976), and comparable features in the Chalk near South Mimms, Hertfordshire, have long attracted attention (Wooldridge and Kirkaldy, 1937; Kirkaldy, 1950; Thorez *et al.*, 1971); there, the largest pipe noted was 10 m in diameter at the base of the pit.

Thorez *et al.* (1971) described the solution pipes at Castle Lime Works, South Mimms, as being filled with sands and pebbly deposits believed to be part of the Thanet Beds (Palaeogene). They argued that the Chalk had dissolved *in situ* beneath a cover of the Thanet Sands, by percolating water, the effects of which were heightened by the anticlinal structure of the Chalk and by a resultingly very low water-table (cf. Walsh *et al.*, 1973; see below) (Wooldridge and Kirkaldy, 1937). Initially, the Chalk was dissolved beneath the Bullhead Bed at the base of the Thanet Sands: at first, this bed supported the sand, but with continued dissolution of the Chalk and enlargement of the cavities, eventually collapsed with the overlying sands into the pipes. Deposits overlying the Tertiary infill are believed to be colluvial and solifluction deposits, which smoothed out irregularities in the local ground surface during the Pleistocene (Thorez *et al.*, 1971).

A dark brown, porous clay lining to the cavities has a more complex origin. Although closely related to dissolution of the Chalk, this is not a pure chalk residue: much of it is oriented and laminated (Thorez *et al.*, 1971), and it is interpreted as an illuvial deposit, washed in from the Tertiary sediments above. Small chalk fragments remain incompletely dissolved towards the base of some cavities (cf. Beer). Here, the Chalk dissolved along joints, eventually becoming sealed on all sides by the illuviated clay. Continued solution of the isolated chalk 'rafts' was effected by ions passing through the relatively porous clay: once completely dissolved, further deposition of clay in the space provided by the dissolved chalk was impossible, and voids were left as the remaining chalk was dissolved (Thorez *et al.*, 1971). The large pore space and low bulk density of the clay have been taken as indicating its relatively recent formation. In older clay-with-flints (e.g. at Beer?), the voids in the clay have frequently been reduced by continual collapse, alternate swelling and shrinking and the continued deposition of illuvial clay (Thorez *et al.*, 1971). Thus, although the same basic geological controls (namely a stable chalk surface overlain by Tertiary sediment) exists at both South Mimms and Beer, albeit in an entirely residual state at the latter, solution of the Chalk may have taken place at radically different times. This is also a conclusion drawn by Chartres and Whalley (1975) who studied dissolution features in chalk at Basingstoke. They argued that a brown clay lining to the cavities there had formed relatively recently, indicating that truly residual clays can form at any time by dissolution of underlying chalk. A similar explanation was put forward by Worssam (1981) to account for clay linings in loess-filled gulls (cambered fissures) at Allington in Kent. Here, large limestone blocks are surrounded by silt and are capped with clay linings: the linings must have been deposited after the blocks became incorporated into the silt, or they would show significant signs of tilting and/or disruption (Worssam, 1981).

In contrast, the large solutional features described in the Devonian limestone near Newton Abbot (Brunsden *et al.*, 1976) could show that the solutional processes there operated over a much more protracted timescale (Figure 3.5). These pipes contain sediments representing the Upper Greensand and the Chalk as well as the Eocene Buller's Hill and Aller gravels, and the beds of the Upper Eocene to Oligocene Bovey Formation (Brunsden *et al.*, 1976; Figure 3.5). It has been suggested that these pipes could therefore be the result of subsidence related either to: 1. prior hydrothermal alteration of the limestone; 2. a cover of permeable Cretaceous and Tertiary sediments; or to a combination of both factors (Brunsden *et al.*, 1976).

Walsh *et al.* (1973) attempted to synthesize evidence from a wide range of sites throughout Britain exhibiting solutional cavities and associated infill materials. They concluded that a common age and origin was unlikely: pipes had clearly developed more than once, and post-Eocene, post-Pliocene and Pleistocene interglacial phases of piping could all be recognized. On balance, most pipe structures were considered to have formed by selective solution effected from beneath by artesian groundwater. The process was considered to be self-propagating: the more chalk eaten away from below, the more progressive the collapse of solution residues and overlying fill-sediments (Walsh *et al.*, 1973). Gravitational collapse of infill sediments was only likely to cease when the local water-table dropped to a position where fissure systems were effectively bridged or shut off from the artesian source. Thus, in areas where water-tables and hydrological conditions had changed radically and repeatedly, complex histories and sequences of pipe development were likely. Walsh *et al.* also recommended that the varied, and often confusing, terminology used to describe 'pipes', 'pockets', 'fissures' and their associated infill, be rationalized to include three principal terms: 1. solution subsidence (the process); 2. solution subsidence deposit (the materials involved); and 3. solutional subsidence mass (the cavity or host body).

