The Paleogene and Neogene of South-West England

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In this account we review the geology of the mainly terrestrial Paleogene and Neogene deposits of South-West England. These are mostly Paleocene to Oligocene in age, but Miocene deposits have been recorded at St Agnes, Cornwall (and possibly at Trewirgie, Camborne, Porkellis and Pendarves, all in Cornwall). Marine deposits of late Pliocene or Pleistocene age are located at St Erth in Cornwall.

This article is essentially a compilation of published work and other sources, with the aim of assembling in one place as comprehensive as possible an account of the deposits. We also look at more recent insights, notably into the geology of the Bovey Basin. There, new information enables a deeper understanding of the stratigraphy and depositional environments of the Eocene-Oligocene Bovey Formation, as well as a description of newly discovered ichnofabrics, and a revised interpretation of the origin of the lignites in the formation; these, previously considered to have been transported into the basin from *Sequoia* forests growing on surrounding uplands, are now interpreted as having formed *in-situ* in swamps.

Recent research on carbon isotope data from the Bovey Formation of the Petrockstowe Basin has provided important new insights into the dating of the sequence. Carbon isotope excursions recognised near the base of the sequence suggest the possibility that the Paleocene-Eocene boundary is present in the basin, with the basal 56–75 m of Bovey Formation being of Paleocene age.

We have also examined the complex and much-discussed evolution of the landscape of the peninsula and the formation of so-called ‘planation surfaces’. It is concluded, along with earlier authors, that the evolution of a single regionally extensive polygenetic subaerial surface (the ‘Reskajeage Surface’) provides the best explanation for their origin.

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Introduction

The Paleogene and Neogene systems, which together with the Quaternary System form the Cenozoic Era, encompass the interval of Earth history from 66.0 to 2.58 million years (Ma) ago. The Paleogene comprises the Paleocene, Eocene and Oligocene series, while the Neogene comprises the Miocene and Pliocene series (Fig. 1). During the Paleogene and Neogene, Britain was mostly land on the western edge of the major north-west Europe Basin. The Paleogene and Neogene deposits of Devon and Cornwall (Fig. 2) have largely been eroded and now comprise scattered and fragmentary outcrops, with more extensive and thicker deposits found in partly fault-controlled basins. The deposits, which include clays, sands, lignites and gravels, are rarely exposed and our understanding of them is based mainly on boreholes, and sections in pits which are, by their very nature, temporary and soon degraded. Dating of these, mainly terrestrial deposits, relies largely on the analysis of plant pollen and spores. They are mostly Paleocene to Oligocene in age, but Miocene deposits have been recorded at St Agnes, Cornwall (and possibly at Trewirgie, Camborne, Porkellis and Pendarves). The only known marine deposits, of late Pliocene or Pleistocene age, are located at St Erth in Cornwall and have been dated using foraminifera and molluscs. Carbon isotope studies of the Petrockstowe Basin have, for the first time, identified potentially dateable horizons near the base of the Bovey Formation, attributed either to the PETM (Paleocene–Eocene Thermal Maximum: ~56 Ma) or the ETM2 (Eocene Thermal Maximum2: ~ 54 Ma) (Chaanda *et al.*, 2023).

Climate

At the beginning of the Paleogene, southern Britain lay at a latitude of about 40º (12º south of its current position) and has gradually drifted northwards. The Paleogene and Neogene were periods of considerable climatic variation, amongst which were a number of brief episodes of oceanic and atmospheric warming (so-called hyperthermals). The ‘greenhouse’ world of the Paleocene, Early Eocene and early mid-Eocene changed with progressive cooling from the late mid-Eocene into an ‘icehouse’ world, with the growth of polar ice sheets from the beginning of the Oligocene.

Around the Paleocene–Eocene boundary (~56.0 Ma) a marked, geologically brief period of global warming, with temperature increase of 5º to 8ºC, is termed the Paleocene–Eocene Thermal Maximum (PETM). Estimates for its duration range from around 90 to 240 kyr (Charles, 2011). It is associated with a massive injection of ^{13}C-depleted carbon into the atmosphere and oceans, reflected in sedimentary rocks as a negative carbon isotope excursion (CIE). The PETM has been much studied owing to its recognition as a possible analogue for future greenhouse-gas-driven global warming. Although breakdown of seafloor methane hydrates was the first source to be suggested (Dickens *et al.*, 1995), there is still much uncertainty over the source, mass and rate of carbon released during the PETM. Another negative CIE is correlated with a hyperthermal termed the Eocene Thermal Maximum 2 (ETM2), dated at ~54 Ma (Ypresian).

The CIE of –2.5‰ at about 586 m depth in a borehole in the Petrockstowe Basin of north Devon is within the lower limit of that associated with the PETM, but was thought by Chanda *et al.* (2023) more likely to be associated with one of the other transient carbon isotopic shifts that occurred after the PETM, for example the ETM2.

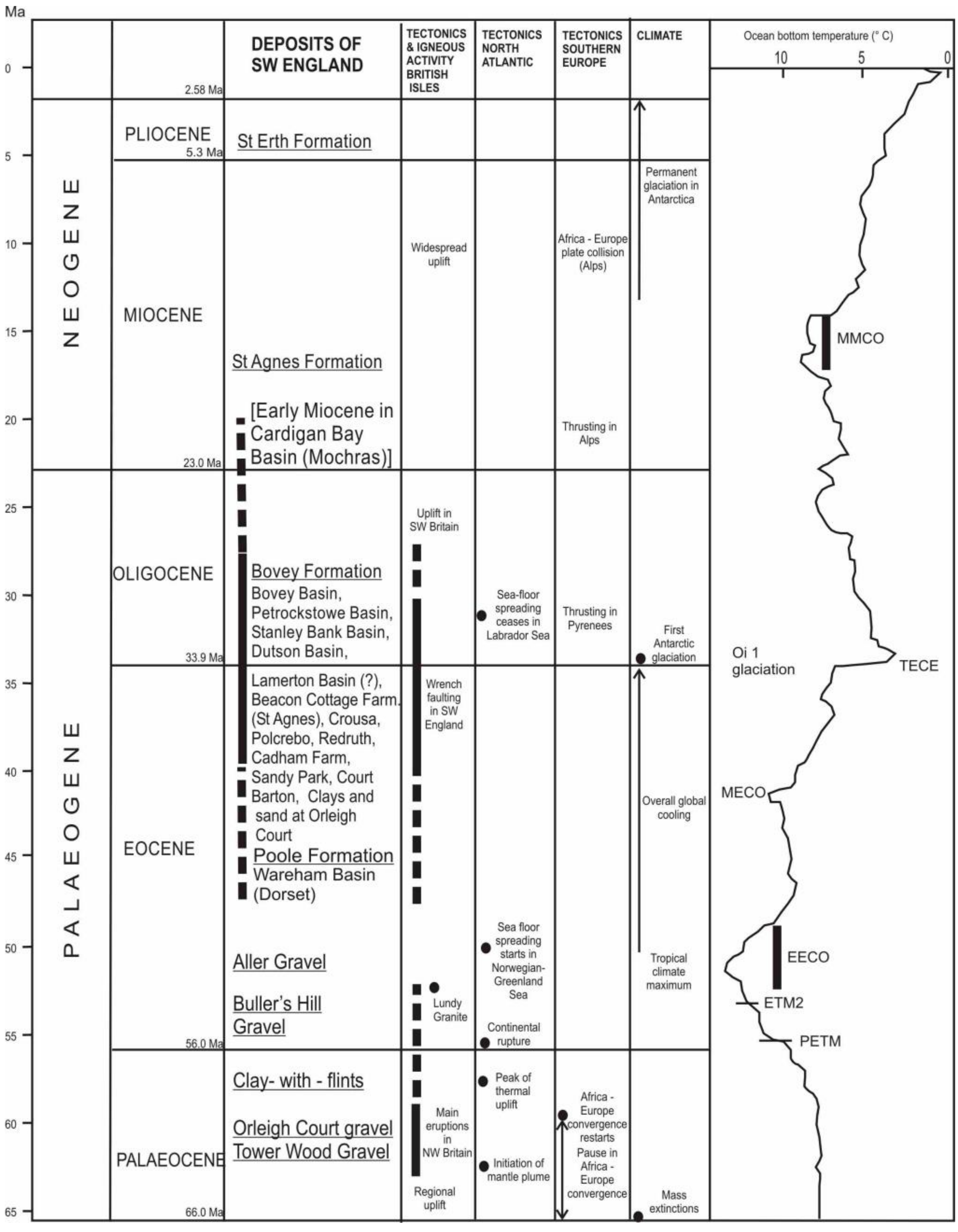

Figure 1. *Sub-divisions of the Paleogene and Neogene, showing the main deposits represented in south-west England. Ma = millions of years. Dates from International Chronostratigraphic Chart, version 2023/06, International Commission on Stratigraphy. Selected events from Anderton (2000, fig. 20.10). Temperature curve from Wright (2001, fig. 7). PETM = Paleocene-Eocene Thermal Maximum. ETM2 = Eocene Thermal Maximum2. EECO = Early Eocene Climatic Optimum. MECO = Middle Eocene Climatic Optimum. TECE = Terminal Eocene Cooling Event. MMCO = Middle Miocene Climatic Optimum.*

From the early Thanetian to mid-Ypresian there was a period of progressive warming culminating at ~53–49 Ma in the Early Eocene Climatic Optimum (EECO; Fig. 1). Following the EECO, global temperatures cooled progressively from the late Ypresian to the late Priabonian, with a brief (~500 kyr) episode of warming: the Middle Eocene Climatic Optimum (MECO) in the early Bartonian (~ 40 Ma). The late Ypresian *Azolla* event (*c.* 48.5 –49.0 Ma), is marked by a bloom of the free-floating fern *Azolla* resulting in the burial of large amounts of organic carbon in anoxic bottom waters, terminated the EECO and began the transition from a 'greenhouse' to an 'icehouse' climate.

The Eocene-Oligocene Transition (EOT; labelled Terminal Eocene Cooling Event (TECE) on Fig. 1) at about 34 Ma (Priabonian–Rupelian) lasted for *c.* 790 kyr and represents a marked and abrupt cooling in climate from a largely ice-free 'greenhouse' world to an 'icehouse' world (Hutchinson *et al.*, 2021), coincident with the establishment of the first ice sheets in Antarctica (Oi1 Glaciation). The climate in the Oligocene and Miocene was generally cooler, with an extended (*c.* 14–17 Ma-long) somewhat warmer interval, the Middle Miocene Climatic Optimum (MMCO). These cooler temperatures coincide approximately with the growth of Antarctic ice sheets which first formed in the early Oligocene, but probably did not become permanent until the Middle Miocene, at which date glaciers may have first formed in Greenland. Towards the end of the Pliocene there was rapid cooling into the Quaternary. Sea level during much of the Paleogene was considerably higher than today, but there was a major and sudden drop in the Late Oligocene (Chattian). During the Neogene, global sea levels were probably controlled mainly by variations in the volume of glacial ice.

The Lundy Igneous Complex

About 700 km south of the main British Tertiary Volcanic Province of western Scotland and Northern Ireland, a granite, numerous basaltic dykes and a few acidic dykes were intruded into Devonian rocks in the late Paleocene and now form

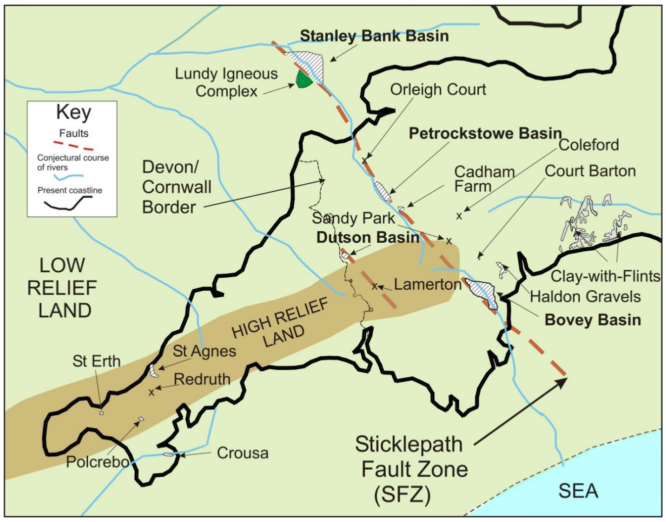

Figure 2. *Palaeogeographical map for the Late Eocene to mid-Oligocene (partly after Murray, 1992), showing the locations of Paleogene and Neogene deposits in South-West England.*

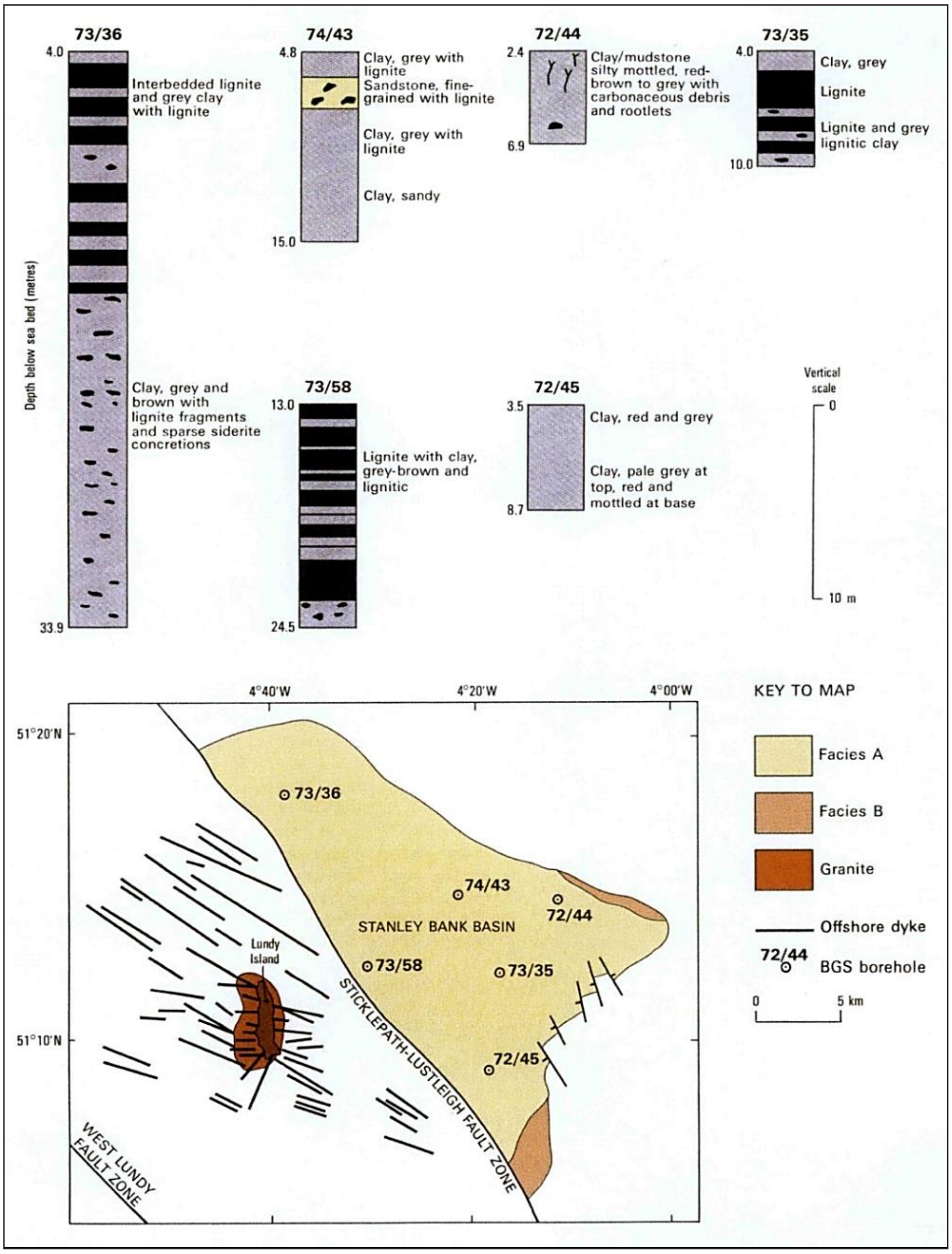

Figure 3. *Distribution of Paleogene rocks in and around the Stanley Bank Basin, with positions of BGS boreholes drilled into the basin. From Tappin* et al. *(1994, fig. 57). Reproduced with the permission of the British Geological Survey © UKRI 2024. All Rights Reserved.*

Lundy Island and the adjacent seafloor in the Bristol Channel (Dangerfield, 1982) (Figs 2, 3). The granite is in contact at the southern end of the island with a small area of Morte Slate (late Devonian). It is a coarse-grained peraluminous leucogranite composed of perthitic orthoclase, subordinate albite-oligoclase and quartz, with muscovite and biotite (Dollar, 1942; Edmonds *et al.*, 1979). Two main successive phases of intrusion (G1 and G2) have been identified, with localised later phases. Pb and Sr isotopic ratios indicate a crustal derivation.

A Rb-Sr whole-rock isochron for the granite yields an age of 58·7 ± 1·6 Ma with an initial $^{87}Sr/^{86}Sr$ of 0·715 ± 0·006 (Thorpe *et al.*, 1990), indicating an earlier (Paleocene: Thanetian) emplacement than the previously accepted Eocene (Ypresian) K/Ar date of 52 Ma (Dodson and Long, 1962; Miller and Fitch, 1962).

Lundy is located close to, and on the south-western side of, the offshore extension of the Sticklepath Fault Zone (Figs 2, 3). The granite is associated with a major, positive gravity anomaly a few kilometres to the north-west that is attributed to an underlying basic body between 2.5 and 4 km thick, at shallow depth (Brooks and Thompson, 1973). Intrusion of the basic body was considered by Bott *et al.* (1958) to have triggered the crustal melting that sourced the granite. The basic body possibly also sourced the tholeiitic basalt dykes that cross the island and are of similar age to the granite (Edmonds *et al.*, 1979). The bimodal igneous rock association, similar to several nearer the centre of the British Tertiary Volcanic Province, has also been thought to represent the roots of a major volcano (Thorpe and Tindle, 1992).

Tectonics and Basin Formation

During the Paleogene and Neogene, Europe was affected by two major tectonic processes. Firstly, seafloor spreading, beginning in the late Cretaceous, led to separation of the North American and Greenland plates and the beginnings of the North Atlantic Ocean. The rifting process became very active in the Paleogene. Secondly, the African Plate was converging on the Eurasian Plate, closing the Tethys Ocean, a process which would culminate in the formation of the Pyrenees and Alps the during the Pyrenean and Alpine orogenies. The most important period of Pyrenean orogenic shortening and crustal thickening took place *c.* 48–28 Ma (Lutetian to Rupelian) (Parrish *et al.*, 2018). The Alpine Orogeny is younger (Late Oligocene to Miocene).

A mantle plume developed in the Faeroe-Greenland area during the Paleocene. This plume initiated widespread igneous activity, and huge volumes of lavas poured out to form the plateau basalts of Skye, Mull and Antrim (the British Tertiary Volcanic Province), which are up to 2000 m thick. Injection of magma formed the associated dyke swarms and the bulk of the activity occurred between 63 and 52 Ma, but most of the eruptions were over by 59 Ma. The dome produced by the mantle plume ruptured at about 56 Ma (close to the Paleocene–Eocene boundary), and ocean floor spreading began between Europe and Greenland.

The extensional tectonics which caused the rifting and spreading of the North Atlantic were also responsible for basin development in south-west England during the Paleogene. Compressional forces of the Alpine Orogeny also extended to southern England at times. These are reflected in inversion events which occurred within the Paleogene but according to Chadwick (1993) reached an acme in the late Oligocene and Miocene. U-Pb dating of vein calcite by Parrish *et al.* (2018) has, however, suggested that the deformation in southern England at 34–30 Ma is primarily due to stress from the Pyrenean Orogeny directly south of the UK, rather than the mainly younger Alpine Orogeny.

There was relatively little tectonic activity during accumulation of the earliest Paleogene sediments of South-West England, such as the Tower Wood and Buller's Hill gravels on the Haldon Hills and the Orleigh Court Gravel in north Devon (Figs 1, 2) since these deposits formed as continuous sheets rather than in subsiding basins. The Tower Wood Gravel is likely to have developed on a gently sloping surface, whereas the Buller's Hill and Aller gravels are relatively high energy fluvial deposits derived from the west. Tectonic uplift provided an impetus to rapid erosion and transport eastwards of the fluvial gravels.

The location, the nature of the sedimentation and the subsequent preservation of most, if not all, of the Paleogene basinal deposits in South-West England are related to the varied tectonic regime caused by the interplay of the two tectonic processes described above. The north-south-directed extension of the region reactivated the NW to SE-trending Variscan strike-slip faults. Their response may have been to move sinistrally, as suggested by Holloway and Chadwick (1986) for Paleogene movements on the Sticklepath Fault Zone. These authors considered that north–south tension, and an interpretation of the faults surrounding the main basins as left-stepping, indicated sinistral movement in the fault zone, leading to the development of pull-apart basins.

Other authors, such as Bristow and Robson (1994), interpreted the fault zone geometry as right-stepping and consequently considered the pull-apart basins to have been generated by dextral wrenching. They also invoked a `locking' effect on the fault zone as it intersects the granite, so promoting the generation of the pull-apart Bovey Basin. These movements, whether dextral or sinistral, controlled sedimentation during the Paleogene. The relative rates of accumulation and erosion of the sediments depended on the amount of subsidence that in turn depended on movements within the fault zone. The episodes of compression and consequent inversion during the Paleogene would have reduced or terminated basin subsidence and disrupted the pattern of river flow. In the Petrockstowe Basin, the deposition in the northern part of the basin of finely laminated lacustrine clays suggests that the rate of subsidence increased to such an extent that a permanent or semi-permanent lake formed. It is also possible that vertical block movements took place on the faults at more quiescent times and controlled differential rates of erosion.

Transpressive forces across the Bovey and Petrockstowe basins caused thrusting to develop along their margins, and sometimes internally on the site of pre-existing faults (Bristow and Robson, 1994). At Ringslade, on the southern margin of the Bovey Basin, Devonian slates were thrust northward over the Bovey Formation (Bristow and Hughes, 1971), and at the Woolladon and Stockleigh ball clay pits at the southern end of the Petrockstowe Basin, Carboniferous sandstones and shales were thrust north-eastwards and south-westwards over the Bovey Formation towards the axis of the basin (Bristow and Robson, 1994). In the northern part of the Petrockstowe Basin, the Paleogene sediments and underlying Carboniferous in the North-East Shelf area were reversely faulted against Paleogene axial trough sediments. There is evidence at both Ringslade and Woolladon that sedimentation continued during the thrusting activity as landslip debris from the advancing thrust mass is found within the Paleogene sediments.

The Bovey Formation of the Bovey Basin is affected by a number of small faults, most of which are oblique-slip normal faults. Vincent (1974) noted that at and west of the Newbridge/Twinyeo Pit (Fig. 4), the faults are mostly parallel to the trend of the Sticklepath Fault Zone, while east of there the direction of faulting is more variable, being north-south in the Southacre and White Pit areas, and north-east to south-west in the south of the basin. In White Pit (Fig. 4), a fault with the Sticklepath Fault Zone trend is apparently truncated by north-south-trending faults, suggesting that these were later. Holloway and Chadwick (1986) suggested that the minor faults overlying the proposed concealed eastern master fault (Bovey Tracey Fault) of the Bovey Basin could be interpreted as Riedel shears suggestive of a dextral shear couple.

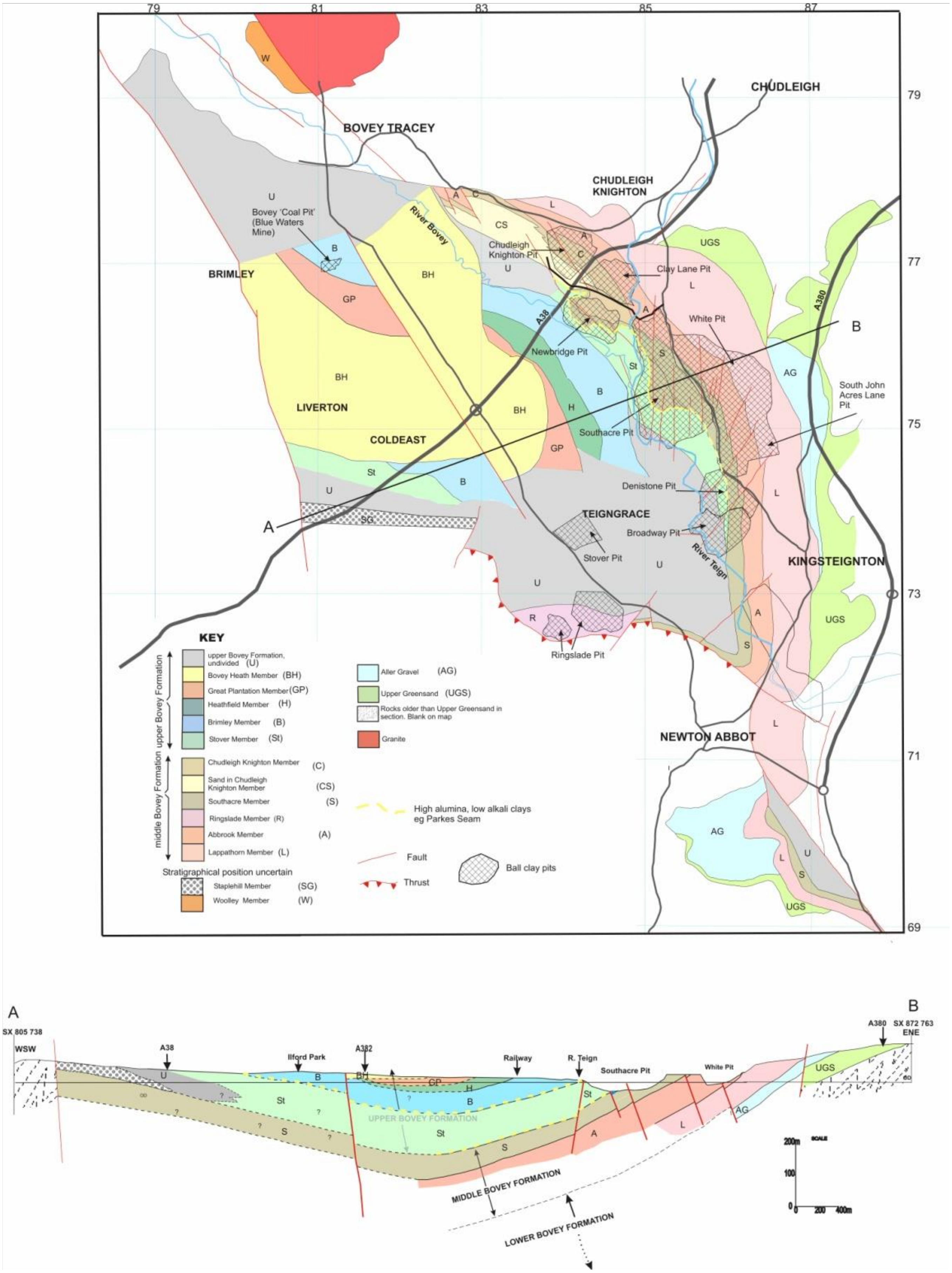

Figure 4. *Geological map of the main Bovey Basin and part of the Decoy Basin, with a provisional cross-section across the main basin. Compiled from BGS 1:10 000-scale geological maps SX87NW, NE, SW, SE and 86NE with modifications and additions from Vincent (1974), and from unpublished data provided by Sibelco and Imerys.*

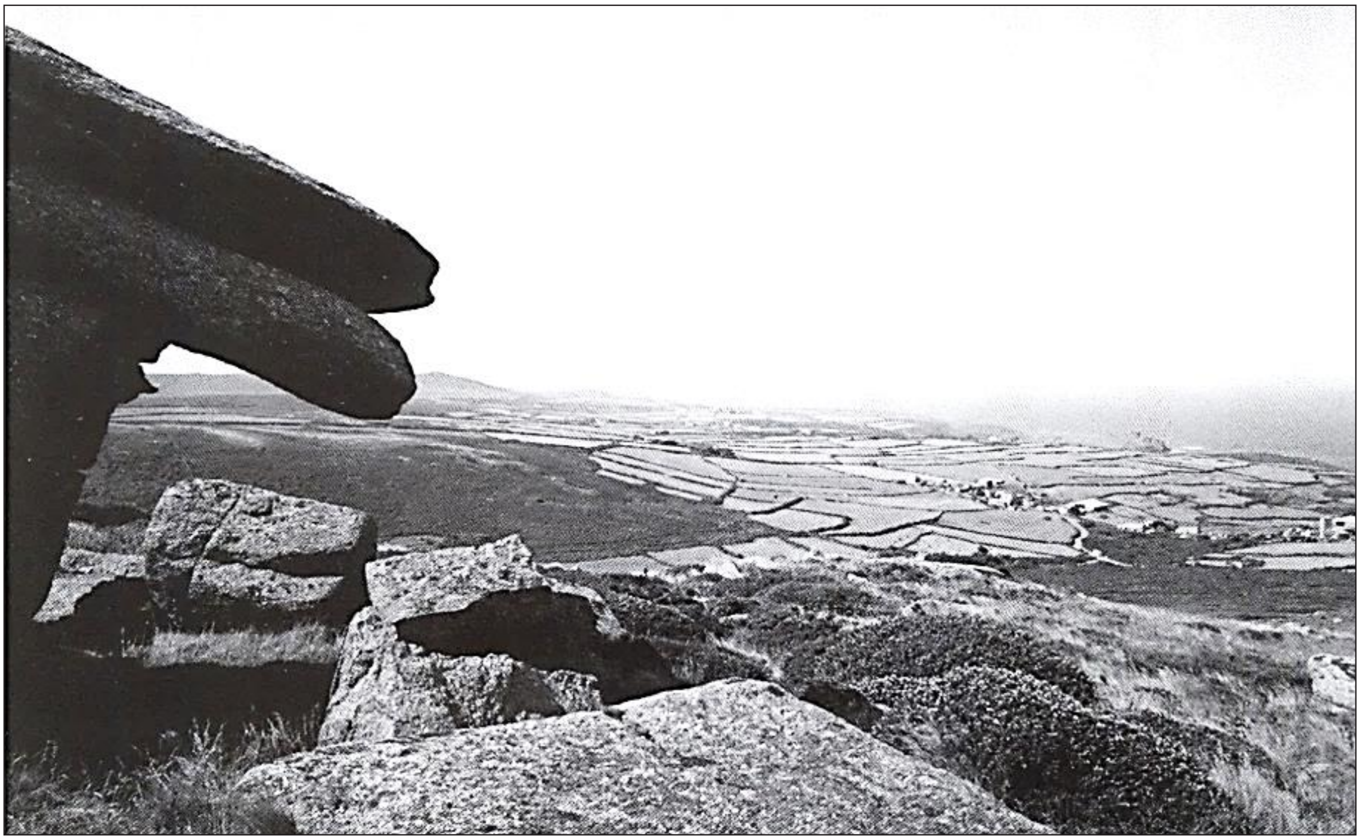

Figure 5. *Zennor Hill. The Reskajeage Surface north of the Land's End Granite with part of the granite in the foreground. British Geological Survey image P1003057 (formerly A11559). Reproduced with the permission of the British Geological Survey © UKRI 2024. All Rights Reserved.*

Planation Surfaces and Landscape Evolution

Many authors studying the landscape of South-West England have recognised sub-horizontal or gently inclined planar surfaces, `platforms' or 'bevels', at varying heights, ranging from the summit levels of Exmoor and Dartmoor down to sea level, which truncate structures in the underlying Paleozoic rocks. The problems of the origin and dating of these surfaces (here termed 'planation surfaces') have been much discussed; Green and Campbell (*in* Campbell *et al*., 1998) reviewed the history of research. The lack of deposits on most of the surfaces causes difficulties in dating, and even where there is a deposit on a surface, it is not necessarily the same age as the surface itself. Much debate has centred on whether particular surfaces were formed by marine or subaerial erosion, a judgement made more difficult by the possibility that some, perhaps all, the surfaces may be polygenetic in origin. The effects of Cenozoic tectonics have also to be considered when considering the correlation of surfaces in separate areas on the basis of height.

A number of mid-twentieth Century researchers invoked a marine explanation for many surfaces. For example, Green (1941) distinguished in east Devon at least six surfaces between 134 and 280 m above Ordnance Datum (O.D.), which were considered to be marine, ranging from Miocene to Pliocene in age. Balchin (1952) recognised eight surfaces on Exmoor, the lower six of which were believed to be marine. Orme (1964) proposed an extensive sequence of closely spaced marine bevels in the South Hams. Numerous other examples can be cited (*see* Walsh *et al*., 1999; Campbell *et al*., 1998). The evidence for multiple marine planation surfaces in South-West England is, however, generally lacking.

The Reskajeage Surface

It is now generally considered that the best model for the evolution of the landscape visualises a single, very extensive, polygenetic lower **sub-aerial** planation surface extending at varying heights over much of the south-west England peninsula; this surface can be subsumed under the heading of the **Reskajeage Surface** (Walsh *et al*., 1987), a term originally relating only to the planation surface of west and central Cornwall between 75 and 131 m O.D., but since more widely applied. The Reskajeage Surface truncates the underlying folded and faulted Paleozoic metasedimentary rocks, with the granite massifs rising above the surface (Fig. 5). Proponents of a subaerial explanation are notably Fryer (1960), Straw (1985, 1995, 2023), Coque-Delhuille (1987, 1991), Walsh *et al*. (1987, 1999) and King (2006).

Coque-Delhuille (1987, 1991) recognised an extensive lower-level polygenetic sub-aerial **Devon-Cornwall Surface**, synonymous with the Reskajeage Surface, ranging between 150 and 250 m O.D., extending over the whole of the basement, excluding Exmoor, and only rarely over the granites: its altitude decreases from north to south and from east to west. The same author also recognised a **post-Hercynian Surface** developed on the upper levels of the granite massifs and Exmoor.

The original designation of the Reskajeage Surface arose from the work of Walsh *et al*. (1987, 1999) who concluded that many 50–150 m O.D. surfaces in western Britain and Ireland were formed by sub-aerial rather than marine processes. One of the most prominent planation surfaces studied in west Cornwall, previously described variously as the 'Coastal Bench', 'Pliocene Platform', '90–131 m surface' and '121 m surface', was named the Reskajeage Surface by Walsh *et al*. (1987) from Reskajeage Downs where it is well developed.

The view that the west Cornwall Reskajeage Surface at 50–120 m O.D. is marine and Pliocene in age was well established in the literature (*e.g*., Reid, 1890; Coque-Delhuille, 1987; Goode and Taylor, 1988), but this has been challenged, notably by Walsh *et al*. (1999). The undoubted marine deposits of St Erth, in west Cornwall, representing the incursion of a late Pliocene (or earliest Pleistocene) sea, rest on a relatively even sub-aerially eroded rock surface at an elevation of 30–37 m OD.

Walsh *et al*. (1999) noted that there was no evidence that the late Pliocene transgression of west Cornwall reached higher than 50 m above sea level or that it left any detectable bevel in the landscape. The St Erth deposits are, thus, at a considerably lower level than the Reskajeage Surface.

The St Agnes Formation rests on the 130 m Reskajeage Surface of west Cornwall and was formerly considered to be equivalent to the St Erth Formation of Pliocene age and to rest on a Pliocene marine platform. The St Agnes Formation is now considered to be Miocene in age, but there is considerable uncertainty about its depositional environment (see below). The marine model preferred by Coque-Delhuille (1987) would require a Miocene transgression with pre-uplift sea levels of 40 m above present levels (Westaway, 2010) for the mid-Miocene. The alternative model of (Walsh *et al*., 1987) suggests a sub-aerial origin and an early Miocene or older date for the Reskajeage Surface. The nearby Eocene Beacon Cottage Farm outlier has a much more irregular base and its relationship to the Reskajeage Surface is uncertain.

Straw (1995, 2023) also recognised a widespread subaerial undulating **Devon Surface** in central and south Devon which evolved in the Eocene and Oligocene and forms part of the Reskajeage Surface. The surface lies between 160 and 300 m OD in central Devon; south of Dartmoor its counterparts were considered to be the South Hams plateau of south Devon at between 130 and 220 m OD (Straw, 1985) and probably the prominent flat platforms around Torquay and Brixham, south Devon, which have surface elevations of around 100 m OD in the north, gradually sloping south (Jukes-Browne, 1907). The differences in height between the central and south Devon areas can be attributed to the development by southward-directed drainage of a fluvial subaerial surface, inclined gently southwards, without the need to invoke a tectonic explanation. The case of that part of Exmoor east of the Combe Martin Fault is different, and here Straw (1995) considered that the upland plain of Exmoor, at over 400 m OD, is in fact the Paleogene subaerial surface uplifted by post-Oligocene (?Miocene) faulting rather than the high-level post-Hercynian Surface of Coque-Delhuille (1987, 1991). Balchin (1952) recognised a series of flats of supposed marine origin on Exmoor, but this claim has been discounted by Straw (2023).

Other analogues of the Reskajeage Surface are represented on Lundy Island in the Bristol Channel and on the Lizard Peninsula of south Cornwall. On Lundy, a well-developed planation surface incised across the late Paleocene Lundy Granite ranges in elevation from 90 to 130 m OD, with the highest elevations in the south. The widespread, remarkably planar surface (the '90 m platform') on the Lizard slopes southwards over several kilometres, from about 110 m to 75 m OD, and cuts across all the underlying rock types. Unusually, a deposit (the Crousa Gravel, *see later*) rests on the deeply weathered surface and it and presumably also the underlying surface, can be dated using palynomorphs as 'Paleogene' although no more precise dating is possible (Scourse and Furze, 1999).

Development of the Reskajeage Surface

A marine transgression during the late Albian deposited extensive, thin sheets of glauconitic sand (the Upper Greensand Formation) over many older land masses. **The sub-Cretaceous surface,** overlain by Upper Greensand, was identified by Coque-Delhuille (1991) with the initiation of the Devon-Cornwall (Reskajeage) Surface. The sub-Cretaceous Surface is preserved beneath the Upper Greensand in east Devon, on the Haldon Hills and in the Bovey Basin. Gunnell (2020) noted that the extensive flat areas of the Lower Surface of Dartmoor (at ~300 m OD) were probably covered by the feather edge of the marine transgression and exhumed during the Cenozoic. The 210 m bench mapped by Brunsden (1963) around the fringes of Lower Dartmoor and interpreted by him as a Calabrian strandline was, instead, considered by Coque-Delhuille (1987) to be an exhumed Cretaceous shore platform representing the initial stage of development of the Devon-Cornwall Surface.

The transgression continued during the late Cretaceous and most, if not all, of South-West England was submerged beneath the chalk sea by the mid-Campanian. Following dissolution of the Chalk, a mantle of residual flint gravels rested on a **sub-Paleogene Surface** that extended over most of South-West England and now is preserved only beneath the Paleogene deposits of east Devon and Haldon. This surface represents the initial post-Cretaceous phase in the development of the Reskajeage Surface. Coque-Delhuille (1987) noted that the sub-Paleogene Surface and the sub-Cretaceous Surface, which are closely spaced, merge into a single surface, the Devon-Cornwall (or Reskajeage) surface.

Following removal of the residual flint gravel cover in the Paleocene, and exposure of the sub-Paleogene Surface, deep lateritic weathering profiles formed in a subtropical to temperate climate on a variety of newly exposed rock types over much of South-West England. Such surfaces may be termed 'etchplains'. Walsh *et al*. (1987) considered that the Reskajeage Surface was an 'etchplain of tropical and subtropical origins, now largely stripped of its former saprolitic cover'. Straw (2023), however, notes that the Reskajeage Surface in central Devon, 'the summit accordance, with none of the sandstones rising higher, points here towards a dominance of subaerial fluvial planation.'

Streams carried very large volumes of the products of weathering profiles formed on the interfluves, mainly clays and sands, into the pull-apart basins (Bristow, 1968). Weathering mantles also developed on the granites and in the case of the Dartmoor Granite were eroded and transported into the Bovey Basin, especially during deposition of the upper Bovey Formation. The period of weathering and transport may have been coeval with the time taken to fill the Bovey, Petrockstowe and Stanley Bank pull-apart basins (Straw, 2023). Infill might have begun as early as the Paleocene-Eocene boundary, continuing throughout the Eocene and into the Oligocene (Rupelian and possibly Chattian), a period of at least 28 million years.

High-level surfaces

High level surfaces at around 1000 ft (305 m OD) and 800 ft (244 m OD), both then thought to be of marine origin, were recognised around Dartmoor (Jukes-Browne, 1904; Reid *et al*., 1912; Ussher, 1913). Barrow (1908) recognised surfaces on Bodmin Moor at 750 and 1000 ft (229 m OD and 305 m OD). Coque-Delhuille (1987, 1991) recognised a **High Dartmoor Surface** at 500–600 m OD (corresponding to the Summit Peneplain of Brunsden (1963) and the Upper Surface of Waters (1960) and Brunsden *et al*. (1964)), which was thought to be a pre-Permian post-Hercynian subaerial feature present at the summits of the granite massifs and Exmoor. As noted above, however, Straw (1995) considered that the high plateau (350–500 m OD) of Exmoor is an uplifted fault block of the Reskajeage Surface.

Paleogene Deposits: Paleocene to Early Eocene

The Paleogene deposits of South-West England can be divided into two main types. The first and older group are flint-bearing gravels of Paleocene and early Eocene age. The second group, included in the Bovey Formation, provide the infill of the pull-apart basins of the peninsula. They are mainly of Eocene and Oligocene age and consist predominantly of kaolinitic clays, sands, lignites and gravels.

The distribution of the flint gravels of Paleocene to early Eocene age in Devon and adjacent areas is shown in Figure 2. Two broad types are represented: 'residual' gravels of Paleocene age, derived partly from the solution of Cretaceous Chalk; and a younger facies mainly of early Eocene age, deposited by rivers.

On the Haldon Hills, Hamblin (1973a) defined the Haldon Gravels Formation (renamed Haldon Formation by Hamblin, 2014), which included a residual facies, the Tower Wood Gravel Member, and a fluvial facies, the Buller's Hill Gravel Member. At lower levels the fluvial Aller Gravel Formation (Edwards, 1973) extends along the east side of the Bovey Basin, and small areas of residual flint gravel of Tower Wood type occur in solution pipes in Devonian limestones near Kingsteignton (Brunsden *et al.*, 1976). The deposit at Orleigh Court, north Devon, is similar to the Tower Wood Gravel, although good exposures are lacking. In east Devon, extensive sheets of Clay-with-flints Formation capping the Upper Greensand and Chalk have a complex origin and history. Possible residual flint gravels are present in the Marazion area of south Cornwall (Coque-Delhuille, 1991, 1987).

Residual flint gravels and silcrete

Up to about 500 m of Chalk Group sediment were deposited in the sea that extended over and probably submerged all or most of the South-West England area. Hancock (1969, 1975) calculated that the depth of the chalk sea during the late Cretaceous was 640–740 m, sufficient to submerge all the land of South-West England (except possibly the highest part of Dartmoor). Following regional uplift and emergence, South-West England became land, and the chalk cover was exposed to active fluvial erosion and chemical dissolution in a tropical or subtropical climate. Danian marine limestones were probably deposited over much of southern England, and it is likely that uplift and erosion of the Cretaceous cover, previously thought to have commenced in the Danian, did not begin until the mid-Paleocene (early Selandian) (King, 2006). Rates of denudation of the chalk after land emergence have been estimated at 100 m/Ma (Migoń and Goudie, 2012). Such a rate would suggest that dissolution of the *c.* 500 m of chalk cover in South-West England took place over a period of about 5 Ma.

Rivers planed a surface (the **sub-Paleogene Surface**) across the chalk and left on it a patchy veneer of sands, gravels and clays (Gallois, 2009). All of the chalk was removed from Sidmouth westwards, leaving up to 75 m of chalk still preserved. The residual gravels contain unabraded flints and other insoluble materials derived from the chalk, but also incorporate fluvial material derived from the veneer deposited on the sub-Paleogene Surface (Gallois, 2009). The result was an extensive deposit of flint-bearing residual gravel mantling much of the land surface of South-West England and now surviving as the Orleigh Court Gravel, Tower Wood Gravel and Clay-with-flints *sensu stricto* of east Devon. Echinoids and belemnites in the flints of the Tower Wood and Orleigh Court gravels indicate the former presence of chalk up to the *Belemnitella mucronata* Zone of the Campanian.

The possible presence of residual flint gravels in the Marazion area of south Cornwall was suggested by Coque-Delhuille (1991), and the presence of numerous 'branched' flints on the beaches of the northern shores of the Isles of Scilly suggested to Coque-Delhuille (1987) that a cover of chalk also formerly extended to that area.

In a series of papers, Isaac (1979, 1981, 1983) postulated, from east Devon, a succession of Paleogene and Pleistocene weathering and depositional events producing lateritic soils, silcretes and fluvial gravels. Gallois (2009), however, noted that, owing to the current state of exposures, none of the events inferred by Isaac could be confirmed: the still accessible type section of the 'Peak Hill Gravels' at Peak Hill Cliff [SY 109 867] shows exposures typical of Clay-with-flints *sensu lato*: the section showing the 'Seven Stones Soil' [SY 1055 8789] at Mutters Moor, Sidmouth, could not be located; and the type section of the Paleocene 'Compbyne Soil' in the Combpyne railway cutting is now infilled. No silcretes can be seen in place, although blocks are relatively common on the Clay-with-flints surface. In view of the above, King (2016) concluded that the succession identified by Isaac was invalid.