The evidence from Beer Quarry, in conjunction with detailed work carried out throughout the Beer and Sidmouth areas (Isaac, 1979, 1981, 1983a, 1983b), is of considerable relevance to understanding the origin of the controversial clay-with-flints and solutional processes operating in limestone terrains. Overwhelming evidence from this area suggests that solutional subsidence deposits, namely flinty residual gravels (= clay-with-flints) were formed as chalk underwent dissolution (solution subsidence) beneath Tertiary deposits. The pattern of structures (largely vertical or slightly oblique pipes) probably reflects major vertical joints in the Chalk subsequently exploited by solution. Well differentiated lateritic weathering profiles, developed in local sediments comparable to the infill material, together with locally developed silcretes, point to weathering, with complex patterns of diagenesis and pedogenesis, in a tropical environment: distinct phases of humid and arid conditions are likely to have prevailed at different times (Isaac, 1981, 1983b).

There is strong local stratigraphic evidence that most of this weathering occurred during the Palaeocene (see above). The concentration of illuvial clay towards the pipe margins at Beer (where there is a distinctly darker or blackened zone) has not yet been proven: in any case, there is evidence elsewhere to suggest that eluviation of clay minerals from overlying sediments could have occurred almost at any time from the earliest Tertiary to the present day. However, the identification of lateritic weathering products in residual flinty gravels found between the Chalk or Upper Greensand and Bovey Formation sediments (Upper Eocene to Oligocene) in east Devon, tightly constrains the age of the weathering event(s) and also, therefore, the principal phase of solutional activity, to the Palaeocene.

This degree of precision contrasts markedly with evidence from elsewhere in Britain and France where the age of the clay-with-flints has been much disputed (Pepper, 1973): most British workers have favoured a Pleistocene age, whereas workers in France have generally accepted ages within the Palaeogene for similar deposits. Neither is there agreement as to the age relationship of the clay-with-flints and its associated silcretes, in the form of 'sarsens' elsewhere in southern England (Isaac, 1979; Summerfield and Goudie, 1980). Thus although: 1. radiometric dates and the stratigraphic relations of the clay-with-flints in Northern Ireland (e.g. Wright, 1924; Fowler and Robbie, 1961; Evans *et al.*, 1973); 2. the evidence from east Devon (e.g. Isaac, 1979, 1981, 1983a, 1983b; Hamblin, 1973a, 1973b); together with 3. climatic evidence (Dury, 1971); and 4. a knowledge of the conditions necessary for silcrete formation (e.g. Watkins, 1967; Watts, 1978) would all support a Palaeocene age for the clay-with-flints at Beer, this can by no means be accepted for all other occurrences of similar deposits. Chartres and Whalley (1975), for example, provided convincing evidence to show that solution of the Chalk at Basingstoke had taken place almost entirely within the Quaternary. Using evidence from clay mineralogy, particle-size analyses and the morphology of chalk rubble within the infill sediments, they showed that the Chalk was affected by frost-action before the infill material (clay-with-flints) was formed, and that solution of the Chalk has since continued to produce an irregular weathering front. The clear implication is that there, no significant solution of the Chalk, in the Tertiary, preceded this sequence of events, or if it did, that evidence was removed first. Such a view has been upheld by Pepper (1973) although it is at variance with French (e.g. Dewolf, 1970; Mathieu, 1971) and some English workers (e.g. Loveday, 1962).

The interpretation of solutional cavities and associated infills is therefore fraught with difficulties: rarely is any firm dating possible. Controversy even exists regarding the origin of the clay-rich zones found in some of the pipes, namely whether they are autochthonous (that is derived directly by decalcification of the Chalk with only superficial pedogenesis) or allocthonous (that is derived from material other than the Chalk, for example, washed in from a permeable cover) (Chartres and Whalley, 1975). Whether the kaolinite found in the residual gravels of east Devon was formed by *in situ* weathering (e.g. Green, 1974a) or derived from the granite mass of Dartmoor (e.g. Hamblin, 1973a, 1973b) where it may have formed by hydrothermal processes, is significant: a supergene origin, at least in part, for the Dartmoor growan is given some credence by the substantial evidence for weathering found in the Tertiary and Cretaceous rocks of east Devon (Bristow, 1968) (see Chapter 4).