The ***Tower Wood Gravel Member*** of the Haldon Formation of Hamblin (2014) occurs on the Haldon Hills (Fig. 6). On Great Haldon it rests on the Upper Greensand Formation (Albian-Cenomanian) and consists of up to 8 m of unabraded pale grey flints in a matrix of white, locally brown-stained, clay and a little sand (Fig. 7). The type section and Site of Special Scientific Interest is at Tower Wood Quarry [SX 8768 8567] at the very northern end of the Haldon Hills

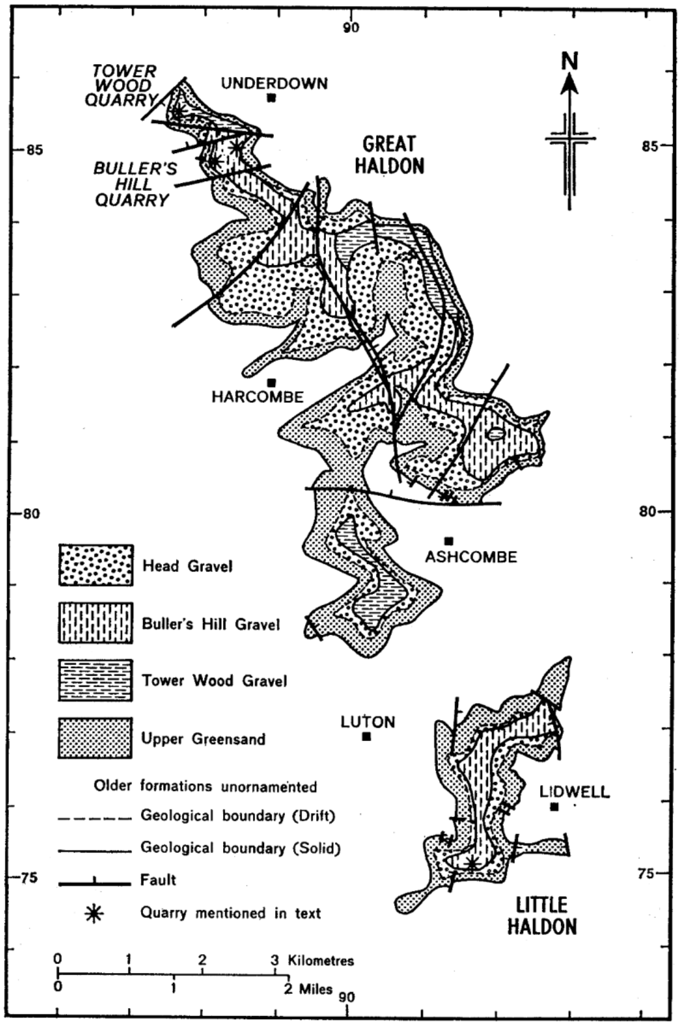

Figure 6. *The distribution of the component members of the Haldon Formation (Hamblin 2014) and Upper Greensand on the Haldon Hills, Devon (after Hamblin, 1973a, fig. 2). Reproduced with permission of the Geologists' Association.*

Figure 7. *Tower Wood Gravel at Tower Wood Quarry [SX 8768 8567], Great Haldon. British Geological Survey image P211200 (formerly A11557). Reproduced with the permission of the British Geological Survey © UKRI 2024. All Rights Reserved.*

(Hamblin, 1973a). In 2024, the quarry face was overgrown, and no good sections were visible. The flints were left behind after the *in-situ* solution of chalk before deposition of the overlying Buller's Hill Gravel. At the junction with the Upper Greensand, a flint-free sand bed 12.5 cm thick containing pebbles of well-rounded quartz and quartz-tourmaline rock may have been derived from flint-free chalk (Grey Chalk Subgroup) following solution (Hamblin, 1973b). This bed is probably Bed c of Coque-Delhuille (1987) who considered it to have been reworked from the Upper Greensand. Selwood *et al.* (1984) considered that the Tower Wood Gravel was present on both Great and Little Haldon, although its presence on Little Haldon was indicated only indirectly by the presence of unabraded flints in Head Gravel.

Hamblin (1974) considered that, along the 11 km length of the Haldon Hills, there was no recorded instance of the Buller's Hill Gravel cutting through the Tower Wood Gravel and into the Upper Greensand. At Buller's Hill, however, Coque-Delhuille (1987) recorded Buller's Hill Gravel resting directly on Upper Greensand with no intervening Tower Wood Gravel: see the account of the Buller's Hill Gravel.

Between the Bovey Basin and the Haldon Hills, karst processes have resulted in very irregular surfaces developed mainly on Middle Devonian Chercombe Bridge Limestone. Solution hollows and pipes in the limestones have been locally infilled by Cretaceous sands (Upper Greensand) and Paleocene and Eocene flint gravels. Tower Wood Gravel, consisting of 'unworn but mainly broken flint nodules' was recorded by Brunsden *et al.* (1976) occupying solution hollows in Chercombe Bridge Limestone in cuttings [SX 874 743 to SX 879 734] for the Kingsteignton–Newton Abbot by-pass road. The gravels, recorded as 'Bed b', were sandwiched between Bed 2 (probable Upper Greensand) and the flint gravels of Bed 3 (identified by Brunsden *et al.* (1976) as Buller's Hill Gravel, but probably Aller Gravel – *see below*). The presence of Tower Wood Gravel provides a further link between the Haldon Hills sequence and the downfolded sequence of similar age along the eastern border of the Bovey Basin.

Ussher (1913, p. 120) referred to seven patches of gravel and sand between Rydon (Kingsteignton) and Ideford, coloured as 'Bovey Beds' on the 1:63,360-scale geological map, Sheet 339 (1913). These were interpreted as:

> 'all more or less primarily derived from Cretaceous rocks, and are probably remaniés of Tertiary beds which once extended over the places where they occur'.

Ussher (1906) noted that the deposits fill solution 'hollows and potholes' in the Devonian limestones. Two patches near Ideford and Luton were shown on the 1913 map as Valley Gravel. On the 1:50,000-scale geological map, Sheet 339 (1976), several of the patches referred to above were distinguished as Upper Greensand or Aller Gravel, but six patches between Humber, Luton and Ideford were classified as 'Sand and gravel of unknown age' (Selwood *et al.*, 1984).

About 2 km east-north-east of Chudleigh at Lower Upcott Quarry [SX 886 805], Ussher (1906) recorded deposits occupying solution cavities in Chercombe Bridge Limestone, noting:

> '…about 200 feet [60 m] lower than the Haldon gravels ……. a mass of fine sand [Upper Greensand], subordinate to coarse sand and fine gravel with some worn chalk flints ….. preserved through the dissolution of the limestone.'

In the north face of Bickleyball Quarry, Kingsteignton [SX 8850 7400], Selwood *et al.* (1984) noted two large fissures reaching the quarry floor and filled with 'slipped' Upper Greensand and flint gravel.

Fossils (mainly brachiopods, echinoids and bivalves) in the flints of the Tower Wood Gravel indicate the former presence of possibly 200 m of chalk ranging from the *Micraster cortestudinarium* Zone to the *Belemnitella mucronata* Zone (Coniacian–Campanian). About 50% of the 8 m thickness of the Tower Wood Gravel is estimated to be clay, and solution of chalk alone is insufficient to account for this amount. Also, the clay is well-ordered kaolinite, unlike that in the chalk. The clay matrix was therefore considered by Hamblin (1973a, b) to have been derived from a hydrothermal kaolinite deposit that formed a layer on top of the chalk and was let down as solution took place.

The ***Orleigh Court Gravel Formation***, named herein, forms a small outcrop at Orleigh Court [SS 4296 2227], north Devon, about 5 km south of Bideford (Fig. 2), shown on the BGS Bude 1:50,000-scale geological sheet (307/308) with a mapped area of about 0.8 km^2. The deposit was investigated by Rogers and Simpson (1937), and further information was provided by Edmonds *et al.* (1979).

The poorly exposed deposit consists of nodular flints in a matrix of buff and brownish-red, fine- to coarse-grained, variably silty and clayey sand. Rogers and Simpson (1937) described the mineral assemblage and listed fossils found as flint-casts. They recognised and mapped 'upper' and 'lower' divisions of the deposit (Fig. 8). The buff-coloured 'lower' gravel contains smaller and relatively few flints. The 'upper' division was coloured red owing to iron oxide, crowded with abundant flint nodules, many fossiliferous, ranging in colour from brownish-grey (common) to black and red (rare). Additionally, the 'upper' gravel includes clasts of indurated ferruginous grit, compared by Rogers and Simpson with material of Lower Greensand age. Edmonds *et al.* (1979) considered that the 'lower' division was derived from the original deposit by downslope movement. Mineralogically, the 'lower' gravel was

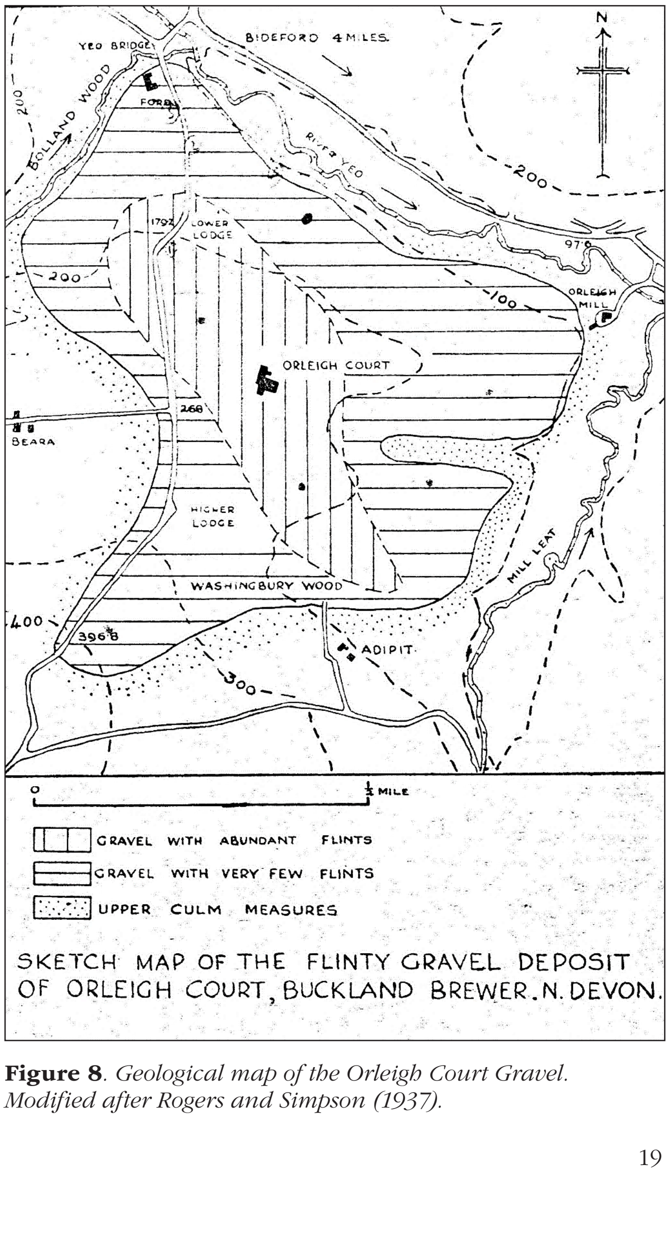

Figure 8. *Geological map of the Orleigh Court Gravel. Modified after Rogers and Simpson (1937).*

characterised by a tourmaline-zircon-andalusite mineral suite and the 'upper' gravel by a zircon-rutile-tourmaline mineral suite. Such a mineralogical difference is surprising in view of the fact that the 'lower' gravel is probably derived from the 'upper' and should therefore be mineralogically similar.

The thickness of the deposit is uncertain, but Rogers and Simpson (1937) recorded 7.6 m of (presumably) gravel resting on yellow clay in a now-infilled pit in The Rookery, just west of Orleigh Court. No detailed description is given, so that it is not possible to say whether the yellow clay is weathered Carboniferous shale or a bed within the Tower Wood Gravel.

Gravity surveys (Edmonds *et al*., 1979) indicated a 2-mGal anomaly over the deposit, indicating a maximum thickness of lighter material close to Orleigh Court. If this was all due to gravel it would indicate a probable maximum thickness of about 50 m, with an average of 20 m over most of the area. Seismic surveys, however, indicate that the gravel layer might be thinner and underlain by a unit lighter than the underlying Carboniferous rocks, but with a similar seismic velocity.

Rogers and Simpson (1937) suggested that the Orleigh Court Gravel was Pliocene, resting on a 400-ft (122 m) platform of supposed Pliocene age. However, the un-abraded nature of the flints suggests that it is most likely that the deposit is a residual gravel of probable Paleocene age, derived partly from the *in-situ* solution of chalk and lithologically comparable to the Tower Wood Gravel of the Haldon Hills. The suggestion of a residual origin had been made earlier by De la Beche (1839) in support of his belief that the chalk had once covered large parts of Devon. The matrix of sand and clay may have been washed in steadily as the chalk dissolved or formed a layer on the chalk and was incorporated into it as solution continued. The chalk fossils in the flints, mostly unabraded, are listed in Rogers and Simpson (1937) and indicate a range similar to that of the Tower Wood Gravel, ranging from the *Sternotaxis plana* (*Holaster planus*) Zone (late Turonian) to the *Belemnitella mucronata* Zone (Coniacian–Campanian). The Orleigh Court Gravel is locally overlain by possible Bovey Formation clays.

In an account of the 'Tertiary' of Devon, Ussher (1906) described gravel [SS 457 138] near Rivaton Farm, Langtree, about 9 km south-south-east of Orleigh Court and by implication linked to Orleigh Court. The deposit is not shown on the BGS 1:50,000 Bude geological sheet (307 and 308) (1980). Ussher (1906) noted small angular and subangular quartz clasts, with occasional pebbles, together with chips and worn nodular black, red and brown flints, and angular and subangular Carboniferous sandstone. Freshney *et al*. (1979) interpreted the deposit as a high-level (152 m OD) river terrace lithologically similar to the terraces of the Petrockstowe Basin and about 90 m higher than those terraces. A correlation of the Rivaton Farm and Petrockstowe terraces would imply a downthrow of 90 m across one or more of the faults of the Sticklepath Fault Zone.

In east Devon, a gently undulating plateau rising to about 250 m OD is formed of Upper Greensand and Chalk capped by ***Clay-with-flints Formation*** (Fig. 11). East of Sidmouth it rests unconformably on the chalk and west of there on the Upper Greensand. The plateau is locally downfaulted to lower levels, and it has been extensively dissected by streams. The deposit is mostly less than 5 m thick, but in places fills solution pipes up to 30 m deep. The cliffs between Salcombe Regis and Beer Head [SY 150 877 to 225 880] show excellent exposures of Clay-with-flints on an irregular karstic surface of chalk and Upper Greensand (Fig. 12), but it is poorly exposed away from the coast. Campbell (*in* Campbell *et al.* 1998) described from quarry faces [SY 213 896 to SY 215 896] at Beer Quarry Caves examples of solution pipes in Chalk, infilled with Clay-with-flints. Solution pipes infilled with Clay-with-flints (Figs 9, 10) at the Shapwick Grange Quarry [SY 311 917], east Devon, show dark margins to the infill of the pipes in sharp contact with the chalk.

Edwards and Gallois (2004) noted that where the thickness of the Clay-with-flints is greater than 20 m, as around Charton

Figure 9. *Detail of Clay-with-flints, Shapwick Grange Quarry [SY 311 917], east Devon. Lens cap for scale (photograph by R.A. Edwards).*

Figure 10. *Clay-with-flints infilling solution hollows in Chalk, Shapwick Grange Quarry [SY 311 917], east Devon (photograph by R.A. Edwards).*

Cross [SY 303 913]. Combpyne Hill [SY 301 928], Hartgrove Hill [SY 307 946] and north of Yawl [SY 321 949], up to 10 m of relatively undisturbed Paleogene deposits may be present beneath Clay-with-flints.

The origins and age of the Clay-with-flints have been much debated. Gallois (2009) has provided an assessment of the origin of the various deposits subsumed under the general heading of Clay-with-flints. He distinguished Clay-with-flints *sensu stricto* and Clay-with-flints *sensu lato* (Table 1). Clay-with-flints *sensu stricto* consists of reddish-brown clay with unabraded flints and a few flint, quartzitic and other pebbles, and rests on a Paleocene planation surface cut into the chalk. Clay-with-flints *sensu lato* contains water-worn flints and other clasts, yellow, brown or grey clays, and significant quantities (>2-3%) of sand or pebbles and does not rest on a Paleocene surface. Outcrops labelled as 'Clay-with-flints' on Geological Survey maps of South-West England ('Clay with Flints and Cherts' on older maps) were classified by Gallois (2009) as Clay-with-flints *sensu lato*. Owing to extensive remobilisation in Pleistocene periglacial climates there are no recorded inland outcrops of the Clay-with-flints *sensu stricto*. Exposures *in-situ* of Clay-with-flints *sensu stricto* are rare even in the cliff sections of east Devon, owing to later solution effects (Fig. 12).

Clay-with-flints *sensu stricto* locally rests (for example, around Beer in east Devon) on beds up to 30 m thick of partially decalcified Upper Greensand and/or Chalk which are the missing link in the process of formation by which the Cretaceous deposits gave rise to Clay-with-flints *sensu stricto*

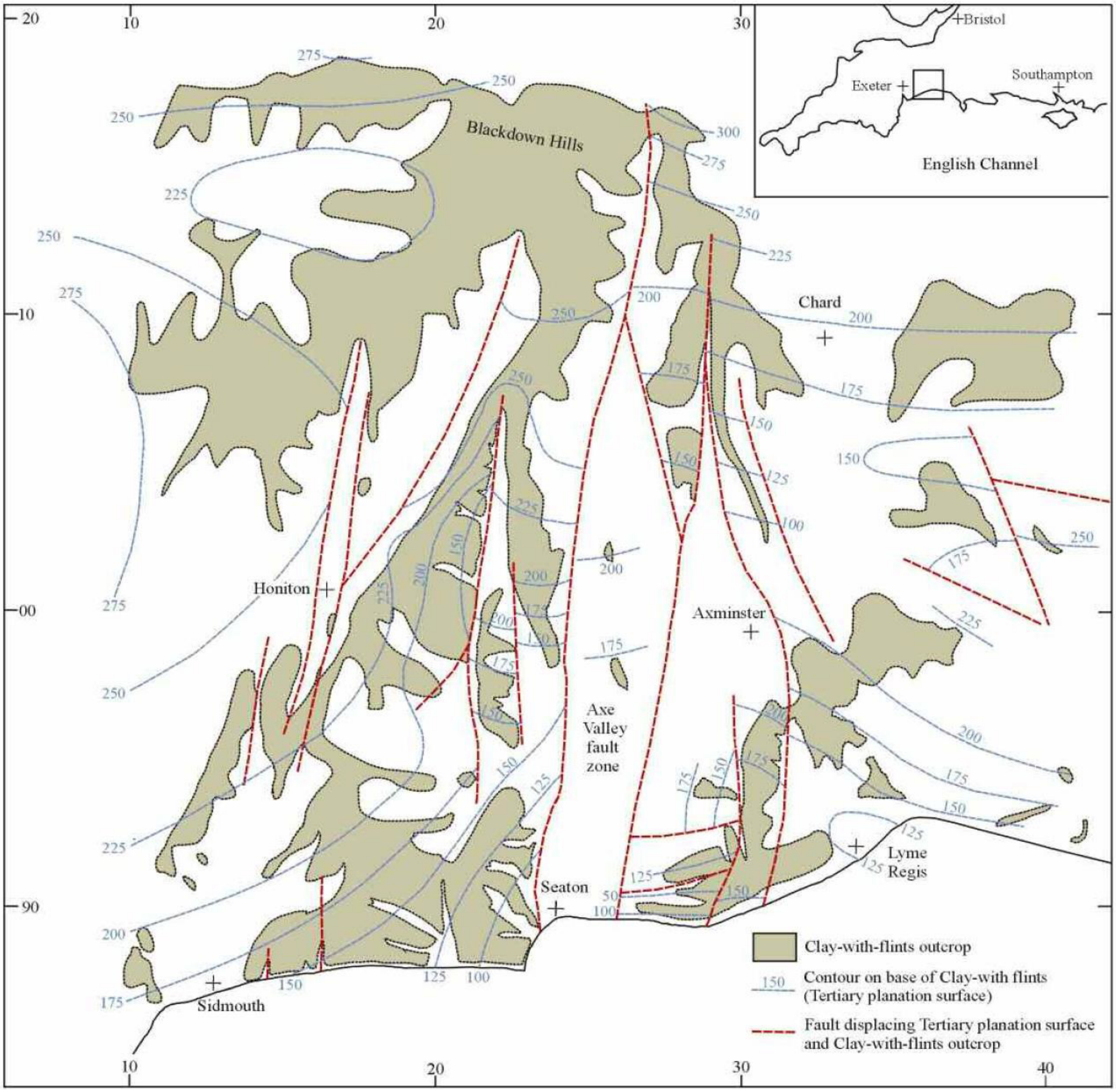

Figure 11. *The Clay-with-flints outcrop in east Devon, west Dorset and south Somerset showing contours on the folded and faulted Paleocene planation surface on which the Clay-with-flints rests. Within the north-south-trending Axe Valley fault zone, the base of the Clay-with-flints is locally displaced by up to 60 m across a single fault. The last reactivation of the fault zone is presumed to have been in the Miocene, the most recent major tectonic phase in southern England. After Gallois (2009, fig. 5). Reproduced with permission of the Ussher Society.*

(Gallois, 2009).

The following stages (Table 1) in the formation of Clay-with-flints have been suggested by Gallois (2009):

1. In the latest Cretaceous and Paleocene, the Chalk was uplifted and extensively eroded. Early Paleocene rivers planed a surface across the chalk and left on it a patchy veneer of sands, gravels and clays.
2. During the Paleocene and Eocene, there was large-scale dissolution of chalk in a warm humid climate, forming Clay-with-flints *sensu stricto*, principally from insoluble residues derived from the chalk, but also incorporating material from the veneer of Paleocene

Figure 12. *Clay-with-flints (reddish-brown) in cliffs east of Sidmouth, showing piping into the underlying white Chalk (photograph by R.A. Edwards).*

Lithology and thickness in south-west England	Origin	Classification, age
Red-brown clay with unabraded flints, minor sand content and a few well-rounded quartzitic and other pebbles; rare traces of lamination; where not affected by later solution rests with marked unconformity on a planar erosion surface cut in Upper Greensand or Chalk. Mostly up to 2 m where undisturbed.	Remanié deposit derived largely from the dissolution of chalk; sand and pebble content derived from veneer of Tertiary deposits; locally chert- and sand-rich where partially derived from the Upper Greensand.	Clay-with-flints *sensu stricto* Late Palaeocene to early Eocene.
Complex, laterally and vertically highly variable mixtures of red-brown stony clay (as above) with the addition of broken, abraded and stained flints, sand and gravel, and yellow and brown clays; confined to plateau areas where it rests on an irregular, solution-affected chalk surface; where preserved, sedimentary structures almost all relate to secondary cryoturbation and solution collapse. Mostly <5 m, but up to 30 m in solution pockets.	Weathered *in situ* Clay-with-flints *sensu stricto* with the addition of younger (mostly Pleistocene) sand and gravel.	Clay-with-flints *sensu lato* Palaeocene to Pleistocene.
Clay-with-flints *sensu lato* with or without the addition of other locally derived materials; commonly crudely bedded with lenses of re-sorted sand and/or gravel; in south-west England outcrops extend up to 1 km downhill from the break in slope that marks the Tertiary planation surface. Mostly up to 5 m at upper edge, locally up to 10 m in hollows.	Solifluction deposit.	Head Deposits that should not be classified as Clay-with-flints. Pleistocene with minor local Holocene modification.
Heterogeneous mixtures of clay, sand, gravel, Jurassic chert and other insoluble materials derived from various non-Chalk sources that rest on Permo-Triassic to Quaternary rocks. Absent in south-west England.	Solifluction deposits.	Mostly Pleistocene Head Deposits that should not be classified as Clay-with-flints.