Conclusion

The lack of detailed work so far carried out at Beer is surprising because the site demonstrates probably the finest examples of solutional pipes found in the Chalk anywhere in southern England: its conservation status can be justified on this basis alone. Although a preliminary description and interpretation of the site have been given here, precise details of the nature and origin of the pipe infill must await more comprehensive laboratory and field examination. Nonetheless, the infill material strongly resembles that studied elsewhere in the region and ascribed, on the basis of pedological and diagenetic characteristics and stratigraphic relationships, to Palaeocene tropical weathering. If, as seems likely, a correlation can be proved between the residual Palaeocene clay-with-flints of the east Devon tableland and the infill sediments at Beer, the latter will be one of very few examples of solutional activity in Britain which can be related to a precise stratigraphic timescale and to a well-established sequence of landscape evolution. The east

Devon tableland deposits, typified by those at Beer, and the residual deposits (growan) of the Dartmoor area (Chapter 4) together record vital evidence for the climatic and denudation history of South-West England during the Palaeogene. Collectively, they demonstrate a long and complex history of pedogenesis and diagenesis which is also typical of other deeply weathered regions of the world (Isaac, 1983b).

Until more detailed evidence is available from a wide range of sites, it is perhaps prudent to regard solutional cavities in general, and indeed the clay-with-flints as polygenetic (e.g. Hodgson *et al.*, 1967; Mathieu, 1971; Walsh *et al.*, 1973; Chartres and Whalley, 1975). It is certain that the debate concerning the origin of both will continue. In this context, Beer Quarry together with other GCR sites at South Mimms, Allington Quarry, Spot Lane Quarry and Bath University, provide a range of contrasting evidence for processes operative in limestone landscape development: these sites will be central to resolving the outstanding controversies.

ST AGNES BEACON

S. Campbell and R.A. Shakesby

Highlights

Rare, non-marine Miocene deposits occur here, and provide unique evidence for the long-term evolution of South-West England's landscape. The survival of the St Agnes sands and 'clays' indicates that this part of the South-West cannot have been overrun by glacier ice nor inundated by the sea since the Miocene.

Introduction

St Agnes Beacon is an important site for the interpretation of Tertiary stratigraphy. The site is also of considerable geomorphological interest because the deposits and the underlying bedrock surface have significant implications for regional landscape evolution – especially for the age and mode of formation of the sub-deposit surface, for its relationship to other 'erosion' surfaces in South-West England, and for establishing the extent and intensity of Pleistocene glaciation in the region. On the basis of these merits, the site has attracted wide interest from Quaternary scientists; hence its inclusion in this volume. The site was apparently first referred to by Borlase (1758) and subsequently by Pryce (1778), Boase (1832), Hawkins (1832), De la Beche (1839), Belt (1876), Davies and Kitto (1878), Ussher (1879a) and Whitley (1882). It was also studied by Reid (1890), Reid and Scrivenor (1906), Milner (1922) and Boswell (1923). More recently, the site has been discussed by Mitchell (1965), Atkinson *et al.* (1974, 1975), Hall (1974), Atkinson (1975, 1980), Edmonds *et al.* (1975), Wilson (1975), Campbell (1984), Coque-Delhuille (1987) and Goode and Taylor (1988). A detailed account of the stratigraphy, sedimentology and palynology of the deposits and their significance was given by Walsh *et al.* (1987). Further investigation of part of the deposits was published by Jowsey *et al.* (1992). The site has also been referred to in general texts by Austen (1851), Whitley (1866), Davison (1930), Gullick (1936); Robson (1944) and Macfadyen (1970).

Description

Although formerly regarded as a single outlier, the deposits at St Agnes are now believed to comprise two distinct outliers; the St Agnes Outlier and the Beacon Cottage Farm Outlier (Walsh *et al.*, 1987; Jowsey *et al.*, 1992; Figures 3.6 and 3.7). The sediments in the St Agnes Formation consist mainly of sands and clays and are arranged in an arc around the north and east slopes of St Agnes Beacon. This outcrop covers 1.6 km^2 and has a residual volume of some 5×10^6 m^3 (Walsh *et al.*, 1987), reaching a maximum exposure thickness of *c.* 10 m. Active workings only occur in New Downs Pits (Doble's Sandpits) (*c.* SW 706509). The following stratigraphy was proposed for the St Agnes Formation by Walsh *et al.* (1987):

3. Upper Sands – Beacon Member
2. Middle 'Clays' – New Downs Member
1. Lower Sands – Doble Member

The St Agnes Formation is underlain by Devonian slates ('killas') or by the St Agnes Granite. There is evidence that this sub-deposit floor is extensive; in New Downs Pits it is sub-horizontal and covers an area of some 1000 m^2. Its junction with the upper slopes of the Beacon appears to take the form of a steep stepped cliff, with an overall gradient of 45° or more (Walsh *et al.*, 1987). Davies and Kitto (1878) raised the possibility that the abrupt break of slope on the east side of the Beacon was a buried sea cliff. In New Downs Pits, the sub-deposit

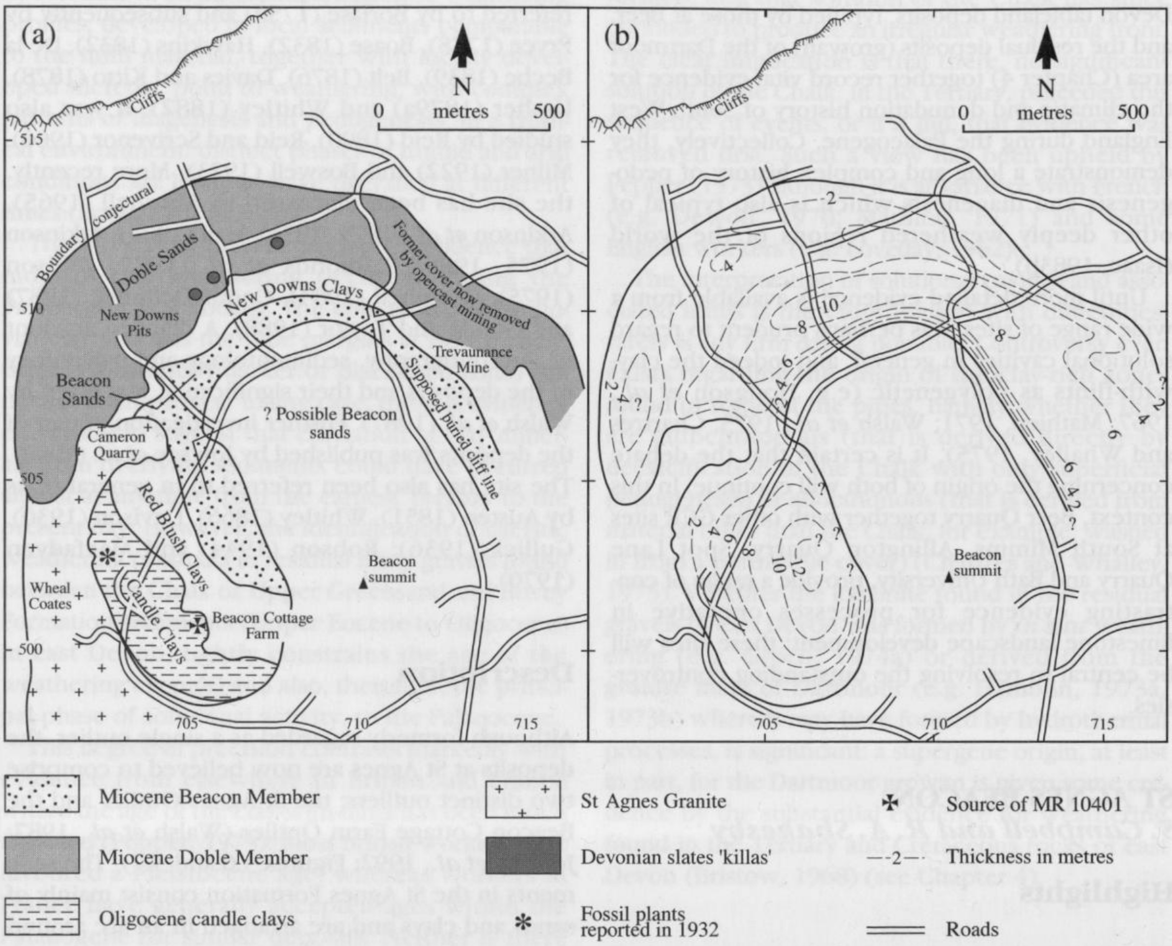

Figure 3.6 (a) The geology of the St Agnes and Beacon Cottage Farm outliers as interpreted by Walsh *et al.* (1987). The area between Cameron Quarry and the Beacon was regarded as problematic and has been re-mapped by Jowsey *et al.* (1992) (Figure 3.7); (b) Isopachs of combined Tertiary and Quaternary sediment. (Adapted from Walsh *et al.*, 1987.)

basement is stained red, lilac and orange to a depth of at least 1 m; derived clasts of stained killas in the overlying beds show clearly that the killas was weathered prior to deposition of the Doble Member (Walsh *et al.*, 1987).

The Doble Member is heavily cemented for a depth of up to *c.* 0.5 m at the base of the bed. The iron content sometimes exceeds 10% by mass and forms tubular structures up to 2 m long and 0.3 m wide – sometimes filled with uncemented yellow sand (Hosking and Pisarski, 1964; Atkinson *et al.*, 1974; Walsh *et al.*, 1987). Reid and Scrivenor (1906) recorded a bed of pebbles towards the base of the St Agnes deposit, although this is no longer evident.