Table 1. *Subdivision, on the basis of origin of formation, of deposits described on geological maps as Clay-with-flints (in the UK) and as Argiles à silex (in France). After Gallois (2009). Reproduced with permission of the Ussher Society.*

fluvial deposits. Partially dissolved nodular chalks and Upper Greensand calcarenites are locally preserved beneath thicker patches of Clay-with-flints.

3. In the Eocene to early Miocene, dissolution of the chalk continued; the Clay-with-flints *sensu stricto* was folded and faulted and locally eroded.
4. In the mid-Miocene to Pleistocene, erosion removed much of the partially decalcified chalk and much of the Clay-with-flints *sensu stricto* There was continued solution of the chalk, and extensive deformation and remobilisation of earlier deposits to produce Clay-with-flints *sensu lato*.

Coque-Delhuille (1987) noted the presence in the Marazion area, south Cornwall, of 'branched' [unabraded?] flints 'scattered in the fields up to an altitude of 100–110 m' (precise location not given; possibly the Ludgvan area [SW 505 332]), testifying to a former cover of Clay-with-flints and therefore a former extension of the chalk sea to this area.

The presence of numerous 'branched' flints on the beaches of the northern shores of the Isles of Scilly suggested to Coque-Delhuille (1987) the former extent of a chalk cover to that area also.

In the Paleocene, deep weathering of aluminium silicates in a warm climate may have released silica, which migrated and was precipitated in soil profiles to form **silcrete**. The distribution of silcrete in the South-West England landscape has been underestimated according to Bristow (2004) and Bristow and Exley (1994), and early writers noted the abundance of quartz boulders littering the Cornish landscape. Most of these have been removed for nineteenth century roadbuilding and other uses. Bristow (2004) noted Cornish examples from St Breock Downs, Wadebridge, of hard silicified boulders underlain by deeply weathered Staddon Grits. In south Cornwall silcrete boulders are seen in the Kea– Baldhu–Carnon area.

Coque-Delhuille (1991) related the development of some silcretes to the evolution of the 'Devon-Cornwall Surface' with a mean elevation of 150–200 m OD. Only occasional blocks remain, for example at Shebbear [SS 4388 0924; SS 4381 1001] and Rivaton [SS 461 138].

Some of the most striking examples of silcrete in South-West England have been recorded from east Devon. Silcrete boulders, consisting of very hard, silica-cemented angular flints were common as surface blocks on the east Devon Clay-with-flints plateau around Sidmouth (Fig. 13a, b) (Isaac, 1979). Most blocks have been removed by farmers or for building Victorian rockeries and grottos (such as that at Bicton Gardens). None are seen *in situ*, and the age of formation is uncertain. Rare fossil plant rootlets show that it formed on or near a land surface, probably during a dry period when silica was deposited as a soil profile dried out.

Bristow (1993) noted numerous examples of possible

Figure 13a. *Block of silcrete on Salcombe Hill clifftop [SY 141 877], Sidmouth. Camera tripod for scale (photograph by R.A. Edwards).*

Figure 13b. *Detail of Figure 13a. Lens filter for scale (photograph by R. A. Edwards).*

silcrete resting on the Paleozoic rocks west of the Bovey Basin and on the southern margin of the basin at Ringslade. They were interpreted as the remnants of a duricrust formed in a Paleocene or early Eocene episode of silcrete/ferricrete formation. This would suggest that the land surface west of the Bovey Basin has not been greatly lowered since the early Cenozoic.

Fluvial flint gravels

Early Eocene fluvial gravels such as the Aller Gravel and the Buller's Hill Gravel formed by intensive erosion in a wet tropical climate of the residual gravels, from upland areas such as Dartmoor, by streams that flowed to the east and south. The (probably) braided streams may have flowed seasonally in a savannah climate (Hamblin, 1973a) onto extensive braidplains. Most of the fluvial gravels have been removed by subsequent erosion but survive on the Haldon Hills as the Buller's Hill Gravel and on the eastern margin of the Bovey Basin as the Aller Gravel. Deposition of the fluvial gravels postdates the residual gravels (formed in the mid to late Paleocene between 61 and 56 Ma) and predates the beginning of the infill of the pull-apart basins. This period could be constrained as closely as between 56 and 54 Ma.

The ***Buller's Hill Gravel Member*** of the Haldon Formation of Hamblin (2014) outcrops on the Haldon Hills (Fig. 6) where it rests on the Tower Wood Gravel (but see the discussion of Buller's Hill Quarry below). It comprises up to 10 m of flint gravel with subordinate clay bodies and beds of sand. The gravel is pale brown or pale grey, with abraded grey flints up to 30 cm across and smaller pebbles of vein quartz, quartz-tourmaline rock, quartzite and altered Carboniferous shale and chert, in a sand and clay matrix. The flints were probably derived from the erosion of an extensive sheet of residual flint gravels left after dissolution of the chalk cover. The type section and Site of Special Scientific Interest is at Buller's Hill Quarry [SX 8821 8465] towards the northern end of Great Haldon (Hamblin, 1973a). In 2024, no good sections were available in the quarry.

The 'Haldon Clay Deposit' of Hamblin (2014) consists of a number of kaolinitic 'ball clay' bodies wholly enclosed in the Bullers's Hill Gravel. Hamblin considered that, rather than having originated as clay-filled abandoned river channels, the deposit originally formed a continuous sheet overlying the Buller's Hill Gravel and was subsequently incorporated into it by Pleistocene periglacial processes. The supposed clay sheet could be regarded as the very first Bovey Formation deposit formed on the fluvial gravel surface shortly before the focus of Bovey Formation deposition moved into the newly initiated pull-apart basin.

Descriptions of the type section of the Buller's Hill Gravel at Buller's Hill Quarry differ and the present (2024) poor condition of the site made it impossible to re-examine the section in order to make a fuller detailed description. In the east face of the quarry, Selwood *et al*. (1984) recorded about 3 m of Buller's Hill Gravel on thin (1 m) Tower Wood Gravel. The Buller's Hill Gravel was described as:

> 'pale greyish brown with frost-shattered chatter-marked flints and exotic pebbles in a matrix of sandy clay which comprises about equal amounts of ordered and disordered kaolinite with a little illite'.

The base of the Tower Wood Gravel was not exposed.

Coque-Delhuille (1987, figs 106, 107) described the sequences at Buller's Hill Quarry [SX 8821 8465] and Deers Hill Quarry [SX 8295 8434]. It is notable that at Buller's Hill Quarry no Tower Wood Gravel was recorded which, if correctly observed, contradicts the statement of Hamblin (1973a) that the Buller's Hill Gravel is never seen to cut through the Tower Wood Gravel to rest on Upper Greensand.

The sequence recorded at Buller's Hill Quarry (Coque-Delhuille, 1987, figs. 106, 107) was:

- **Bed g. Head.** With gelifracted flints and a few pebbles. Pipes with loamy matrix. About 1 m.
- **Bed f. Buller's Hill Gravel**. 4 to 8 m.
- **Bed c. 'Sables jaunes' [Yellow sands]** reworked [?] from the Greensand. 3 to 4 m.
- **Bed b. 'Dalle silicifiée' [Silicified ?flagstones]** corresponding to the emergence level of the second half of the Cenomanian. c 0.75 m.
- **Bed a. Greensand**. 1.0 m +
- At Deers Hill Quarry the sequence recorded (Coque-Delhuille, 1987, fig. 106) was:
- **Bed d. 'Argile a silex' [Tower Wood Gravel].**
- **Bed c. 'Sables jaunes' [Yellow sands].**
- **Bed b. 'Dalle silicifiée' [Silicified ?flagstones].**
- **Bed a. Greensand.**

Coque-Delhuille (1987) considered that the Buller's Hill Gravel (**Bed f**) was reworked partly from the Tower Wood Gravel, as indicated by the presence of unabraded flints, and includes material originating from Dartmoor and its borders. Pebbly layers contain numerous flints, sometimes rounded, as well as quartz, tourmaline and rocks from the metamorphic aureole of the Dartmoor Granite. Clasts range in size from 3 to 12.5 cm. The sandy-clayey matrix differs clearly from that of the underlying yellow sands, due to a high proportion of feldspars (16–19% at 0.31 mm; 22–24% at 0.63 mm; and 30–35 % at 1 mm) and a high proportion of angular quartz (80–85%). The presence of a few medium-grained sand lenses in the Buller's Hill Gravel was interpreted as indicating a fluviatile origin.

Solifluction has affected the gravels, indicated by absence of structure and the presence of numerous shattered flints which indicate the effects of gelifraction.

Bed c., the 'Sables jaunes' [Yellow sands] of Coque-Delhuille (1987) are of uncertain origin and nature and have not been recorded by other authors. At Buller's Hill, **Bed c** consists of 3 to 4 m of yellow sands with a few pebbles and minerals of Dartmoor origin. The bed was also recorded from Deers Hill Quarry [SX 8925 8434] on the eastern side of Great Haldon, where it was overlain by Tower Wood Gravel, apparently absent at Buller's Hill Quarry. The bed was interpreted by Coque-Delhuille (1987) as a fluviatile deposit 'partially reworked' from the Upper Greensand and attributed to the '2nde moitié du Cénomanian'.

At Royal Aller Vale Quarry [SX 882 847], Coque-Delhuille (1987) noted that the greensands pass, at the top, into yellow sands without glauconite, locally gravelly and with layers of fossiliferous cherts. Thin limestones were also present. **Bed c** is not shown on the section of Royal Aller Vale Quarry in her figures.

Bed b. Underlying **Bed c** at both Buller's Hill Quarry and Deers Hill Quarry, and also present at Royal Aller Vale Quarry [SX 882 847], Coque-Delhuille (1987) recorded a thin (less than 1 m) bed of 'Dalle silicifiée' [silicified ?flagstones] overlying **Bed a**, indicating 'an episode of emergence'. The bed was not described in detail. It is apparently visible in Coque-Delhuille (1987, photo 29, p. 371) where it occurs immediately beneath the sharply defined base of the Aller Gravel (identified by the position of a geological hammer).

Bed a. Glauconitic sands (Upper Greensand Formation) were recorded beneath Unit b at Buller's Hill Quarry, Deers Hill Quarry and Royal Aller Vale Quarry (Coque-Delhuille, 1987).

Flint gravels, termed the ***Aller Gravel Formation*** (Edwards, 1973), crop out along the eastern side of the main Bovey Basin and around the Decoy Basin south of Newton Abbot (Fig. 4). They have been worked mainly in pits at Sands Copse near Sandygate, Kingsteignton, and in the large Zig-Zag [SX 881 691] and Royal Aller Vale [SX 877 693] quarries at Aller, Kingskerswell; the latter is listed (as 'Aller Sand Pit' [SX 879 695]) as a Site of Special Scientific Interest. The BGS Lexicon notes a 'partial type section' at the Royal Aller Vale Quarry; neither the top nor the base of the formation is visible. The SSSI was not visited during this study, and its condition in 2024 was not known. In 2024 Zig-Zag Quarry was nearing the end of its working life. In the Quarry, Aller Gravel has at times, depending on the state of working, been seen in places overlying Upper Greensand Formation (probably Cullum Sands-with-Cherts Member; Selwood e*t al*., 1984), with layers of nodular brown chert. Current exposures show no evidence of Tower Wood Gravel in the quarry.

The formation, which dips westwards at between 4° and 10° in the Aller area (averaging 7°) and at 2° to 3° in the Sands Copse area, overlies the Upper Greensand and underlies the Lappathorn Member of the Eocene-Oligocene Bovey Formation. On the eastern side of the Bovey Basin, it is overlapped by the Lappathorn Member (middle Bovey Formation; ?Rupelian), but in the axial part of the basin is likely to underlie lower Bovey Formation and is early Eocene in age. It comprises grey to brown flint gravel and sand with lenses and beds of white to pale grey silt and silty clay (Figs 14, 15, 16).

The outcrop extends from Sands Copse [SX 865 756] in the north, through Kingsteignton, and into the Decoy Basin south of Newton Abbot. The formation is absent north of Sands Copse, probably having been overlapped by the Lappathorn Member of the Bovey Formation. Little is known of the formation in the Kingsteignton area owing to urban development. South of Kingsteignton the formation is probably overlapped by Bovey Formation.

Small exposures of about 1 m of Aller Gravel resting on Devonian slate and overlain by Staplehill Member gravel have been reported from the fault-bounded southern side of the

Figure 14. *Aller Gravel at Royal Aller Vale Quarry [SX 879 693]. British Geological Survey image P211202 (formerly A11559). Reproduced with the permission of the British Geological Survey © UKRI 2024. All Rights Reserved.*

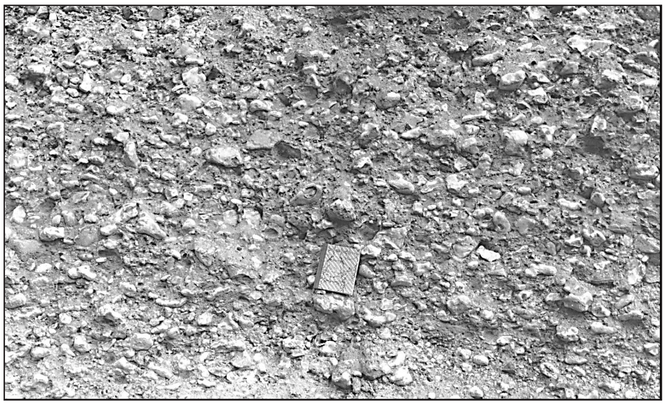

Figure 15. *Detail of a flint gravel bed in the Aller Gravel at Royal Aller Vale Quarry. The notebook measures 15 x 20 cm (photograph by R.A. Edwards).*

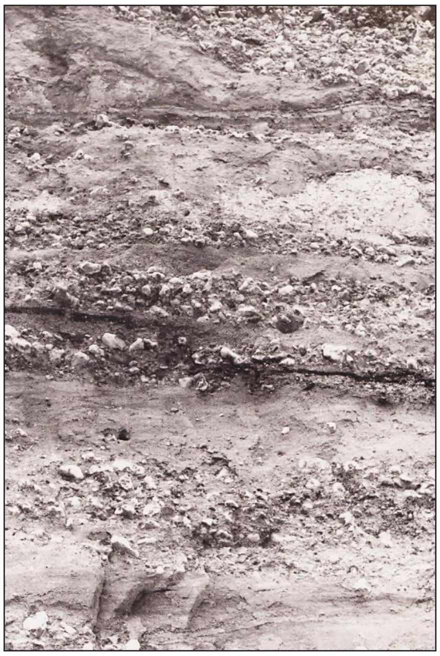

Figure 16. *Interbedded flint gravels and sands in the Aller Gravel at Royal Aller Vale Quarry (photograph by R.A. Edwards).*

Ringslade Pit [SX 846 726] on the southern margin of the Bovey Basin (B.L. Jones and M.R. Harvey, *pers. comm.*, *in* Edwards and Freshney, 1982). There is, however, some uncertainty about the validity of these observations which have been queried (F. Locke, *pers. comm.*) as representing material brought into the pit to provide the fill for drainage ditches.

There is little reliable information about the thickness of the formation. In the northernmost part of the outcrop, a borehole [SX 862 755] in White Pit, Higher Sandygate, recorded 13 m of Aller Gravel overlain by 97 m of Bovey Formation and underlain by 11 m of Upper Greensand. Near Kingsteignton, the BGS Sandygate Borehole [SX 8772 7507] proved Aller Gravel at a depth of 17.4 m beneath red-mottled clays and sands (Lappathorn Member of the Bovey Formation), thus providing direct evidence of the Eocene age of the Aller Gravel. The maximum thickness of the formation is on the east side of the Decoy Basin south of Newton Abbot, where estimates of thickness have varied between 38 m (Edwards, 1970), 25 m (Selwood *et al*., 1984) and up to 37 m (Coque-Delhuille, 1987).

At Sands Copse, former quarry workings [SX 8653 7595 to SX 8685 7550] showed up to 3 m of coarse flint gravels with cross-bedded coarse-grained sands, dipping at 2° to 3° west; the gravels comprise flint, quartz and tourmaline rock, with some Greensand chert. An exploratory pit in the Sands Copse area showed up to 4 m of flint gravel on Upper Greensand. Boreholes at Sandygate (*e.g*., [SX 8707 7494]) proved 9.4 m of Aller Gravel without reaching the Upper Greensand.

Poorly exposed outlying patches of Aller Gravel on Upper Greensand between Kingsteignton and Little Haldon are probable remnants of a formerly continuous sheet connecting the two areas, now dipping westwards as a result of subsidence associated with the formation of the Bovey Basin.

In road cuttings [SX 874 743 to SX 879 734] for the Newton Abbot by-pass east of Kingsteignton, Brunsden *et al*. (1976) recorded sediment-filled solution cavities in Middle Devonian Chercombe Bridge Limestone. They identified a bed of gravel (Bed 3), the base of which was at about 76 m OD. The lower part was mainly flint, together with Greensand chert, quartz and metamorphic rocks, and was identified with the Buller's Hill Gravel of the Haldon Hills on the grounds that it is composed largely of flint. However, much of the Aller Gravel is also composed largely of flint and thus this lower part of Bed 3 could equally be Aller Gravel, especially since it contains Greensand chert which is apparently not present in the Buller's Hill Gravel (Hamblin, 1974).

The upper part of Bed 3 also contains flint, but is finer-grained, and quartz was recorded as the main component. It was identified by Brunsden *et al*. (1976) with the Aller Gravel, apparently on the basis that the Aller Gravels are largely quartz-rich rather than flint-rich. Both the Aller Gravel and Buller's Hill Gravel are, however, mainly flint-rich and the quartz-rich gravels of Bed 3 are probably a local variant of the lithologically diverse Aller Gravel.

The dominant clasts of the Aller Gravel are moderately abraded flints (Fig. 15) together with vein quartz, quartz-tourmaline rock, Upper Greensand chert, Carboniferous chert and sandstone, dolerite and hornfels. The sequence is dominantly gravel and sand; clays and silts are scarce and normally fill abandoned channels (Fig. 14). Stacks of lenticular channels are separated by erosional bases. The sediment that fills the channels is generally poorly sorted, and cross-bedding is common; fining-upwards sequences, from gravel at the base to clay at the top, are present in some channels. The overall sedimentary features of the Aller Gravel suggest deposition in braided rivers (Edwards, 1973). Coque-Delhuille (1987, fig. 122) has demonstrated an overall fining-upward trend in the sequence from coarse gravel at the base (Level I in *op. cit*., 1987, fig. 122) to fine-grained sand and clay at the top (Levels IV and V in *op. cit*., 1987, fig. 122).

Coque-Delhuille (1987, fig. 122) shows sections in the gravels at the Royal Aller Vale Quarry [SX 878 693] exposed in several working levels I to V; Level I is the lowest and V the highest. This quarry is now disused.

Levels IV and V (approximately 17 m). This facies is mainly fine-grained, locally cross-bedded sand, and clay. It is overlain by 1 to 2 m of cryoturbated Quaternary head with palaeosols.

Levels II and III (6 -7 m). There is a relative increase in fine-grained material compared to Level I, but there are still numerous alternating beds of gravel with smaller pebbles (≤ 10 cm) (Fig. 16). Sandy lenses are commoner than in Level I, and lenses of white clay appear (Fig. 14). Ferruginization develops at these levels, and masses of pebbles with a coarse-grained sand matrix are cemented into conglomerate.

Level I (7 m). The sequence is predominantly very coarse gravel with flint pebbles, Greensand chert, other chert and quartzite, with large lenses of fine-grained to gravelly sand at oblique angles (20–25°). Grey to black flints predominate and they are typically 10–12 cm in diameter but locally up to 40 cm along the long axis.

De la Beche (1839), Clayden (1906) and Edwards (1970, 1973, 1976) favoured a direct correlation between the Aller Gravel and the Buller's Hill Gravel, considering both deposits to be part of the same sheet that extended over the area of the Bovey Basin and Haldon Hills immediately before formation of the Bovey Basin. Hamblin (1974), however, suggested that the Aller Gravel was formed after the Buller's Hill Gravel during the earliest stages of the down-folding of the Bovey Basin. Hamblin (2014) considered that the Aller Gravel contains clasts of Upper Greensand chert, supposedly absent from all three units of the Haldon Formation, suggesting that the Aller Gravel post-dates the Buller's Hill Gravel Member. However this statement contradicts Hamblin (1969) who notes the presence of Greensand chert, albeit as a supposedly rare constituent. In addition, other authors (*e.g*., Reid, 1898; Reid, *in* Ussher, 1913) have referred to the presence of Greensand chert as a prominent component of the Haldon gravels. For example, Reid (*in* Ussher, 1913, p. 103) refers to the presence of 'large subangular blocks of chert and flint'. Thus, the precise relationships between the Aller Gravel and the Buller's Hill Gravel remain uncertain.

In the ***Petrockstowe Basin***, at depths of 655–661 m in BGS Borehole 1B [SS 5202 1041], about 6 m of clayey gravel and gravelly sand rest unconformably on Upper Carboniferous rocks. The clasts range up to 10 cm across, but most do not exceed 2 to 3 cm. They are mainly quartz, with flints fairly common, together with scattered pebbles of very soft green Carboniferous sandstone. These gravels are the first Paleogene deposits to infill the basin, and clearly a flint-bearing cover of some description was locally available to provide a source of flints. The relationship of these flint-bearing gravels to the Aller Gravel or Buller's Hill Gravel is not clear. No Upper Greensand is present beneath the basal gravels.

About 400 m west of ***Coleford*** (Fig. 2), a 1.5 m-deep pit showed pale buff gravel with small pebbles of subangular quartz, broken abraded flints, and some dark grey slate (Ussher, 1906). Another pit [SX 766 013] was formerly worked for flints, and large irregularly shaped flints, up to 0.22 m long, are common in soils south-south-east of the pit; they are rarely found to the west, and the western boundary of the deposit may be determined by a north-north-west-trending fault (Edmonds *et al*., 1968). The deposit is not shown on the BGS Okehampton 1:50,000 sheet (324). It appears to rest on a kaolinised weathering profile developed on Permian breccias and may be of Paleogene age. The presence of large irregular apparently relatively unabraded flints suggest that residual flint gravels were formerly present in the vicinity.

On the summit of Chapel Down, St Martin's, ***Isles of Scilly***, Barrow (1906) recorded an outlier of subangular gravel, 'largely composed of Chalk-flints and Greensand-chert'. Coque-Delhuille (1987), however, showed that flint and greensand chert only represented a quarter of the clast content of the deposit with the petrographic composition given as follows: flint 24%; chert 1%; fine-grained granite 8%; red 'primary' sandstone 7%; other 'primary' sandstone 35% ; dykes, 'primary' schists and mica schist 5%.

The deposit is shown on the 1: 63,360-scale geological survey map (1906), labelled '**i**', the map code for 'Gravel (Eocene?)'. No detailed description was given, but Barrow considered that the deposit was Eocene in age and comparable to the Haldon gravels. The gravels were thought to be 'the last relic of an old table-land over which Eocene rivers, probably radiating from Dartmoor, flowed outwards'. However, subsequent studies (Mitchell and Orme, 1967; Coque-Delhuille and Veyret, 1984; Coque-Delhuille, 1987; Scourse, 1991) have shown that these gravels are Pleistocene glacial deposits. Mitchell and Orme (1967) suggested a fluvio-glacial origin.