The Doble Member (Lower Sands – bed 1) is around 5–6 m thick and consists largely of yellow or buff, well-sorted and fine-grained silty, quartz-rich sand. The bed becomes paler towards its junction with the overlying bed 2, with which it has a gradational contact (Walsh *et al.*, 1987). Epsilon-type planar cross-beds are evident, varying considerably in size; palaeocurrent directions indicate a source from the north-west (Walsh *et al.*, 1987). This sand bed is interrupted by a 10 cm-thick band, 1.8 m above the base of the bed, comprising rounded pebbles of vein quartz and sandstone and large angular cobbles of stained killas.

The succeeding New Downs Member (bed 2) is a pale-grey deposit up to *c.* 3.5 m thick. It has frequently been described as a clay, but in fact comprises mostly silt and sand with some clay. Isolated vein quartz pebbles occur towards the top of the bed, which is sharply truncated. Sediments

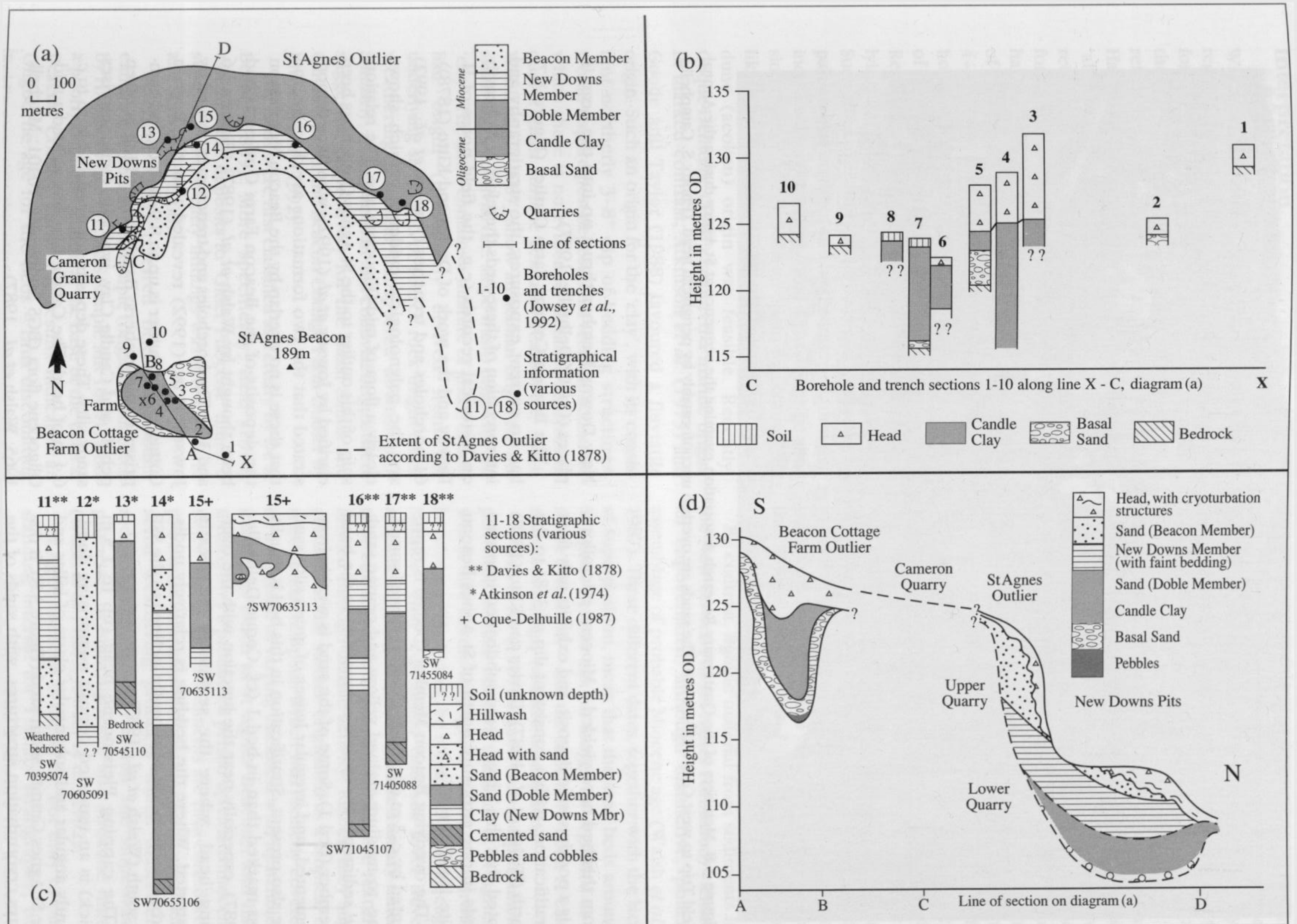

Figure 3.7 (a) A revision of the St Agnes and Beacon Cottage Farm outliers by Jowsey *et al.* (1992). (b) Borehole and trench sections along line X–C (diagram a), adapted from Jowsey *et al.* (1992). (c) Stratigraphic sections along line D–C (diagram a), compiled from various sources. (d) Schematic reconstruction of the Beacon Cottage Farm and St Agnes outliers, based on Jowsey *et al.* (1992).

Figure 3.8 Members of the Quaternary Research Association examine the sequence at St Agnes during the Annual Field Trip to west Cornwall in 1980. The sands are overlain unconformably by periglacial head. (Photo: S. Campbell.)

from this bed have yielded a Miocene microflora. It is a poorly sorted deposit, and exhibits only faint stratification, with a consistent dip of 3–8° to the north (Walsh *et al.*, 1987). Davies and Kitto (1878) noted that the 'clays' were subdivided into two beds in one exposure north of St Agnes Beacon (Site 16; Figure 3.7).

The overlying Beacon Member (bed 3) is represented by *c.* 3 m of cross-bedded, very well-sorted, fine- to medium-grained yellow and orange sand; the sediments are closely comparable to the basal member (bed 1). Some of the sand is weakly iron-cemented, and irregular lenses of green silty sand are also present. Stratification in this bed is usually less marked than in bed 1 (cf. Coque-Delhuille, 1987), especially near the junction with the overlying head, where the sediments are greatly distorted. Where the bedding is relatively undisturbed, foresets are dominantly inclined to the SSE or south (Walsh *et al.*, 1987).

The capping Pleistocene head (up to 1.5 m thick) is an unsorted deposit comprising dominantly angular and subangular clasts of killas and the St Agnes Granite set in sand (Figure 3.8). It displays cryoturbation structures, with sands of the New Downs Member thrust up into the head in places (Coque-Delhuille, 1987).

The Beacon Cottage Farm Outlier (Figure 3.7) has no current exposures: the stratigraphy and interpretation of these beds therefore rests heavily on historical records (e.g. the field notes of H. Dewey and the work of Davies and Kitto (1878)), 61 boreholes and trenches (Jowsey *et al.*, 1992) and the palynological evidence, which shows clearly a flora of mid-Oligocene age. The relationship of this outlier to the St Agnes Outlier has been clarified by Jowsey *et al.* (1992), who have demonstrated that the two formations are discrete and that there is no overlap by the Beacon Member on the deposits of the Beacon Farm Outlier as had been thought by Walsh *et al.* (1987) (Figures 3.6 and 3.7). The boreholes and trenches excavated by Jowsey *et al.* (1992) revealed that the Beacon Cottage Farm Outlier is up to 8.9 m thick and comprises two members: Basal Sand which is often pebbly and Candle Clay, which in fact comprises sandy silts. These deposits are overlain by up to *c.* 6.4 m of head. The Candle Clay has yielded a mid-Oligocene flora (BGS Sample MR 10401; Mitchell, 1965; Walsh *et al.*, 1987).

Interpretation

William Borlase in 1758 (Macfadyen, 1970) regarded the St Agnes beds as marine, having been formed by an event that could be 'no other than the universal deluge'. The sediments were also referred to by Pryce (1778), Boase (1832) and Hawkins (1832), the latter considering them to be 'alluvial'. Davies and Kitto (1878), however, returned to the proposition that the sands had formed in a marine environment, with the clay having been deposited in 'a sheltered embayment of the sea'. An apparently 'shingle-worn' cliff some 4–8 m high and a postulated sea-stack, caves and hollows – exposed by mining in 1875 to the east of the Beacon – led Davies and Kitto and, later, Reid and Scrivenor (1906) to regard the sands overlying and banked against these features as marine. Such an explanation for the beds was supported by particle-size analyses and by the interpretation that individual sand grains showed signs of marine abrasion (Milner, 1922). Such an origin was considered likely by Boswell (1923), who also noted that a dune (aeolian) origin was feasible. Recently, Coque-Delhuille (1987) favoured a marine origin. In marked contrast, Atkinson *et al.* (1975) and Goode and Taylor (1988) favoured a fluviatile origin. Such an origin for the 'clay', with its consistent northerly 3–8° dip of bedding structures, would require post-depositional tectonic action for which there is no evidence. Detailed analyses of quartz grain surface textures (Campbell, 1984; Walsh *et al.*, 1987) show an aeolian origin for the sands and a colluvial (i.e. slope-wash) origin for the 'clay'. The latter contains a mixture of grains of aeolian origin (presumably derived from the underlying sand) and of source rock origin (rock weathering products transported downslope). Similarly, mainly aeolian and colluvial origins were suggested respectively for the Basal Sands and Candle Clay of the Beacon Cottage Farm Outlier by Jowsey *et al.* (1992).