In addition to the St Martin's (Chapel Down) deposit at 40–45 m OD, Coque-Delhuille (1987) mapped similar deposits on the north of Tresco (35 m OD) and the north of Bryher (Shipman Head Down, 33–35 m OD) and on St Mary's at Peninnis Head, and close to the airport (about 33 m OD).

Paleogene Deposits: Eocene to Oligocene (Bovey Formation)

The Eocene to Oligocene Bovey Formation, comprising clays, lignites, sands and gravels, is mostly contained in a series of partly fault-controlled non-marine pull-apart basins which formed along north-west – south-east-trending faults. The term 'Bovey Formation' was introduced by Edwards (1969) to replace the 'Bovey Beds' of Reid (*in* Ussher, 1913) and earlier authors. The type area is the Bovey Basin of south Devon. Three pull-apart basins are present along the Sticklepath Fault Zone: the Bovey Basin between Bovey Tracey and Newton Abbot in south Devon; the Petrockstowe Basin in north Devon; and the offshore Stanley Bank Basin east of Lundy Island in the Bristol Channel (Fig. 2). Other basins are present in Cornwall - at Dutson near Launceston, and possibly at Lamerton north-west of Tavistock. Outside the main basins, there are scattered Bovey Formation remnants at Cadham Farm south of Petrockstowe; Sandypark (Chagford); Court Barton (Christow); and, in Cornwall, at St Agnes, Crousa and Polcrebo (Fig. 2). The Bovey Formation deposits of Devon contain no known animal fossils (although possible burrows have been recorded), and no igneous rocks suitable for isotopic dating. However, studies of plant macrofossils and microfossils (pollen and spores) have yielded Eocene and Oligocene dates. King (2016) considered that most of the palynofloral assemblages previously interpreted as Chattian (Late Oligocene) can now be re-interpreted as Rupelian (Early Oligocene).

Chaanda *et al*. (2023) provide the first non-biostratigraphical evidence for the age of the Bovey Formation. Studies of a borehole through the full thickness of the Bovey Formation in the Petrockstowe Basin suggested that a carbon isotope excursion near the base of the sequence may be related either to the PETM (~56.0 Ma) or to the ETM2 (~54 Ma). If the excursion represents the PETM then it suggests that the Paleocene–Eocene boundary is present in the Petrockstowe Basin, with about 56–75 m of Paleocene strata present between the PETM at 586–605 m and the base of the Bovey Formation sequence on Carboniferous rocks at 661 m depth.

Middle Eocene (Bartonian) dates based on palynomorphs have been recorded from an unknown level of the Bovey Formation in the Dutson Basin (Freshney *et al*., 1982), and the fill of the middle and upper Bovey Formation of the Bovey Basin is considered on palynomorph evidence to be Rupelian (King, 2006); there is currently no evidence for Chattian or younger strata in the Bovey or Petrockstowe basins. Palynomorph evidence indicates that the Stanley Bank Basin is at least in part of Rupelian age, but Chattian strata may be present.

The Bovey and Petrockstowe basins are noted for their commercially important resources of ball clay, widely used in the ceramic industry. Ball clays are fine-grained, highly plastic, mainly kaolinitic, sedimentary clays that fire to a white or near white colour. The term originates from an early method of working in which the clays were cut into blocks about 25 cm cube which acquired rounded edges during handling and transport, giving them a ball-like form.

Bovey Basin

The Bovey Basin (Fig. 4) lies along the course of the major NW–SE-trending Sticklepath Fault Zone (Fig. 2). The main part of the basin extends for about 11 km between Bovey Tracey in the north-west and Newton Abbot in the south-east. A smaller, roughly circular, part of the basin south of Newton Abbot is called the Decoy Basin. A gravity survey (Fasham, 1971) indicated a maximum depth at the centre of the main basin of 1245 m, based on the assumption that the density-depth variation for the Bovey Formation of the Bovey Basin was similar to that in the Petrockstowe Basin. Vincent (1974), however, revised the estimated depth estimate of the Bovey Basin to 1100 m on the basis that, unlike the Petrockstowe Basin, lower density lignites were present in the Bovey Formation of the Bovey Basin. It is probable that most of the thickness consists of Bovey Formation sediments, with Eocene flint gravels (Aller Gravel) and Cretaceous sands (Upper Greensand) likely to be present at depth beneath the Bovey Formation. Pollen and spore assemblages indicate an Oligocene (Rupelian) age for the upper and middle Bovey Formation.

The basin originated as a pull-apart basin developed between right-stepping *en echelon* faults along the Sticklepath Fault Zone. A dextral shift of about 1.3 km is evident at the margin of the Dartmoor Granite near Lustleigh. A major structural feature is the NNW-SSE-trending Western Margin

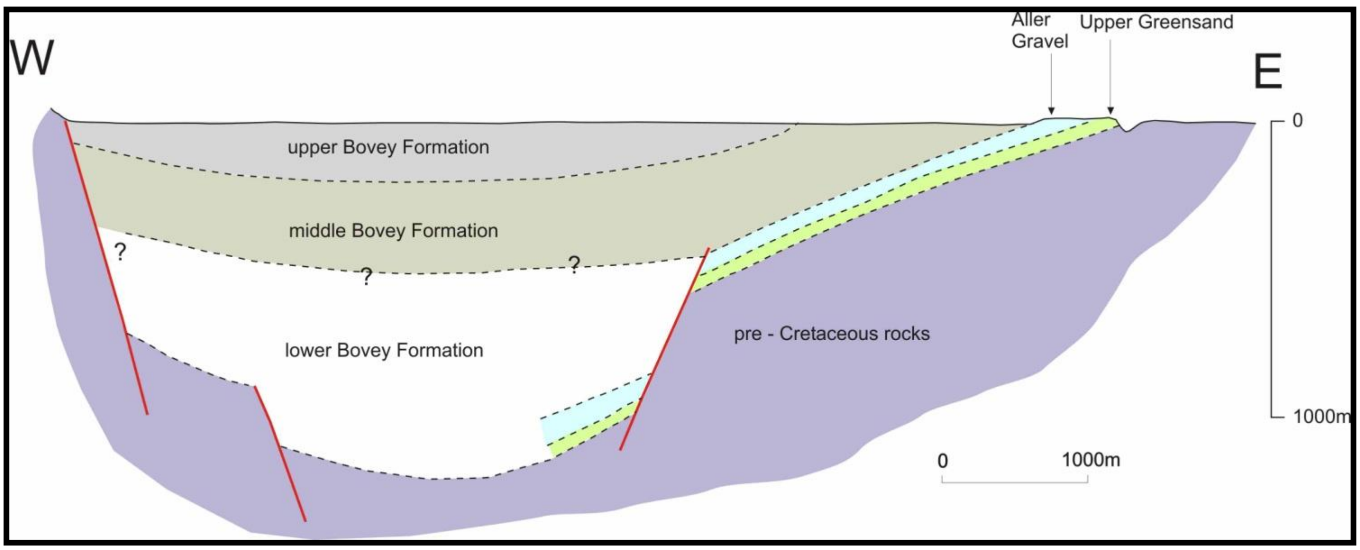

Figure 17. *A conjectural east-west cross-section of the Bovey Basin.*

Fault, which is a continuation of the main line of the Sticklepath Fault; gravity modelling shows it to be an easterly-dipping (63°) normal fault, continuing to a depth of 700 m (Fasham, 1971). Sub-parallel to, and about 1–1.6 km east of the Western Margin Fault, the NW-SE Bovey Tracey Fault is inferred to continue at depth into the basin, concealed by later sediments, to link with the branch of the fault system that reaches the coast at Torquay. The Bovey Formation of the basin is affected by a number of small, mostly oblique-slip, normal faults (Fig. 4), some of which may overlie the proposed concealed extension of the Bovey Tracey Fault and could be interpreted as Riedel shears suggestive of a dextral shear couple. In the central part of the basin, a poorly constrained internal NW–SE fault affecting upper Bovey Formation sediments extends from Bovey Tracey to near Stover Pit (Fig. 4). Transpressive forces across the pull-apart basins of south-west England caused thrusting to develop along some margins, and on the southern margin of the main Bovey Basin, around Ringslade, up to 40 m of Devonian slate were apparently thrust over the Bovey Formation (Bristow and Hughes, 1971).

A model for the evolution of the basin suggests that in a first phase up to 700 m of Bovey Formation sediments were laid down within a trough bounded by the Western Margin Fault to the west and the continuation of the Bovey Tracey Fault to the east (Fig. 4). This concealed lower Bovey Formation sequence is likely to be Eocene in age; it has not been penetrated by any borehole and thus its lithology is not known. In a second phase, bounding faults became less active and sediments spread out over a wider area to form the middle and upper parts of the Bovey Formation, totalling about 500 m (Fig. 17).

Straw (2023) postulated that the process of stripping off and transporting the weathering products from the Reskajeage Surface was coeval with the time taken to infill the pull-apart basins of Bovey, Petrockstowe and Stanley Bank. Carbon isotope data suggest that infill of the Petrockstowe Basin may have begun as early as the Paleocene/Eocene boundary (~56.0 Ma) and in the Stanley Bank Basin may have continued into the Chattian, a total infill period of at least 28 million years.

The original areal extent of the upper and middle Bovey Formation may have been greater than the modern extent. A 137 m-deep borehole very close to the western margin fault of the Bovey Basin near Wilsworthy [SX 802 764] showed a 'normal' Bovey Formation sequence (Bovey Heath, Great Plantation and Brimley members) with no marginal facies, suggesting that the fault is entirely post-depositional. As suggested by Vincent (1974), the Bovey Formation probably

Member	Lithology	Thickness
Upper Bovey Formation		
Bovey Heath Member	Grey and yellow clayey gravelly sands	Up to 50 m
Great Plantation Member	Sideritic clayey silts, silty clays and sands	Up to 107 m
Heathfield Member	Clays, silts and sands, locally lignitic	About 40 m
Brimley Member	Lignites and brown clays. Locally sands and clays	73-128 m
Stover Member	Mainly grey clays and sands. Locally lignites and clays. Parkes Seam at the base. Ball clays.	Up to 190 m
Middle Bovey Formation		
Southacre Member	Lignites and brown clays. Ball clays.	30-105 m
Chudleigh Knighton Member	Grey, greyish-brown and brown clays, silts and sands. Thin lignites at base. Ball clays.	About 50 m
Ringslade Member	Brown, greyish-brown and grey clays. Thin lignites at base. Locally mottled clays with slate fragments. Ball clays.	About 19 m
Abbrook Member	Grey clays, silts and sands. Ball clays.	Up to 70 m
Lappathorn Member	Red-mottled clays and sands	80-100 m
Lower Bovey Formation	**Lithology unknown**	Not exposed. Up to 700 m estimated
Stratigraphical position uncertain		
Woolley Member	Grey siliceous sandstones and conglomerates	Up to 24 m
Staplehill Member	Grey gravels and sands	About 10 m

Table 2. *Lithostratigraphical subdivisions and thicknesses of the Bovey Formation of the Bovey Basin.*

extended farther west before the Western Margin Fault became active, possibly extending about 4 km onto the edge of the Dartmoor Granite.

The eastern extent of the Bovey Formation similarly was also likely to have been greater. The basal middle Bovey Formation (Lappathorn Member) has an unfaulted contact with the Aller Gravel. Bovey Formation sediments have been recorded in solution hollows in Devonian limestones, up to at least 1 km east of the present main outcrop (Brunsden *et al.*, 1976).

As noted above, Hamblin (2014) suggested that the kaolinitic 'ball clay' bodies ('Haldon Clay Deposit') wholly enclosed in the Bullers's Hill Gravel of the Haldon Hills originally formed a continuous sheet overlying the Gravel. The conjectural clay sheet could be regarded as the very first Bovey Formation deposit formed on the fluvial gravel surface shortly before the focus of Bovey Formation deposition moved into the newly initiated pull-apart basin.

A geological map of the basin and an east-west cross-section are shown in Figure 4. The distribution of the component members is incompletely known in parts of the basin and consequently the formation is shown as undivided in those areas. The current lithostratigraphical subdivisions of the Bovey Formation in the Bovey Basin are shown in Table 2, and descriptions of the individual members are given below. Lithological qualifiers for members used in earlier accounts (*e.g.*, Edwards, 1976; Selwood *et al.*, 1984) are not used in this account since they do not recognise sufficiently the lithological variation present in many of the members.

The Bovey Formation is largely concealed beneath up to 9 m of Quaternary gravels, sands and clays, probably mostly of fluvial origin, and sections are seen only in working clay pits. In several pits a notable feature of the upper part of the sequences is the presence of contortions extending up to 13 m below the present surface (Fig. 18). A periglacial origin has been generally accepted (Dineley, 1963; Jenkins and Vincent, 1981) with Dineley (1963), Gouldstone (1975) and Coque-Delhuille (1987) suggesting the possibility that some of the structures were related to pingo formation.

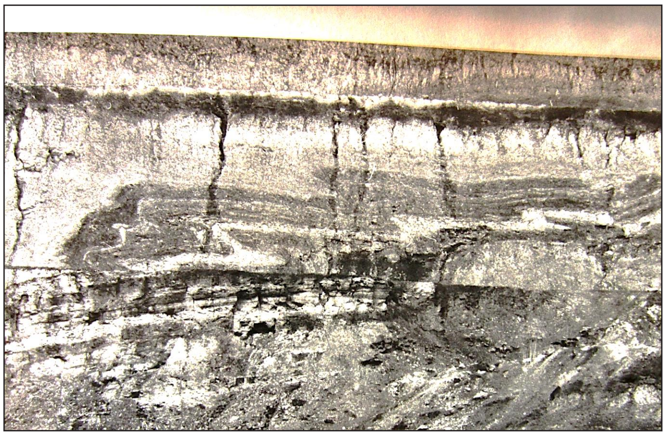

Figure 18. *Periglacial deformation structures in the Bovey Formation at East Golds Pit [SX 860 730]. The field of view is about 8 m across (photograph by R.A. Edwards).*

Figure 19. *Rootlet bed in the upper part of the Southacre Member, Southacre Pit [SX 852 756]. The pen is 13.5 cm long (photograph by E.C. Freshney).*

Lithology

The known sedimentary infill of the Bovey basin (middle and upper Bovey Formation) consists of two main lithofacies: **1**). Lignite-clay; and **2**). Clay-sand. Minor lithofacies of mottled clay and sand, and gravel and conglomerate are also present. The lithology of the lower Bovey Formation fill is currently unknown.

Lignite-clay lithofacies. This lithofacies occurs chiefly within the Southacre, Brimley and Stover members and consists of rhythmically interbedded lignites and clays. The lignites are brown to black, containing compressed fossil wood fragments, including tree trunks at some levels, elsewhere with variable proportions of clay. They form beds that are laterally persistent (>800 m) within the clay pits. The lignite beds are generally less than 1 m thick, but beds up to 8 m thick are developed locally in the lower part of the Southacre Member and in the Brimley Member. The lignites have sharp to gradational contacts with adjacent clay beds. According to Chandler (1964), the bulk of the lignite beds in the Bovey Basin are composed of *Sequoia couttsiae* (now re-assessed as *Quasisequoia couttsiae*) as masses of woody material, together with the herbaceous fern *Osmunda*. Large and small twigs, together with cones and seeds, are present abundantly. No author has yet carried out a study of the petrography of lignites in the Bovey Formation.

The carbonaceous clays range from pale brown to very dark brown or black in colour and are generally free from silt or sand grains. They may contain lignitic material as discrete fragments coarser than 0.1 mm set in a clay matrix, and as a carbonaceous colloidal coating to clay and mica particles. Lamination is mostly unrecorded.

Rootlet beds in the clays between lignite beds occur in the upper part of the Southacre Member (Fig. 19), but it is currently uncertain whether similar rootlets are present throughout the Southacre sequence. Small tree-stumps, not normally exceeding 100 mm in diameter, have been recorded in the growth position, always at the very top of a lignite bed (F. Locke, *pers. comm.*). No well-developed soil horizons are present in the rooted 'seat-earths' beneath lignite beds, and no work has been published on any soil-forming processes that may have affected them.

Previously undescribed ichnofabrics in lignitic clays, first recorded in 2017 by the authors and F. Locke from the Newbridge/Twinyeo Pit [SX 843 764/844 762], were also recorded in 2022 by G. Witte from about 20 m above the base of the Southacre Member in Southacre Pit [SX 852 756]. At Newbridge/Twinyeo the structures are present at various levels in the lower 5.6 m of the Stover Member, down through most of the Southacre Member, a vertical thickness of about 29 m. A distinctive bed about 0.6 m thick with abundant trace fossils has its base about 3 m above the base of the Parkes Seam. It consists of dark grey carbonaceous clay transected by a network of pale grey clay-filled structures, many of which

Figure 20. *Ichnofabrics in a c. 0.6 m-thick carbonaceous clay in the basal Stover Member, about 3 m above the base of the Parkes Seam, at the Newbridge/Twinyeo Pit [SX 844 762] (photograph by F. Locke).*

are subvertical, but also inclined and sub-horizontal (Fig. 20). They are mainly less than 10 mm in diameter, and some are cylindrical in form; visible portions are about 60 mm long. At Southacre Pit, the structures have been recorded from the lower lignitic part of the Southacre Member.

Other beds typically show, in vertical section, very dark grey clay traversed by irregular flattened subspherical patches and lenses of pale grey clay, many of which are sub-horizontal; some thin lenses are about 30 mm long and about 1 mm wide. Others are irregularly subspherical patches 5 mm or less in diameter. Bedding surfaces show irregular, patchy, locally elongate structures which are the lenses seen in profile.

Dr D. Knaust (*pers. comm.*) has examined images of the structures and concluded that most are likely to be root casts or root traces, formed by the decay of plant roots and subsequent infill by sediment from above. R.W. Gallois (*pers. comm.*) has compared them to *Phragmites* rootlet traces in Holocene UK Fenland sequences.

Burrow-like structures of uncertain designation have also been observed (Fig. 21), and it is possible that the supposed root traces occur together with animal burrows. Bioturbated texture in the form of a mottled fabric might be present in the background sediment.

Clay-sand lithofacies. A. *Middle Bovey Formation*. The clays of the middle Bovey Formation are generally grey, variably silty and sandy, forming relatively structureless beds. In the Abbrook Member, Chaanda (2016) recorded several fining-upward units up to 4.5 m thick with sandy bases, and channelled bases to sand units have been recorded (Edwards, 1976; Chaanda, 2016) in the same member. Lignites are scarce in this facies. The Chudleigh Knighton Member contains horizons of intraformational breccias, comprising angular to subrounded grey clay clasts in a matrix of similar clay, possibly formed as a result of channel-bank undercutting (Fig. 22). Sands with channelled bases are also present. No definite rootlets have been identified in the Abbrook Member, but rootlets have been recorded in other units, for example, the Ringslade Member, Stover Member and Great Plantation Member.

B. *Upper Bovey Formation*. Currently (2024) sands within the Stover Member are exposed only in the basal few metres of the member at Ringslade Pit, Southacre Pit, Denistone Pit and Newbridge/Twinyeo Pit. Sands are exposed at Stover Pit (?Stover Member). No sections are available in the higher members of the upper Bovey Formation (Heathfield, Great Plantation and Bovey Heath members). Commercial boreholes in these higher members commonly record coarse-grained 'granitic' sands, but there are no detailed descriptions.

Figure 21. *Vertically sliced core sample showing possible burrowing and bioturbation. Southacre Member, Newbridge/ Twinyeo Pit [SX 844 762]. Core diameter 10 cm (photograph by R.A. Edwards).*

Figure 22. *Clay-pellet breccias from the Chudleigh Knighton Pit. Scale is about 8 cm from top to bottom (photograph by R.A. Edwards).*

Figure 23. *Channelled, cross bedded, coarse-grained sands and gravels, Stover Pit. Probable braided-stream deposits (photograph by F. Locke).*

Figure 24. *Massive, very poorly sorted, thickly-bedded sands and sandy pebble gravels with bedding indistinctly picked out by impersistent clay laminae. Ringslade Pit (photograph by F. Locke).*

The available sections in the Stover Member show two broad categories of coarse-grained sediment: **1**). Gravelly sands, sandy gravels, and sands, probably deposited in a high-energy braided stream environment, showing well-developed gravel-filled channels, erosional surfaces and cross-bedding (Fig. 23). The clasts are dominantly angular quartz, rarely exceeding 10 mm (pebble gravel). The sediments are grey to pale grey, locally yellow- and orange-stained. Ferruginous cement is developed locally. **2**). Finer-grained, massive, very poorly sorted, thickly-bedded sands and sandy pebble gravels exhibiting bedding indistinctly picked out by impersistent clay laminae, with thin clay beds locally present (Fig. 24).

The grains in both types of sands, predominantly quartz with some tourmaline and composite quartz-tourmaline, are angular and show little sign of abrasion. Grain-size analysis of a sample from the lower Stover Member overlying the Southacre Member at Southacre Pit showed it to consist of 16% gravel, 72% sand, 5% silt and 7% clay (very poorly sorted gravelly clayey sand). Another sample from the Bovey Heath Member was very poorly sorted gravelly clayey sand (gravel 26%, sand 46%, silt and clay 28%). The Bovey Heath Member sands are distinguished by the presence of feldspar amongst euhedral quartz grains and abundant tourmaline, but feldspar was not seen in the Stover Member sands at Southacre Pit (Vincent, 1974, p.184). The composition of the sands indicates a Dartmoor Granite source.

Silty sands are also recorded in commercial boreholes in the upper members of the Bovey Formation (Vincent, 1974), but there are no data on their sedimentary features. A lack of available sections means that it has not been possible to carry out detailed analysis of the sands. Cross-sections plotted by Vincent (1974) using commercial borehole data indicate that the sand units form laterally extensive sheets, interbedded with clay beds shown to be laterally persistent on the evidence of borehole correlations based on lithology, geochemistry and ceramic data (Vincent, 1974).

Mottled clay and sand lithofacies. This lithofacies is represented in the Lappathorn Member which comprises siliceous clays and sands stained red, pink and brown by ferric hydroxide. Mottling is locally present in the Ringslade Member where it is largely due to included fragments of Devonian slate.

Gravel and conglomerate lithofacies. Within this lithofacies are included the gravels and sands of the Staplehill Member, outcropping along the south-western margin of the Bovey Basin, and the Woolley Member, consisting of grey, well-cemented, siliceous coarse-grained sandstone and conglomeratic sandstone.

Bristow (1993) identified scattered occurrences of siliceous rocks west of the Bovey Basin and interpreted them as silcrete duricrusts. Their age is uncertain, but thought most likely to be Paleocene or Eocene, suggesting that the land surface west of the Bovey Basin has not been greatly lowered since the early Cenozoic or possibly the late Mesozoic.

Stratigraphy

The chief ball clay-bearing strata of the Bovey Formation extend along the eastern side of the basin between Chudleigh Knighton and Newton Abbot, where they dip to the south-west at around 10° – 15° on the eastern limb of a broad synclinal structure (Fig. 4). There was an early recognition of a two-fold division into a 'Stoneware Group' and an overlying 'Ball Clay Group' (*e.g.*, Scott, 1929). Edwards (1969, 1970) introduced the term Bovey Formation to encompass the former Bovey Beds and divided the eastern outcrop into the Abbrook Member and overlying Southacre Member, corresponding approximately to the Stoneware Group and Ball Clay Group. The strata overlying the Southacre Member, occupying much of the central and western part of the basin, were included in Edwards' Blatchford Member. Additional units recognised were the Chudleigh Knighton Member and the Ringslade-Mainbow Member. The Staplehill Gravels (Edwards, 1970) were described from along the south-western margin of the basin, and the Woolley Grit from north of the main basin, near Lustleigh. In Edwards and Freshney (1982) the Bovey Formation was informally divided into a lower concealed part, overlain by middle Bovey Formation and upper Bovey Formation (Table 2).