The beds were first classified as Tertiary by De la Beche (1839). More specifically, Reid (1890) assigned the deposits to 'Older Pliocene' times: a summary of the early findings was given by Reid and Scrivenor (1906).

Mitchell (1965) referred briefly to pollen extracted from a lignite sample (originally collected by H. Dewey in 1932; BGS Sample MR 10401) from a poorly defined location at the base of the beds at Beacon Cottage Farm: the results indicated an Oligocene age for the beds – thus discounting Reid's view that the platform underlying the sand beds (the 130 m platform of Cornwall) was Pliocene in age, and that the St Agnes Beacon had been an island in the sea at this time. Further palynological examination of Dewey's sample (Atkinson *et al.*, 1975) led to a more precise ascription of the beds to the Middle–Upper Oligocene.

New dating evidence for the St Agnes beds was provided by Walsh *et al.* (1987). Their work shed additional light on the ages of the beds which have important implications for the long-term landscape evolution of west-central Cornwall. A re-analysis of the microflora in the BGS Sample (MR 10401) from sediments in the Beacon Cottage Farm Outlier confirmed a mid-Oligocene age for the flora (cf. Atkinson *et al.*, 1975) and suggested low-energy deposition for the 'clay' in a lacustrine environment (Walsh *et al.*, 1987), although later sedimentological analysis indicates a colluvial origin, as for similar deposits in the St Agnes Formation (Jowsey *et al.*, 1992). These sediments were tentatively correlated with equivalent beds of the Bovey Formation of Devon (that is of Palaeogene age).

By contrast, lignitic material from sediments in the New Downs Pits (St Agnes Formation) yielded an impoverished, although distinctive, pollen assemblage of probable Miocene age (Walsh *et al.*, 1987). These different dates, together with the lack of superposition, mean that the sand beds around St Agnes Beacon can no longer be regarded as a single formation – and the beds have been re-classified accordingly (see site description).

Walsh *et al.* (1987) argued that the prominent planation surface beneath the beds at St Agnes, which also occurs throughout much of Cornwall between *c.* 75–131 m, be termed the Reskajeage Surface. They concluded that sea level never reached this height in mid- and late Tertiary times, thus eliminating the possibility that the feature formed through marine activity. Rather, they suggested that the surface originated as a tropical or subtropical etch plain which was formerly covered by a saprolite of varying thickness with upstanding inselbergs (such as St Agnes Beacon), and had formed over a protracted period up to late Miocene times. The St Agnes sediments are thus considered to be small remnants of tropical or subtropical subaerial weathering products which underwent redistribution by wind action and slope-wash processes in mid-Oligocene and Miocene times (Walsh *et al.*, 1987; Jowsey *et al.*, 1992).

St Agnes Beacon is therefore not only of outstanding interest for Tertiary stratigraphy, but demonstrates important evidence for long-term landscape evolution in South-West England. The sediments of the St Agnes Outlier, with their microflora of Miocene age, are one of only five on-land Miocene deposits known in the British Isles (Walsh *et al.*, 1996): this has major implications for interpreting the Cornish landscape. Ascription of the Beacon Cottage Farm Outlier to an earlier date than the St Agnes Formation, despite similar sedimentological characteristics, hinges on a museum sample for which there is no good locational or stratigraphic control. Indeed, Coque-Delhuille (1987) regards the provenance of this sample as too uncertain, and on these grounds rejected an Oligocene age for the Beacon Cottage Farm Outlier. If, as suggested, however, the sand and 'clay' beds around St Agnes Beacon do comprise two distinct outliers of mid-Oligocene and Miocene ages (Walsh *et al.*, 1987; Jowsey *et al.*, 1992), then the relationship of the Reskajeage Surface to these sediments is vital to understanding the age and mode of formation of this important macro-element in the Cornish landscape. Although it is clear that the surface underlies the Miocene St Agnes Formation, until recently the relationship of the surface to the older (mid-Oligocene) Beacon Cottage Farm Outlier has been less certain. Walsh *et al.* favoured the view that part of the St Agnes Outlier overlay that of the Beacon Cottage Farm (Figure 3.6), the surface of the latter possibly representing a stained and deeply weathered soil of mid-Tertiary age underlying the sub-Miocene unconformity. This view, however, is no longer tenable as there appears to be no overlap of the two formations (Jowsey *et al.*, 1992). If, as Walsh *et al.* have suggested, the Reskajeage Surface had been cut in Miocene times, and the overlying Miocene sediments (wind-blown and colluviated) have never been subject to marine inundation, then the same must be true of the mid-Oligocene Beacon Cottage Farm Outlier which lies at a similar altitude (Walsh *et al.*, 1987). The surface cannot therefore have been formed by marine agencies in the interval between the mid-Oligocene and Miocene. This tends to demolish the often-expressed view that this surface is of marine origin; especially implausible is the suggestion of marine planation cutting across wide areas of hard Devonian metasediments and forming steep slopes in granite at Carn Brea, yet at the same time not also removing the weak Tertiary sands and 'clays' exposed on the northern slopes of the St Agnes Beacon (Walsh *et al.*, 1987). The simplest hypothesis then is to regard the Reskajeage Surface as a subaerial surface; by implication, any marine transgression or fashioning of the west-central Cornish landscape by marine agencies has been confined to levels below the Reskajeage Surface, and/or to pre-mid-Oligocene times.