Vincent (1974) distinguished the Lappathorn Member as the lower part of Edwards' original Abbrook Member. He recognised within the upper Bovey Formation (in ascending order) the Twinyeo Member, Stover Member, Brimley Member, Heathfield Member, Great Plantation Member, and Bovey Heath Member. The term Blatchford Member was retained but restricted to sands of uncertain stratigraphical position in the south of the main basin. According to Vincent's analysis of commercial ball clay boreholes, the post-Southacre members form packages separated by low-angle unconformities, indicating breaks in deposition probably related to tectonic movements associated with the Sticklepath Fault Zone, causing the focus of sedimentation to vary at different times across the basin. The original extent of the members is not known owing to subsequent erosion, so that palaeogeographical reconstructions (*e.g.*, Vincent, 1974) are conjectural.

The lower Bovey Formation, estimated to be about 700 m thick, is concealed beneath younger strata. No borehole has yet penetrated this sequence and lithologies are unknown, but by

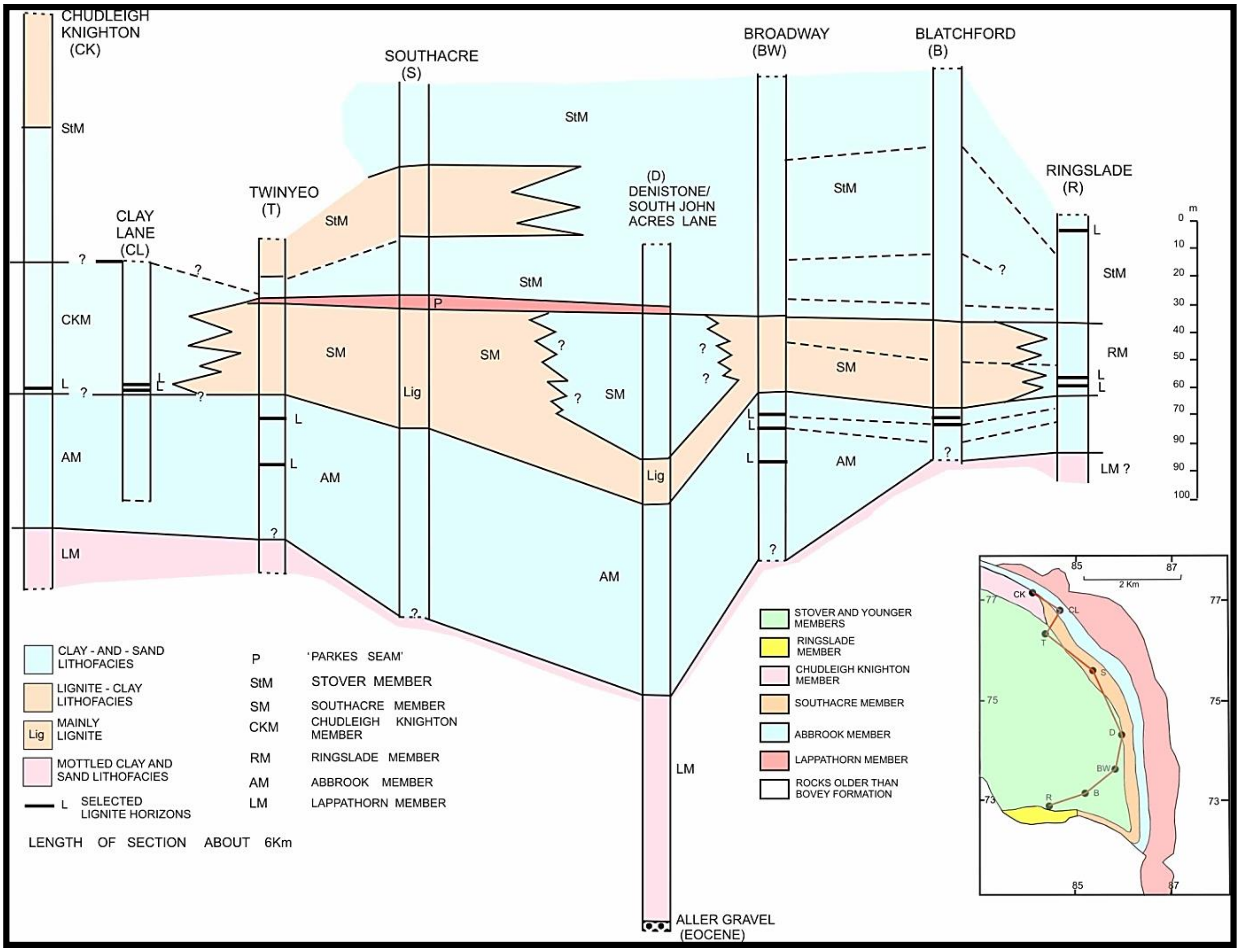

Figure 25. *Correlation of sections through the Bovey Formation of the eastern outcrop of the Bovey Basin between Chudleigh Knighton and Ringslade, showing variations in thickness and lithology. The inset map shows the locations of the sections on a simplified geological map of part of the Bovey Basin. CK = Chudleigh Knighton. CL = Clay Lane. T = Twinyeo. S = Southacre. D = Denistone/South John Acres Lane. BW = Broadway. B = Blatchford. R = Ringslade.*

comparison with the trough deposits of the Petrockstowe Basin, may consist of silts, sands, gravels and extremely sandy clays.

The middle Bovey Formation includes the main productive ball clay beds. It crops out along the eastern side and northern and southern margins of the basin (Fig. 4) where the following units, in ascending order, have been recognised: ***Lappathorn Member***, ***Abbrook Member***, ***Southacre Member***, ***Chudleigh Knighton Member*** and ***Ringslade Member***.

Named from Lappathorn Copse [SX 865752] near Sandygate, Kingsteignton, the ***Lappathorn Member*** forms the basal member of the middle Bovey Formation and comprises a mottled clay and sand lithofacies, principally red- and pink-mottled silty clays and clayey silty sands (the ‘pinks’ of the clay workers). No ball clays are present, but some siliceous clays in the member have been worked in the past for brick clay. The Lappathorn Member is 80 to 100 m thick in the Lappathorn area. It extends along the eastern side of the basin from near Chudleigh Knighton to Newton Abbot and is also probably present in the Decoy Basin (Fig. 4). It rests unconformably on the Aller Gravel and Upper Greensand, or, near Chudleigh Knighton, on Carboniferous rocks. In the Ringslade Pit area [SX 845 727] at the southern margin of the basin, 10 m of red- and purple-mottled pale grey sandy silty clay, probably Lappathorn Member, were recorded in boreholes beneath Abbrook Member.

The ***Abbrook Member*** (Abbrook Member of Edwards (1970) and Vincent (1974); Abbrook Clay and Sand Member of Edwards (1976) and Edwards and Freshney (1982); Abbrook Clay-and-Sand Member of Selwood *et al*., (1984)), is an important source of Group 3 and 4 ball clays; it rests on the Lappathorn Member and outcrops from Little Bradley [SX 828 778] (west of Chudleigh Knighton), southwards to near Newton Abbot (Figs 4, 25). It is shown as absent in the Decoy Basin where Vincent’s 1974 map showed the Southacre Member apparently resting directly on Lappathorn Member, but there is much uncertainty in this interpretation.

The member, named from Abbrook Farm [SX 866 745] near Kingsteignton, consists of up to 70 m of grey silty clay, clayey silt and sand with scarce carbonaceous horizons. It extends in the subsurface westwards at least as far as Stover Park, where a borehole penetrated at least 30 m of mainly grey and brown clays and a few sand beds, beneath Southacre Member.

The clays in the member form relatively structureless beds. Almost all show variable amounts of sideritic staining, and sideritic concretions and spherulites are developed locally. Chaanda (2016) recorded several fining-upward units up to 4.5 m thick in South John Acres Lane Pit [SX 862 748]. In the same pit, impersistent beds of structureless coarse-grained sand with lignite fragments are locally developed; Chaanda (2016) interpreted these as the product of small debris flows. In 2024 the Abbrook Member was being worked in the South John Acres Lane Pit [SX 862 748] and in the northern part of White Pit [SX 860 757].

In the Chudleigh Knighton Heath area, the Abbrook Member is about 50 per cent sand and about 50 per cent clay

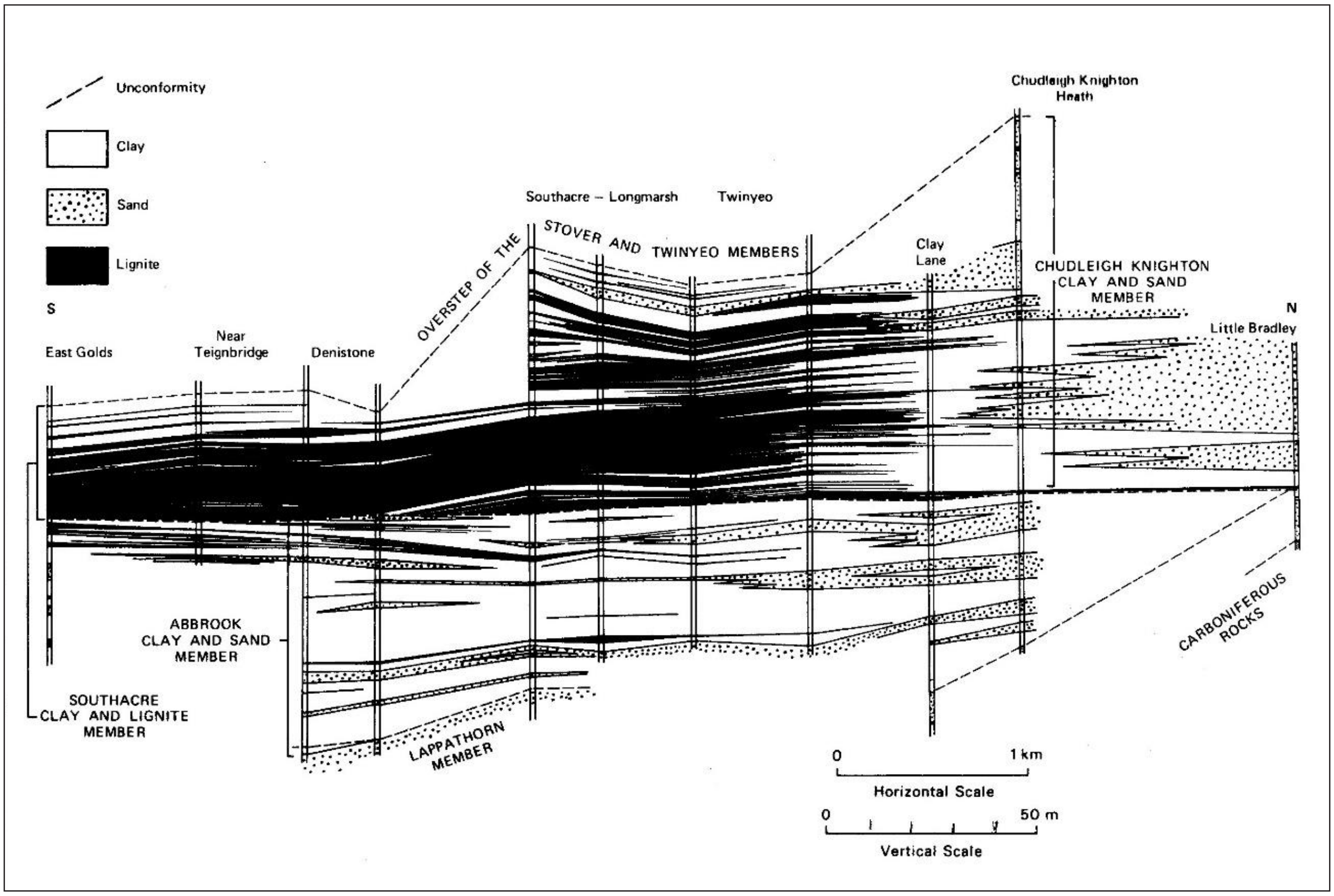

Figure 26. *Section of the Bovey Basin between Newton Abbot and Chudleigh Knighton, showing lateral variation in the Abbrook Member and Southacre Member (after Vincent, 1974, fig. 6.3). The Twinyeo Member is now regarded as part of the Stover Member. Abbrook Clay and Sand Member = Abbrook Member. Southacre Clay and Lignite Member = Southacre Member. Chudleigh Knighton Clay and Sand Member = Chudleigh Knighton Member.*

Figure 27. *Southacre and Stover members at Newbridge/Twinyeo Pit [SX 843 764], 2017. The yellowish-brown-weathering bed about halfway up the face is the Parkes Seam (labelled P) at the base of the Stover Member. Below are clays and lignites of the Southacre Member. Above, the Stover Member contains grey clays, channelled sand, and a lignite-clay sequence. See Figure 28 for a graphic log of the sequence in this area (photograph by E.C. Freshney).*

(Vincent, 1974). The sand beds interfinger and pass out laterally southwards towards Twinyeo where clay becomes dominant, with a thin lignite bed near the base and another about two-thirds above the base. In the Denistone to East Golds area this upper lignite expands into several leaves of interbedded lignite and brown clay near the top of the member (Fig. 26). The upper 14 m in the South John Acres Lane Pit [SX 862 748] contain beds of carbonaceous clay. In a pit at Rixey Park [SX 852 763], now infilled, the member contained two thin beds of dark carbonaceous clay showing well-developed brecciation with angular clasts of dark and pale clay in a matrix of dark clay. At least part of the sequence of clays worked in the Chudleigh Knighton Pit [SX 841 772] may be Abbrook Member, but detailed correlation in this area is uncertain.

The lateral changes in the Abbrook Member between Newton Abbot (East Golds) and Chudleigh Knighton, noted above, are shown in Figure 26, which is based on a section constructed by Vincent (1974, fig. 6.3).

Abbrook Member is present beneath Ringslade Member in the Ringslade Pit [SX 845 727] area where it is up to 23 m thick. About two-thirds of the thickness is beds of grey coarse-grained sand and fine gravel up to 3 m thick, interbedded with beds of pale grey very silty clay up to 2 m thick.

The ***Southacre Member*** (Southacre Member of Edwards (1970) and Vincent (1974); Southacre Clay and Lignite Member of Edwards (1976) and Edwards and Freshney (1982); Southacre Clay-and-Lignite Member of Selwood *et al*., (1984)), is a very important resource of Group 1 and 2 ball clays, with Group 2 clays present in the lower part. Named from the Southacre area [SX 853 755] (where an SSSI has been defined at 'Southacre Clay Pit'), it consists of between about 30 and 105 m of rhythmically-interbedded lignites and carbonaceous brown and black clays (Fig. 27), with subordinate grey to greyish-brown silty clays and sands. Thicker lignites dominate in the lower half of the member along the eastern outcrop and may exceed 6 m in thickness. In the Denistone area, the upper 53 m of the member consists of clays and sands with few lignites, resting on a predominantly lignitic sequence about 17 m thick (Fig. 25). The base of the Southacre Member is normally fairly sharply defined by lithological change on the underlying Abbrook Member. The outcrop (Fig. 4) extends from the Newbridge area in the north, southwards via Preston (Southacre), Denistone and Teignbridge to the East and West Golds Marshes near Newton Abbot, where it swings abruptly westwards through 110° to form the southern synclinal closure of the main basin. It is also possibly represented by a thin sequence in the Decoy Basin.

The lateral changes in the Southacre Member between Newton Abbot (East Golds) and Chudleigh Knighton, especially an interpretation of the lateral transition between the Southacre Member and the Chudleigh Knighton Member, are shown in Figure 26, which is based on a section constructed by Vincent (1974, fig. 6.3). The relationship of the 'typical' Southacre Member of the Newbridge/Twinyeo Pit area to the sequence in the Chudleigh Knighton Pit [SX 841 772] area is discussed below.

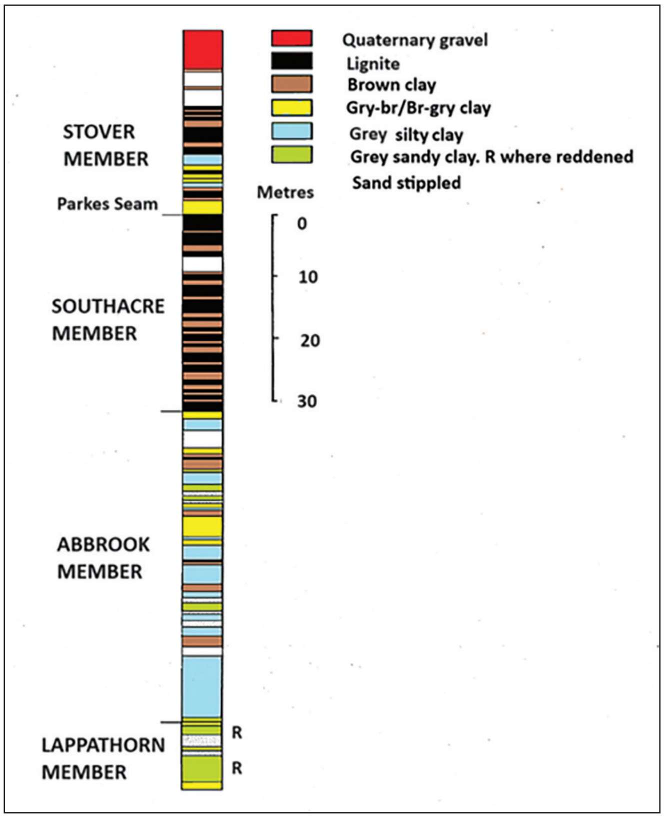

Figure 28 *Generalised section through the Newbridge/Twinyeo Pit area [c. SX 844 762] (Figure 27), based on a cored borehole, courtesy of Imerys. The section shows the uppermost 12 m of the Lappathorn Member, overlain by a complete 53 m-thick sequence of Abbrook Member, overlain by a complete 35 m-thick sequence of Southacre Member. The base of the overlying Stover Member is defined by the Parkes Seam.*

In the sub-crop beneath Bovey Heath [SX 827 768], Vincent (1974, section line 3) showed the Southacre Member to be in a clay-sand lithofacies. Farther south, section line 5 of Vincent (1974) was interpreted as showing the Southacre Member to extend in the subcrop to at least as far west as Higher Brocks Plantation [SX 839 756], where it is 73 m thick and almost entirely lignite. Southacre Member, overlain by Stover Member, has been proved by boreholes (Vincent, 1974, section line 6)

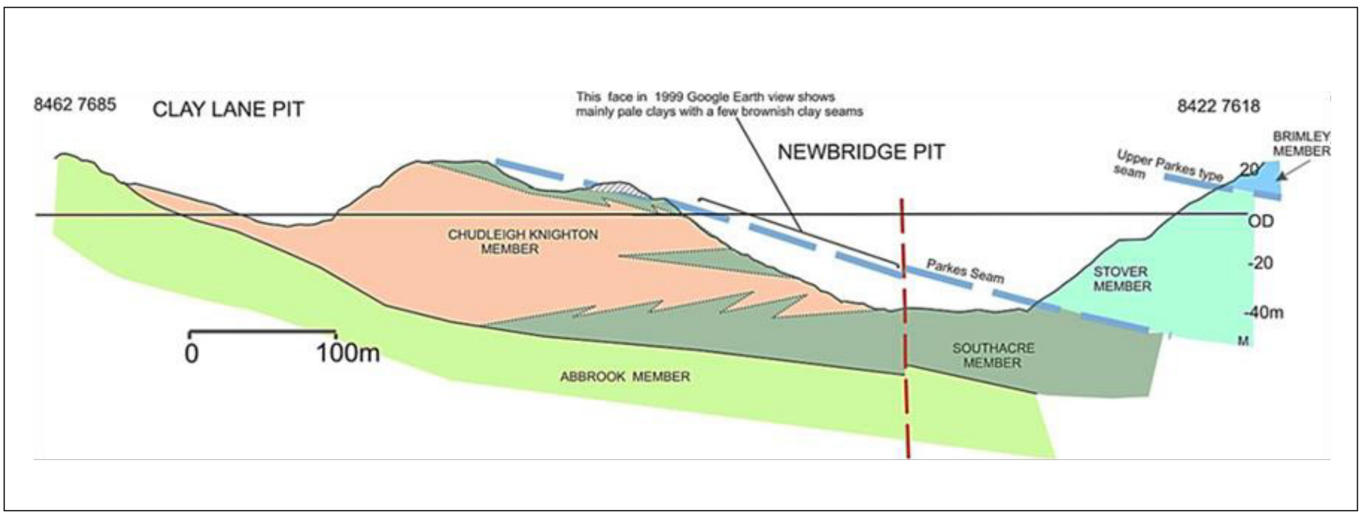

Figure 29. *An interpretation of relationships in the Bovey Formation between Newbridge/Twinyeo Pit and Clay Lane Pit.*

beneath Ventiford and Stover Park. In a borehole [SX 8472 7467] near Ventiford Bridge, the Southacre Member is 89 m thick and contains in the lower half 30 m of lignite with occasional clay beds. Beneath Stover Park the thickest recorded sequence of the member is about 105 m thick and again predominantly lignite in the lower part.

In the Ilford Park area (Fig. 4), boreholes proved a sequence at least 12.8 m of grey variably silty clays. Its position beneath the Parkes Seam indicates an equivalence to at least part of the Southacre Member, but in a non-lignitic facies.

The northernmost pit in the Southacre Member is at Newbridge/Twinyeo [SX 843 764/SX 847 762] where the member is 35 m thick (Figs 25, 28) and consists of interbedded brown clays and lignites (Fig. 27). In its type area, at Southacre [SX 852 756], the member is about 47 m thick and consists of a lower lignitic unit 26 m thick overlain by about 21 m of interbedded clay and lignite. In the Denistone area [SX 859 743] the Southacre Member is about 70 m thick and comprises a lower lignitic sequence 17 m thick overlain by about 53 m of clays and sands with few lignites; the interbedded clays are paler in colour (grey to fawn) and are classified as Group 1 Light Ball Clays (informally termed 'Group 1 Lights'). Farther south, in the East and West Golds areas, the Southacre Member is 24 to 61 m thick, mainly interbedded brown clay and lignite.

For the most part, earlier studies of sections in the Southacre Member recorded no rootlet horizons in the clay beds, although Edwards (1970) recorded rootlets at the now infilled East Golds Pit [SX 860 730]. Rootlet beds occur in the upper part of the Southacre Member at Southacre Pit [SX 852 756] (Fig. 4). Chaanda (2016) recorded rootlet horizons throughout the Southacre sequence at the South John Acres Lane Pit [SX 862 748] but this observation has not been confirmed by the authors. As noted above, trace fossils are present in carbonaceous clays in the Southacre Member at the Newbridge/Twinyeo Pit [SX 844 762] and in the lower lignitic part of the Southacre Member at Southacre Pit.

Boreholes and pit sections in and around the Chudleigh Knighton Pit area [SX 841 772] showed at least 25 m of grey sandy clays, slightly silty grey or greyish-brown clays, grey silts and sands, and smooth brown clays, included in the ***Chudleigh Knighton Member*** (Chudleigh Knighton Member of Edwards (1970); Chudleigh Knighton Clay Member of Edwards (1976); Chudleigh Knighton Clay and Sand Member of Edwards and Freshney (1982); Chudleigh Knighton Clay-and-Sand Member of Selwood *et al*. (1984)). One or two thin lignite beds at the base of the sequence mark the boundary between the Chudleigh Knighton Member above and the Abbrook Member (about 50 m thick) below, which in turn rests on about 22 m of the topmost Lappathorn Member (Fig. 25). In the area around Clay Lane Pit [SX 845 828], presumed Abbrook Member at least 37 m thick, consisting of mainly sand and grey clay, is overlain by at least 50 m of brown clays (some grey) and thin lignites which may be equivalent to the Chudleigh Knighton sequence. Farther west, towards Little Bradley, the clay facies of the member apparently pass into a sand facies.

The geological map (Fig. 4) and sections along the eastern outcrop of the Bovey Formation (Figs 25, 26) show the Southacre Member passing laterally into the clay facies of the Chudleigh Knighton Member, as envisaged by Vincent (1974), but there are still uncertainties in understanding the relationship of the Chudleigh Knighton sequence to the Southacre Member sequence of the Newbridge area.

Boreholes through Clay Lane Pit showed mainly pale grey clays with a few pale brown beds, classified as Chudleigh Knighton Member, resting on Abbrook Member, a situation comparable with that in the Chudleigh Knighton Pit immediately to the north-west. The Chudleigh Knighton Member dips under Clay Lane and should daylight again in the northern part of Newbridge/Twinyeo Pit. Sub-horizontal bedding in the northern part of Newbridge/Twinyeo Pit was visible on a 2018 Google Earth image and was interpreted as dominantly pale clay with subordinate pale brown seams, similar in aspect to the Clay Lane Chudleigh Knighton sequence. There is probably interdigitation between Chudleigh Knighton Member and Southacre Member passing southwards across Newbridge/Twinyeo Pit. This area has now been removed by working and partly obscured by fill. An interpretation of the relationships between the Newbridge/Twinyeo Pit and Clay Lane Pit is shown in Figure 29.

The Chudleigh Knighton clays contain horizons of intraformational breccias, comprising angular to subrounded grey clay clasts in a matrix of similar clay (Fig. 22), possibly formed as a result of channel bank undercutting. Sands with channelled bases are also present.

At the southern margin of the Bovey Basin between Blatchford [SX 850 730] and the Ringslade Pit [SX 845 727], the clays and lignites of the Southacre Member pass laterally into the ***Ringslade Member*** (Fig. 25), formerly termed the Ringslade-Mainbow Member (Edwards, 1970) and Ringslade Clay Member (Edwards, 1976, Edwards and Freshney, 1982, Selwood *et al*., 1984). Ball clays are worked from the member in the Ringslade Pit. The Ringslade Member overlies at least 20 m of Abbrook Member sands and clays and is overlain by Stover Member (Fig. 25). It consists of about 19 m of smooth to silty, brown, brownish-grey and pale grey clays with a few thin beds of lignite and carbonaceous clay. Rootlets are present at several horizons. The lower 5 m of the member consist of brown to brownish-grey smooth clays with two lignite beds at the base. It is overlain by about 6 m of pale grey silty to slightly silty clay, with a lenticular unit up to 2 m thick of pale grey silty sand. Above are about 8 m of brown clay with four thin units of brown carbonaceous clay.

Farmer (2016) showed that in the Ringslade Pit there was an association of iron sulphide mineralisation, mainly in the form of pyrite and marcasite, within the lignitic seams near the base of the Ringslade Member. Rootlets were present within the clays immediately above and below the main lignitic horizon. Erosional bases to sand beds were recorded by Farmer (2016).

The Ringslade area is of particular interest in showing the development of a mottled clay facies related to possible thrust tectonics. This 'Ringslade Mottled Clay' (Edwards, 1976) wedges out from the southern margin of the basin and consists of pale grey sandy clay with mottles of purple, red, yellow and grey, much of which are due to included fragments of Devonian slate. It is not currently (2024) exposed in the Ringslade Pit. Boreholes and exposures (now concealed) along the southern edge of the open pit showed up to 30 m of Devonian slate apparently thrust over the Ringslade Member (Bristow and Hughes, 1971). Deposition of the Ringslade Mottled Clay was probably related to contemporaneous movement of the thrust, with material derived from the nose of the thrust and deposited within the area of ball clay sedimentation. A similar sequence (the 'West Golds Mottled Clay') has been proved in boreholes below Knowles Hill, Newton Abbot.

Bristow (1993) noted that further development of the Ringslade Pit had revealed a drag fold in the Bovey Formation on the south side. Large boulders of silcrete or ferricrete breccia up to 3 m in diameter were present just below the sole of the thrust [SX 845 726] and may have been brought up along the thrust from somewhere in the vicinity of the Paleogene/Paleozoic unconformity.

Sequences above the Southacre Member are included in the upper Bovey Formation, divided into five members. Vincent (1974) showed that these members generally lie discordantly upon each other, reflecting changes in depocentres attributed to fault movements. They comprise, in ascending order, the Stover, Brimley, Heathfield and Great Plantation and Bovey Heath members (Fig. 4). Most consist of clay and sand, but the Brimley Member is largely in a lignite-clay lithofacies.

The ***Stover Member***, named by Vincent (1974) from Stover Park [SX 844 741], is dominantly grey sand and silty sand, gravelly at some horizons, with subordinate beds of clayey silt, clay and local units of lignite-clay lithofacies. It overlies the Southacre Member along the eastern crop from about Twinyeo southwards and extends into the central part of the basin (Fig. 4). In 2024 ball clays were worked from the lower part of the Stover Member in Newbridge/Twinyeo Pit, Southacre Pit, Denistone Pit, and possibly in Stover Pit where, however, the sequence is of uncertain age.

The base of the Stover Member is defined by a marker horizon, the 'Parkes Seam', first recognised and named by geologists working with the ball clay company Watts Blake Bearne (now Sibelco), and characterised by the presence of well-ordered kaolinite, high-alumina and low alkalis and abundant siderite. It consists of pale grey clay, silty in places, locally laminated and possibly burrowed. In places (for example in the Newbridge/Twinyeo Pit [SX 844 762]), rootlets are present; elsewhere it contains breccias comprising clasts of grey laminated clay in a grey clay matrix. It forms a marker bed (Figs 4, 25) extending from the eastern outcrops into the subcrop in the central part of the basin. In the Southacre and Twinyeo areas, the Parkes Seam is present at the base of the Stover Member and is about 2.4 m thick. It is overlain by about 30 m of clay and sand with ball clays of Group 1 Light type. Above are about 78 m of lignite and clay, also containing Group 1 Lights; this sequence was termed the 'Goosehams Member' and 'Modified Goosehams Member' in unpublished literature by the ball clay company Watts Blake Bearne (now Sibelco) which regarded them as informal subdivisions of the Stover Member, with no formal stratigraphical validity. The 'Goosehams Member' is equivalent to the 'Twinyeo Member' recognised by the ball clay company Imerys. This 'Goosehams/ Twinyeo' sequence appears, however, to be a locally developed more lignitic facies which passes laterally into a more typical sand-rich Stover-type sequence and is thus included by the present authors in the Stover Member.

In the Newbridge area, the Parkes Seam was exposed in 2024 in the working pit [SX 843 764] (Fig. 27). The overlying lower Stover Member consists of about 7 m of grey, brownish grey and brown clay with a channel sand, overlain by about 14 m of brown clays and woody and clayey lignites. In the Newbridge/Twinyeo Pit [SX 844 762], near the base of the Stover Member sequence, some previously unrecorded trace fossils (Fig. 20) are present.

In a borehole at Higher Brocks Plantation [SX 839 756], the Parkes Seam at about 190 m depth marks the base of the Stover Member and overlies the Southacre Member. It is overlain by about 80 m of lignite and clay, formerly included in the 'Twinyeo Member' of Vincent (1974), now classed as a lignitic facies of the Stover Member, succeeded by about 45 m of sand and clay (upper Stover Member). At Ventiford Bridge, near Stover Park, a borehole [SX 8472 7467] proved 123 m of Stover Member, mainly sand with some clay beds, resting on 4 m of grey sideritic clay (Parkes Seam).

In the Ringslade Pit [SX 845 727] Stover Member overlies Ringslade Member. Kaolinitic clays are present at the base of the Stover Member but cannot be confidently assigned to the Parkes Seam owing to the lack of data between Ringslade and areas of known Parkes Seam occurrence. The lower 17–23 m of the Stover Member at Ringslade are mainly grey to pale grey sandy silt with a few beds of pale grey silty clay. The sequence above, about 45 m thick, is dominated by beds of pale grey coarse-grained sand and fine gravel, with beds of pale grey silty sand, sandy clayey silt and pale grey sandy silty clay. Two thin units of brown lignitic clay and clayey lignite are present.

Edwards (1970) used the term Blatchford Member (named from Blatchford Farm [SX 851 729]) to include all the post-Southacre sand and clay strata. Vincent (1974) restricted its use to the southern area of the main basin, where it was thought to be almost exclusively sand, and of uncertain stratigraphical position. However, the Blatchford Member is now not considered to be a separately identifiable unit and is here regarded as a sand-dominated facies of the Stover Member. The sands in the Stover Member include thick-bedded units of grey, poorly sorted sands, very coarse-grained to gravelly in parts of the sequence, consisting predominantly of angular to subangular quartz grains with lesser amounts of tourmaline and quartz-tourmaline grains, derived from the Dartmoor Granite.

In the Ilford Park area (Fig. 4), a composite borehole section [c SX 829 746] shows an easterly-dipping section, summarised below, in which the Stover Member as currently identified is 68.19 m thick and rests on the c 4 m-thick Parkes Seam. An overlying unit of predominately fawn to brown clays is of uncertain stratigraphical position but may be Brimley Member.

Stratigraphical position uncertain

- **Clay**, pale grey, slightly silty to silty with occasional **sand** beds, reportedly high in iron 16.65 m

?Brimley Member or ?Stover Member

- **Clay**, fawn to brown, silty to smooth, with lignitic fragments in some beds, with subordinate **clay**, grey, variably silty. Sharp base 11.60 m

?Stover Member

- **Clay**, grey, variably silty, with occasional beds of **sand** 68.19 m

Parkes Seam

- Variable sequence of high-alumina grey **clays** and **sands** 3.97 m

?Southacre Member

- **Clay**, grey, variably silty 12.80 m +

In the west of the basin, Stover Member probably outcrops south of Liverton (Fig. 4), but there are no exposures. Cored commercial boreholes between Langaller [SX 807 766] and Liverton showed the probable Stover Member sequence beneath Brimley Member to consist of up to 47.5 m of grey and brownish-grey sands with subordinate grey and greyish-brown clays, with a few units of clayey lignite. The sands are mostly grey, poorly sorted, clayey, medium- to coarse-grained. Rootlets were recorded at several levels in grey or brownish grey clays.

The ***Brimley Member*** of Vincent (1974), named from Brimley [SX 799 771] near Bovey Tracey, comprises 73-128 m of interbedded lignite and brown clay, becoming dominantly sand in the topmost part. It includes the beds in the Bovey 'Coal Pit' (Blue Waters Mine) [SX 812 770] (Pengelly, 1862) which thus belong to a higher stratigraphical sequence than the Southacre Member with which they had previously been correlated (British Geological Survey, Newton Abbot 1:50 000-scale geological sheet 339, 1976). The Brimley Member generally rests on the Stover Member and is overlain by the Heathfield and Great Plantation Members. Vincent (1974) noted that between Great Plantation and Heathfield, the Brimley Member is mainly sand in the west, passing eastwards through clays to a dominantly lignitic facies. A bed high in alumina and low in alkalis, comparable to the Parkes Seam, locally forms a marker at the base of the Brimley Member.In the Ilford Park area (Fig. 4) an 11.60-m thick sequence of predominantly fawn and brown clays without lignite beds resting sharply on probable Stover Member is provisionally assigned to the Brimley Member. An overlying sequence of iron-rich pale grey clays with occasional sand beds is of uncertain stratigraphical position.

In the area between Stover Park and Ringslade there are uncertainties in the interpretation of the sequence. Vincent attributed to the Stover Member a thickness of about 190 m of mainly sands and clays, penetrated in a borehole [*c*. SX 8425 7428] (223 of Vincent, 1974, section line 6) near Stover Park. He noted (*op. cit.*,1974, p. 224) one bed (possibly at about 90.4 m depth in borehole 223) which 'shows many of the characteristics of Parks, with the usual coarseness, lack of mica and white firing, but containing much less siderite and not as well-ordered kaolinite...'. High Al_2O_3 clays are also present at about 76 m depth, above a lignite, in a borehole (S21) [SX 8434 7405] at Stover Park. This corresponds with the 'Parkes-type' bed noted above in borehole 223. If this bed marks the base of the Brimley Member, then the beds above must be attributed to the Brimley Member, although not in the characteristic lignitic facies of that member, and the beds worked in the Stover Park Pit [SX 843 739] would then be attributed to the Brimley Member.

At Stover Park Pit the worked sequence of brown ball clays associated with a lignite horizon occurs within predominantly sands (locally gravelly), sandy grey clays, and grey clays. Clays in a now infilled part of the pit [SX 845 740] showed distinctive soft-sediment disturbance attributed by Best and Fookes (1971) and Edwards (1976) to gravity-induced disruption, possibly caused by earthquake shocks related to movement on faults, and these beds may be examples of 'seismites' (Fig. 30). In view of the uncertainties in interpretation, the sequence in the Stover area is shown on the geological map (Fig. 4) as undivided.

The Brimley Member was proved in cored commercial boreholes in the western Bovey Basin between the Bovey 'Coal Pit' [SX 812 770] and Liverton [SX 805 751]. Marked lateral facies and thickness changes can be demonstrated and probably represent a transition from forest swamp deposits in the north into mainly overbank vertical accretion floodplain deposits. The member is well defined in several boreholes, with sharp upper and lower boundaries; it can be traced northwards to the Bovey 'Coal Pit' sequence (Pengelly, 1862). The thickness increases from 57 m in northern boreholes to 128 m in southern boreholes, an increase of about 100% over a distance of about 1.1 km. The member consists of interbedded lignites (variously recorded in the commercial cored boreholes as 'woody', 'woody and clayey', and 'clayey'), and brown (occasionally greyish-brown) clays; towards the south of area there are interbeds of sand. Lignite forms up to 81% but its proportion decreases to 11% farther south, at a place just east of Liverton. The lower part is dominantly 'woody' lignites, in beds up to 8 m thick. The base of the Brimley Member in this western area is mainly sharply defined by lithological contrast on the Stover Member, but it is not clear if there is a break in deposition at this level. Commonly, lignite (or less commonly brown or greyish-brown clay) rests sharply on sand at the top of the Stover Member.

At the Bovey 'Coal Pit' (Blue Waters Mine) [SX 812 770], now disused and flooded, Pengelly (1862) recorded 38.1 m of interbedded lignite and clay with one bed up to 3.38 m thick of coarse-grained quartz sand which thinned rapidly eastwards to a thickness of 0.25 m in a distance of 207 m. The plant fossils were identified by Heer (1862). Edwards (2011) has given an account of lignite mining in the Bovey Tracey area.

The ***Heathfield Member***, defined by Vincent (1974), is about 40 m thick, and comprises in its upper part brown clay with occasional lignite, becoming sandy towards the base. It overlies the Brimley Member and is generally overlapped to the west by the Great Plantation Member and the Bovey Heath Member. It has a small outcrop area at Heathfield [SX 835 760], from where it is named. Clays were formerly extracted from the Heathfield Member at the Heathfield Pit (`Candy's Pit') [SX 832 761].

Vincent (1974) named the ***Great Plantation Member*** after its thickest development in boreholes in the Great Plantation area [SX 820 757]; it is extensively and discordantly overlain by the Bovey Heath Member. It comprises up to 107 m of mainly sideritic clayey silt, grey silty clay, and sand. Siderite-cemented sand occurs at some horizons. Former small workings at Halford [SX 810 746] were probably in this member.

In the western part of the basin, cored commercial boreholes between Bovey Tracey and Liverton proved a southward-thickening variable Great Plantation Member sequence of between 20 and 60 m of grey, greyish-brown and brown clays (some with rootlets) with scarce lignites; locally sands are present in the lower half, some showing fining-upwards motifs. In some boreholes in the north of the drilled area, the entire sequence is largely medium- to coarse-grained sand. The sequence is most clearly defined in the northern boreholes but farther south there is considerable uncertainty in recognising

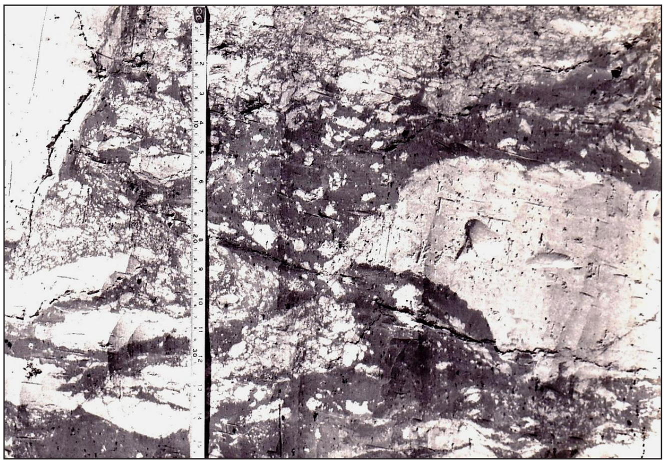

Figure 30. *Soft-sediment deformation structures indicating possible 'seismites' at Stover Park Pit [SX 845 740], 1970 (photograph by R.A. Edwards).*

the boundary between the Great Plantation Member and the Bovey Heath Member. The clays are mainly pale grey to brownish grey, silty to very silty and sandy, locally sideritic, with rootlet beds recorded at several levels. Thicker clay units up to 6 m are present, but they are mainly less than 1.5 m thick. Fragmental lignite is commonly present. The proportion of sand to clay varies considerably from borehole to borehole, and no generalized vertical section can be recognised. A thin (up to 1.4 m) lignite-brown clay unit can be traced laterally in some boreholes over a distance of about 1.3 km.

The Great Plantation Member generally rests sharply on the underlying Brimley Member, with marked lithological contrast between the grey clays and sands above and the lignites and brown clays below. There is no definite evidence of unconformity between the two sequences. However, the lignite-brown clay unit, referred to above, varies in height above the top of the Brimley Member from 21.9 m in the east to 18.2 m in the west and this may indicate some discordance between the Brimley and the post-Brimley sequences.

The ***Bovey Heath Member***, named by Vincent (1974) from Bovey Heath [SX 824 765], was considered by him to be the youngest member of the Bovey Formation in the Bovey Basin. It is present over much of the north-west of the main Bovey Basin and lies almost horizontally and unconformably over the Great Plantation and Heathfield members. The thickest section recorded is about 50 m of dominantly grey and yellow, clayey gravelly sand with a single bed of lignitic clay towards the base. The sands in the Bovey Heath Member contain feldspar amongst the euhedral quartz grains and abundant tourmaline and were clearly derived from the Dartmoor Granite.

Cored commercial boreholes in the western part of the basin between Bovey Tracey and Liverton proved the member to consist of at least 50 m of fine- to coarse-grained, locally gravelly, clayey sands, with some units of grey and brown clay. 'Granitic sand' was recorded towards the top of the sequence. The base of the member is fairly sharply defined in some boreholes, but not in others where a sand facies is present in the underlying Great Plantation Member.

The ***Woolley Member***, of uncertain stratigraphical position, is renamed herein from the Woolley Grit Member of Edwards (1970, 1976), Edwards and Freshney (1982), and Selwood *et al.* (1984). It is included in the gravel and conglomerate lithofacies and comprises up to 24 m of grey, hard, siliceous, coarse-grained sandstone and conglomeratic sandstone outcropping in two small partly fault-bounded outliers outside the main Bovey Basin north-west of Bovey Tracey (Fig. 4). The first outcrop is at Woolley (Wolleigh on newer maps) near Wolleigh House [SX 802 797], and the second, more extensive, in Higher Knowle Wood [SX 792 810], near Lustleigh. Blyth and Shearman (1962) described cross-bedding and channel structures and noted the presence of poorly preserved coniferous wood fragments indicating an age range from early Cretaceous to late Tertiary. The association of similar chalcedonic conglomerate and Bovey Formation silt and clay at Sandypark north of Chagford supports the inclusion of the Woolley Member in the Bovey Formation.

The ***Staplehill Member*** (gravel and conglomerate lithofacies), renamed herein from the Staplehill Gravels of Edwards (1970), Staplehill Gravel of Edwards (1976) and Staplehill Gravel Member of Edwards and Freshney (1982) and Selwood *et al.* (1984), comprises an uncertain thickness (possibly around 10 m) of very poorly exposed pale grey gravel and sand with clasts of quartz, pale grey Carboniferous chert, dark grey igneous rock, sandstone, and rare flint and Greensand chert, outcropping along the south-western margin of the Bovey Basin (Figure 19). Its stratigraphical position is uncertain. Reid (*in* Ussher, 1913, p. 115) noted at Staplehill 'marginal deposits, banked against a steep slope of Devonian slate' and dipping 50° north. A pit showed coarse gravel, consisting largely of quartz, grit, chert, and igneous rocks, with Greensand chert, some Chalk flints and a few pieces of Devonian limestone. The gravel dips beneath 9 m of coarse-grained 'granitic' sand which in turn dips northward beneath white clay.

Gouldstone (1975) recorded sections through the Staplehill Member (his 'Blackpool Wood Deposits') in road cuttings [SX 8140 7140] for the A38 road improvement in 1972. He noted at the base of the cutting 5 to 20 cm-thick beds of kaolinitic clay, grey clayey silt, and gravelly sand, together with very coarse gravel containing clasts of black chert in association with finer quartz-tourmaline gravel with feldspar. The sequence was locally orange-stained.

About 3 km east-southeast of the main outcrop, small exposures of possible Staplehill Member gravel resting on possible Aller Gravel have been reported from the Ringslade Pit [SX 846 726] (B.L. Jones and M.R. Harvey, *pers. comm.*, *in* Edwards and Freshney, 1982) but have not been confirmed by the authors. The supposed Staplehill Member consisted of pale grey gravel with quartz, grey Carboniferous chert and dark grey igneous rock.

Derivation of the sediments

Earlier researchers considered that the Bovey Formation was derived by the decomposition of Dartmoor granite, with the feldspar breaking down to produce kaolinitic clays and the quartz grains contributing to the sands (*e.g.*, Reid, *in* Ussher, 1913; Groves, 1931). However, it is now considered that the Bovey sediments were derived both from a granite source and from weathering mantles developed on a variety of other rocks. Bristow (1968) suggested that much of the Bovey Formation in the Petrockstowe Basin was derived from weathering mantles developed on Carboniferous rocks during the early Paleogene. Vincent (1974) also showed that while the coarse material in the Abbrook Member of the Bovey Basin is of granitic origin, the disordered nature and fine grain size of the kaolinite argue against derivation from a granite source, possibly because the granite was only partially unroofed. In the Southacre Member, however, the kaolinite of the clays is well ordered and probably derived from hydrothermal kaolinite developed on granite. Mixtures of kaolinite of both types occur in the southern part of the Southacre Member outcrop.