This interpretation supports very strongly the view that the Cornubian Peninsula was more or less in its present form as early as the Eocene (Freshney *et al.*, 1982; Walsh *et al.*, 1987), and has subsequently only undergone what may be regarded as minor geomorphological alterations. Post-Eocene landscape evolution must therefore have been extremely slow; the only evidence for marine incursion on to the peninsula is a minor transgression at St Erth (Mitchell, 1965; Mitchell *et al.*, 1973a) during the Late Pliocene, and even this left no obvious bevel in the landscape (Walsh *et al.*, 1987).

This interpretation of the west Cornish landscape finds a close analogue with work carried out in Wales by Battiau-Queney (1984, 1987). She argued that in Wales there is only one, polygenetic planation surface, the original constituent landforms having been shaped in a tropical or subtropical environment with associated weathering products (e.g. Trefgarn Rocks – see Campbell and Bowen, 1989). Large-scale altitudinal variations were attributed by her to late Tertiary warping along relatively few major structural axes, the smaller-scale landforms, such as the tors at Trefgarn and Preseli (St Davids), being regarded as true 'inselbergs' (Battiau-Queney, 1984). Walsh *et al.* (1987) speculated that the Reskajeage Surface is also therefore present in Wales, citing tightly folded and planed Upper Palaeozoics in south Dyfed overlain by postulated Oligocene clays at Flimston (Murchison, 1839). This view has been strengthened by the recent discovery of fossiliferous Miocene deposits on Anglesey, which lends further support to the concept of a widespread 'Reskajeage/Menaian Surface', and to the possibility that large areas of Britain were formerly smothered by extensive sheets of Miocene sediment (Walsh *et al.*, 1996).

The Tertiary deposits near St Agnes Beacon therefore provide critical evidence to suggest that the macro-elements of the landscape in Cornwall (and perhaps farther afield) have changed comparatively little since the early Tertiary. In post-Tertiary times, geomorphological change has been essentially limited to comparatively small-scale modifications such as coastal denudation, valley incision and the redistribution of Tertiary weathering products (and less weathered rock) mainly by periglacial activity during Pleistocene cold phases.

The dating of the St Agnes beds as Tertiary, their highly eroded nature and location on a prominent headland on the north Cornish coast, make the proposition that Cornwall was ever inundated or even impinged on by a southward-moving ice sheet (even as early as the Anglian Stage) unlikely. The giant erratics of the Cornish coast (see Porthleven; Chapter 6), however, pose an intriguing problem as regards their mode of emplacement, as does the evidence for glacier ice having reached the nearby Isles of Scilly (e.g. Mitchell and Orme, 1967; Scourse, 1985a, 1987, 1991).

Conclusion

The St Agnes beds are not only of interest because of their Tertiary stratigraphy and implications for tectonic activity and high-level marine action, but also because of the important implications for landscape development during the Quaternary. First, the survival of these unconsolidated deposits on a promontory of the north Cornish coast is important evidence against glacier ice ever reaching Cornwall during the Pleistocene. Second, it also implies that repeated periglacial activity in the Pleistocene has been comparatively ineffective in redistributing unconsolidated sands and sandy silts on exposed slopes, even though freeze-thaw activity led to the production of angular debris from the bedrock slopes of St Agnes Beacon: thicknesses of up to *c.* 6.4 m of solifluction debris (head) were laid down and cryoturbation of upper sediment layers occurred. At the macro-scale, however, the implication is that the Cornish landscape has undergone only minor alteration to its late Tertiary form, notably with coastal modifications, valley incision and more limited alteration to general relief through periglacial action than some workers have advocated.