Lignitic clays in the Stover Member are typically composed of medium-ordered kaolinites showing little similarity to the two preceding members. The kaolinites may be mixtures of well-ordered kaolinite derived from the erosion of hydrothermally altered granite and poorly-ordered particles derived from weathering mantles on country rock or may have been derived from the weathering of feldspar in the granite. Vincent (1974) noted that:

> 'the seam in the middle of the Stover Member is the last known occurrence of a comparatively well-ordered kaolinite in the sedimentology of the Bovey Basin, and it must be assumed that, at this time, the last china clay deposits were being removed from the south-eastern part of Dartmoor'.

The upper Bovey Formation members contain abundant sand derived from the Dartmoor Granite, and the kaolinite appears to have been derived from the weathering of granitic feldspar. Siderite is present abundantly in the Great Plantation Member, and Vincent (1974) suggested that the carbonate was sourced from Devonian limestone outcropping south-west of the Bovey Basin, from which carbonate-rich waters were derived before entering an environment with near-neutral pH values.

Ball clays

The Bovey Basin is noted for its commercially important resources of ball clay, widely used in the ceramic industry. The chief workings are in the middle Bovey Formation along the eastern side of the main basin (Fig. 31). Ball clays are fine-grained, highly plastic, mainly kaolinitic, sedimentary clays that fire to a white or near white colour in an oxidising atmosphere. The term 'ball clay' originates from an early method of hand working in which the clays were cut into blocks about 25 cm cube which acquired rounded edges during handling and transport, giving them a ball-like form (Hart and Nicholas, 2024). In 2024, there were nine working ball clay pits in the Bovey Basin, operated by two companies (Imerys and Sibelco): Newbridge/Twinyeo, Ringslade, and Stover (Imerys); and Chudleigh Knighton, Clay Lane, White Pit, Southacre, Denistone and Broadway (Sibelco) (Fig. 4). An account of the ball clay mines is given in Edwards (2011).

Ball clays are sedimentary clays that have been transported into their place of deposition and consist predominantly of kaolinite, quartz and mica; minor amounts of material such as carbon, iron and titanium can also affect the ceramic behaviour of the clays. The nature of the kaolinite, whether ordered or disordered, is very significant for the unfired strength and plasticity of the clays. In contrast, china clay, derived from the *in-situ* decomposition of granite, contains mainly crystallographically well ordered, comparatively coarse-grained kaolinite. The granite batholith of Devon and Cornwall is a well-known host to extensive deposits of china clay. The transported kaolinite particles in ball clays in the Bovey Basin were derived not only from china clay deposits or the breakdown of Dartmoor Granite, but also from weathering mantles developed on Paleozoic rocks (Bristow, 1968), giving rise to more crystallographically disordered finer-grained kaolinite. These mixtures of mineralogy and particle size in the Bovey Basin ball clays produce a wide range of strength, plasticity and firing characteristics. China clay-derived particles provide white-firing characteristics, while clays derived from weathering mantles on Paleozoic rocks give unfired strength and plasticity.

Four groups of ball clay have been distinguished in the Bovey Basin, based on the irreversible thermal expansion curves of the clays (Ashcroft–Hawley and Mitchell, 1960); this classification was used by the ball clay company Watts Blake Bearne and its successors, but is also of more general applicability. The four-fold division is also reflected in the mineralogy of the clays (Fig. 32). They consist predominantly of three minerals: kaolinite; a micaceous mineral; and quartz, and the irreversible thermal expansion curves are largely determined by the relative proportions of the three minerals. Minor amounts of material such as carbon, iron, and titanium can also affect the behaviour of the clays. The nature of the kaolinite, whether ordered or disordered, is very significant for the unfired strength and plasticity of the clays. Kaolinite in the Petrockstowe Basin ball clays is mainly fine-grained and disordered, and consequently the clays are highly plastic. Ball clays in the Bovey Basin contain both types of kaolinite in different parts of the sequence and are therefore more diverse in their properties. The variation in kaolinite types in the Bovey Basin clays reflects their derivation from both a granite source and from weathering mantles developed on Carboniferous and other rocks during a period of intense tropical weathering. Clays with the highest content of ordered kaolinite were largely derived from weathered granite, while those with disordered kaolinite tend to be derived from weathered country rocks.

Group 1. *Extra-white-firing ball clays*. These clays are characterised by exceptional whiteness when fired at over 1200° C. They have the highest kaolinite content (at around 70%) of the four groups, are low in silica, Fe_2O_3 and TiO_2 and are locally carbonaceous. 'Group 1 Dark Ball Clays' (informally termed 'Group 1 Darks') occur especially in the lower, more lignitic part of the Southacre Member. The upper part of the Southacre Member contains clays which are paler in colour (grey to fawn) and are classified as Group 1 Light Ball Clays (informally termed 'Group 1 Lights'). The Stover Member is also a significant resource of Group 1 Lights. The Chudleigh Knighton Member contains clays with a high content of ordered kaolinite which show some similarities to Group 1 clays of the Southacre Member. Owing to changed production methods, the higher carbon Group1 Darks are currently in less demand than the Group 1 Lights.

Group 1 clays from the Southacre and Stover members contain higher proportions of coarser grained and well-ordered kaolinite probably derived from weathering profiles developed on the Dartmoor Granite, or on china clay bodies within the granite. At the base of the Stover Member the proportion of coarse-grained well-ordered kaolinite in one bed is so high that it resembles china clay; this high-alumina (>35%) and low alkali (<1%) bed is termed the 'Parkes Seam'. A similar 'Parkes'-type marker bed is present at a stratigraphically higher level, at the base of the Brimley Member.

Group 2. *Dark blue ball clays*. These clays, occurring in the lower part of the Southacre Member, are also mainly kaolinitic, with more micaceous material and quartz than Group 1 clays. They are very fine-grained, somewhat carbonaceous clays with high unfired strengths, white-firing between 1000° and 1100° C, but tending to fire off-white at higher temperatures.

Group 3. *Light blue ball clays*. These clays, present in the upper part of the Abbrook Member, are somewhat siliceous clays, with silica averaging 55%, and low in carbon (less than 0.5%). They fire white between 1000° and 1100° C, but at higher temperatures fired colours are off-white to ivory. They are very plastic with intermediate strengths.

Group 4. *Siliceous ball clays*. This group corresponds to the 'Stoneware' clays of older classifications (Scott, 1929). They are non-carbonaceous, with high percentages of free quartz. They fire off-white below 1100° C and buff above that temperature. Group 4 clays are stratigraphically the lowest ball clays worked in the Bovey Basin, occurring in the central part of the Abbrook Member. Group 3 and 4 clays contain fine-grained disordered kaolinite, probably derived mainly from weathering profiles on country rocks (mainly mudstones).

The clays in the higher members of the Bovey Formation contain kaolinite which is not as fine grained or as disordered as that of the Abbrook Member and, hence, do not have their plasticity. They lack the white-firing characteristics of

Figure 31. *Aerial view of the eastern side of the Bovey Basin, looking southwards, showing the locations of pits working ball clays (photograph courtesy of the Ball Clay Heritage Society and reproduced by permission of Prof. P. Doyle, Editor-in-Chief,* Geology Today*). CK: Chudleigh Knighton Pit. CL: Clay Lane Pit. S: Southacre Pit. N/T: Newbridge/Twinyeo Pit. S: Southacre Pit. W: White Pit. K: Kingsteignton. NA: Newton Abbot. TE: Teign Estuary.*

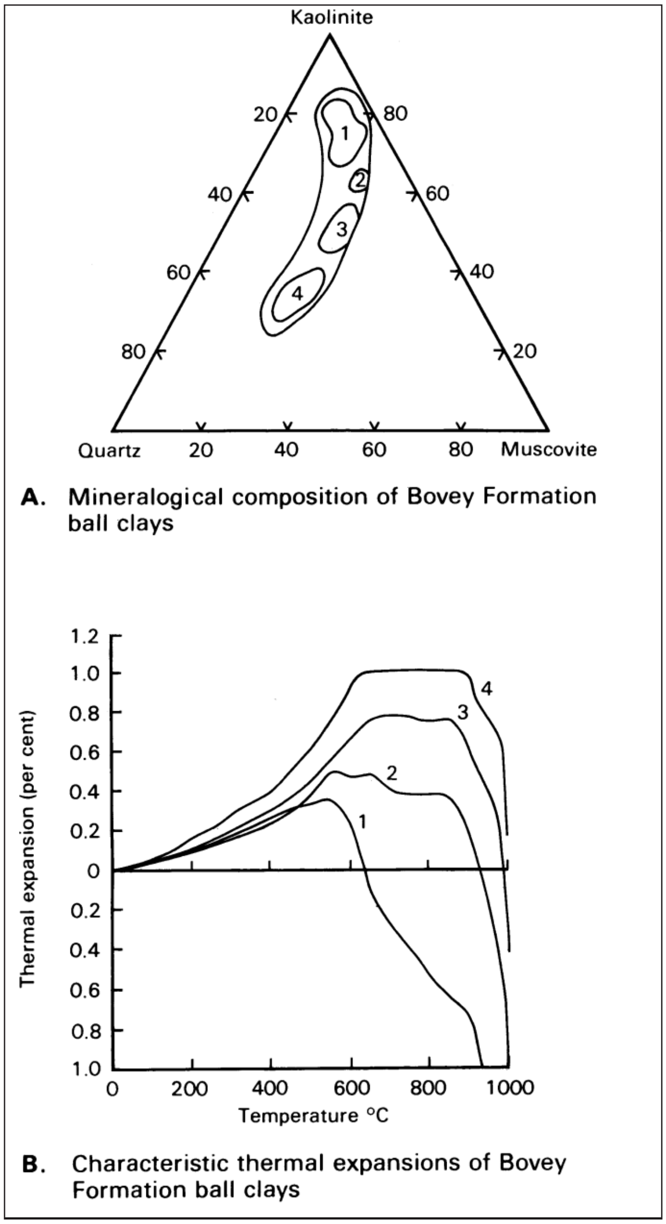

Figure 32. A. *Mineralogical composition of Bovey Formation ball clays. **B**. Characteristic thermal expansions of Bovey Formation ball clays. From Selwood* et al. *(1984, fig. 27). Reproduced with the permission of the British Geological Survey © UKRI 2024. All Rights Reserved.*

the well-ordered kaolinites of the Southacre Member clays. The absence of any extremes of crystallinity in the kaolinite suggests that there was one uniform source of kaolinite, that is, weathered granitic feldspar, which was finer-grained than the hydrothermal kaolinite but coarser than the kaolinite derived from country rock (Vincent, 1974).

Palaeobotany and age

The Bovey Formation of the Bovey Basin contains no known animal body fossils, probably owing to solution by highly acidic waters (although possible burrows have been recorded), and no igneous rocks suitable for isotopic dating. Studies of plant macrofossils and microfossils (pollen and spores) have, however, yielded Eocene and Oligocene dates.

On the evidence of plant macrofossils, the Brimley Member sequence at the Bovey 'Coal Pit' [SX 812 770] was originally regarded as Miocene (Heer, 1862), but plant macrofossils studied by Chandler (1957, 1964) from the Bovey 'Coal Pit' (Brimley Member), Heathfield/Candy's Pit [SX 832 761] (Bovey Heath Member), and 'a pit at Kingsteignton' (exact stratigraphical horizon uncertain, possibly Southacre Member), were thought to all be of Oligocene, possibly Middle Oligocene age.

Studies of pollen and spores from Paleogene deposits in the western British Isles (Bovey Basin, Petrockstowe Basin, Lough Neagh, Mochras, Stanley Bank Basin and Canna Basin (Sea of Hebrides)) by Wilkinson and Boulter (1980) have resulted in assessments of Oligocene ages. Most assemblages have in the past been interpreted as Chattian, but according to King (2016), most of these records can be re-interpreted as indicating Rupelian dates. King noted that the presence of *Boehlensipollis* indicates a Rupelian (early Oligocene) age; its last occurrence apparently corresponds to the Rupelian-Chattian boundary (early–late Oligocene; 27.82 Ma).

Wilkinson and Boulter (1980) studied pollen from the Higher Brocks Plantation Borehole [SX 839 758] near Heathfield, in the centre of the Bovey Basin, which penetrated 185 m of upper Bovey Formation (Heathfield, Brimley and Stover members) on 69 m of Southacre Member, on 51 m of Abbrook Member. The sequence was considered to be largely Oligocene (Chattian) in age. However, the presence of *Boehlensipollis* throughout the drilled section, down to and including the Abbrook Member indicates that the entire sequence is likely to be Rupelian in age (King, 2016). Members younger than the Heathfield Member (that is, the Great Plantation Member and Bovey Heath Member) have not been sampled for palynomorphs and are of unknown age. The Eocene indicators *Anacolosidites* (represented by only three specimens) and *Pompeckjoidaepollenites* (represented by only two specimens), recorded from below 290 m depth, are probably reworked, suggesting that the Eocene-Oligocene boundary (33.90 Ma) is located not far below. King (2016) notes that the last occurrence of *Anacolosodites* in Germany was at the top of Zone SP4 (Middle Eocene) and the last occurrence of the *Pompeckjoidaepollenites hercynicus* group was also at this level. The lower Bovey Formation has not been cored and no age determinations are possible, but on general grounds and comparison with the Petrockstowe Basin the sequence is likely to be Eocene although the presence of Paleocene strata cannot be excluded.

Ting and Hailwood (1991) studied the magnetostratigraphy of a composite section through the Abbrook and Southacre members and found it to be of dominantly reversed polarity, with four normal polarity intervals. They suggested a correspondence to Chrons C12n – C10n (early Oligocene: mid-late Rupelian).

Macroflora. The fossil conifer material making up the bulk of the lignites in the Brimley Member of the Bovey 'Coal Pit' [SX 812 770], near Bovey Tracey, was referred by Heer (1862) to *Sequoia couttsiae*, but importantly, Kunzmann (1999) has revised *Sequoia couttsiae* to *Quasisequoia couttsiae*, a common coal-forming conifer growing in swamp forests (*e.g.*, Teodoridis, 2003). Jukes-Browne (1909) had earlier questioned the identification of *Sequoia couttsiae* and suggested instead that *Arthrotaxis* (a species related to the swamp cypress *Taxodium*) was present.

Apart from *Quasisequoia couttsiae*, an important element of the macroflora from the Brimley Member of the Bovey 'Coal Pit' [SX 812 770] is the herbaceous fern *Osmunda lignitum*, found in beds 7, 17 and especially 25 (bed numbers of Pengelly, 1862) where the rhizomes were up to 1.5 m long. The fern commonly grew in swamp forests. *'Sequoia couttsiae'* and *Osmunda* were together reported by Chandler (1964) to form the bulk of the lignite beds. Other macroflora include: *Calamus* (sweet flag, growing in wet places); several species of *Nyssa* (deciduous trees, most highly tolerant of wet soils and flooding); mostly evergreen plants such as *Magnolia*, *Meliosma* (a deciduous tree), *Symplocos* (flowering plants in the order Ericales), *Cinnamomum* (Cinnamon tree), *Ficus* (Fig) and *Laurus* (Laurel) indicate year-round warmth and humidity, and together with them grew several species of *Vitus* (Vines) and *Parthenocissus* (Virginia Creeper), and *Rutaspermum*;

deciduous hardwoods are less common but include *Corylus* (Hazel), *Quercus* (Oak), *Fagus* (Beech) and *Carpinus* (Hornbeam). Water and marsh plants include *Potamogeton tenuicarpus* (an aquatic freshwater plant), *Stratiotes websteri* (submerged aquatic plants, commonly known as 'water soldiers') and *Brasenia ovalis* (an aquatic plant, 'water shield'). Other marsh plants include *Lysimachia* (a flowering plant growing in damp conditions), probably *Microdiptera parva*, *Spirematospermum wetzleri*, *Caricoidea nitens* and *Salvinia* sp.. *Rubus microspermus* (bramble) grew at the waters' edge.

Palynology. The sequence in the Higher Brocks Plantation Borehole [SX 839 758] (Wilkinson and Boulter, 1980) is dominated by the fern spore *Polypodiaceaesporites* which suggests damp conditions, the tricolporate pollen *Tricolporopollenites* which is associated with trees, shrubs and herbs of broad affinity, and the conifer pollen *Pityosporites* which represents an 'upland' flora. Other representatives of the flora are *Nyassapollenites* and *Salixipollenites* which are similar to the pollen of modern plants growing in wet and humid conditions. *Polyvestibulopollenites* (pollen similar to modern *Alnus* (Alder)) does not occur until Stover times. A warm and swampy environment is indicated by the conifer pollen *Inaperturopollenites* which is similar to the modern swamp cypress (*Taxodium*), deposited near the place of growth, and is especially evident from early Stover Member times. The simple monocolpate morphology of *Arecipites* and *Monocolpopollenites* is characteristic of palm pollen, suggesting that the climate was relatively frost-free. Overall, the flora was dominated by shrubs/herbs and trees, and ferns, associated with other wet-loving plants and a stable 'upland' coniferous vegetation. There was no significant botanical variation through the sequence studied. Minor changes are evident at the beginning of the Stover Member with the introduction of a richer flora.

Depositional environments

The absence of marine fossils, abundance of plant macrofossils, pollen and spores, presence of lignite and the kaolinitic clay mineralogy together indicate a continental origin for the Bovey Formation of the Bovey Basin. Similar lithologies occur in other non-marine Paleogene basins along the Sticklepath Fault Zone - at Petrockstowe and in the offshore Stanley Bank Basin - and farther north in the Cardigan Bay (Mochras) Basin and in Northern Ireland at Lough Neagh. All these sequences have been interpreted as being of fluvial origin. The Bovey Basin was in the past commonly cited as an example of a 'lake basin', a view which persists even in some modern textbooks. Modern studies have, however, shown that the deposits of the basin are largely fluvial, consisting of lignites and clays which formed in forest swamps and shallow lakes; floodplain clays and sands deposited by meandering streams; and sands and gravels formed on alluvial fans.

The evidence of shallow water deposition at several intervals within the Bovey Formation suggests that subsidence of the basin and sedimentation must have kept pace with each other for much of the time. The current broadly synclinal form of the deposits indicates post-depositional sagging following sediment loading. Rapidly shifting focii of deposition produced discordance between the members, especially within the upper Bovey Formation.

Forest swamps

It has been a long-held view (*e.g.*, Pengelly, 1862; Chandler, 1957, 1964) that the material forming the lignites of the Bovey Basin was transported into the basin from forests, mainly of the conifer *Sequoia couttsiae*, growing on the uplands surrounding the basin. In contrast, we now consider that the vegetation grew largely in place in forest swamps. This re-evaluation is supported by the reassessment by Kunzmann (1999) of *Sequoia couttsiae* to *Quasisequoia couttsiae*, a common coal-forming conifer growing in swamp forests (*e.g.*, Teodoridis, 2003). Such forests typically contain plants that prefer environments with stagnant water or periodical, relatively long-lasting floods. Interestingly, as long ago as 1909, Jukes-Browne argued against the transport of the lignitic material from outside the basin and considered that the lignites had formed in a forest swamp. Significantly, he believed that the so-called *Sequoia* of Heer (1862) did not belong to that genus, but was probably an *Arthrotaxis*, a relative of *Taxodium* which is a notable tree of forest swamps.

The lignite-clay lithofacies, present mainly in the Southacre, Brimley and Stover members, is interpreted as having formed as peat-forming mires in backswamps on an alluvial floodplain. The swamps were dominated by the conifer *Quasisequoia couttsiae* and other plants which decayed into peats. The swamp forests were periodically flooded to form extensive shallow, probably short-lived, lakes, in which clays were deposited from suspension. This process was repeated many times, and the resulting sequences are preserved as stacked piles consisting of rhythmical alternations of lignite and carbonaceous clay. The potential causes of the cyclicity in the lignite-clay lithofacies are many, but currently uncertain. The carbonaceous clays interbedded with the lignites represent periods of quiet low-energy sedimentation by fall-out from suspension. The general lack of lamination may indicate extensive bioturbation or, more likely, rapid settlement in a flocculated condition from high concentration 'slurries', strongly affected by fine-grained carbon, fine-grained quartz, and the acidity of the environment (Vincent, 1974).

Chaanda (2016) interpreted the Southacre Member at South John Acres Lane Pit [SX 862 748] as the product of an 'ephemeral lake or lake margin'. As noted above, we agree that ephemeral lakes probably resulted owing to flooding of mires, but the evidence for marginal lake environments is less clear.

Lateral transitions from swamp deposition to meandering river environments occurred in several places within the Bovey Basin, for example in the western basin, lignitic Brimley Member (44% lignite) passes rapidly southwards within a distance of 0.5 km into a mainly non-lignitic facies (11% lignite) at a place near Liverton. Similar transitions can be seen in the south of the basin between the Southacre Member and the Ringslade Member, and in the north of the basin between the Southacre Member and the Chudleigh Knighton Member.

At the Bovey 'Coal Pit' (Blue Waters Mine) [SX 812 770], now disused and the site of an ornamental lake, Pengelly (1862) recorded 38.1 m of interbedded lignite and clay with one 3.38 m-thick bed of coarse-grained, fining-downwards, quartz sand; this thins rapidly eastwards to a thickness of 0.25 m in a distance of 207 m and may represent a debris flow. The plant fossils were identified by Heer (1862).

Wilkinson and Boulter (1980) considered that the main vegetation type in the Bovey Basin was comparable to the *Nyassa-Taxodium* swamp forest described by Teichmüller and Teichmüller (1968). It is noteworthy that Wilkinson and Boulter (1980) recorded no pollen grains with morphology similar to that of modern *Sequoia*; they considered that the upland flora appeared to be related to modern *Pinus* or *Cathaya*, and the taxodiaceous conifer pollen was most like that of a *Taxodium*-like swamp forest growing *in-situ*. The palaeoenvironmental significance of the trace fossils occurring in the lignite-clay lithofacies of the Bovey Formation has yet to be fully assessed, but currently it is considered that the main horizon is dominated by root casts, with possible burrows at other levels.

Meandering streams

The clay-sand lithofacies of the middle Bovey Formation (Lappathorn Abbrook, Ringslade and Chudleigh Knighton members) and upper Bovey Formation (Great Plantation Member) shows features mostly consistent with deposition by meandering streams. The meandering stream facies is characterised by channels with sharply-defined erosional bases, filled with sand that may fine upwards, recorded, for example, in the Chudleigh Knighton Member and in the Abbrook Member. Some of the sands may represent lateral accretion deposits such as point bars, while the clays were deposited by vertical accretion on a river floodplain. Intraformational breccias of clay clasts in a clay matrix (recorded for example from the Chudleigh Knighton Member) were probably formed by erosional channel-bank undercutting of clays, possibly on a floodplain (Fig. 22). Brecciated clays formed by possible desiccation of temporary lakes on floodplains were recorded by Best and Fookes (1971). Examples of brecciated lignitic clays were recorded from the Abbrook Member (Edwards, 1976, plate 1B).

Chaanda (2016) interpreted the Abbrook Member at South John Acres Lane Pit [SX 862 748] as the deposits of a 'long-lived lake or lake centre' but the presence of several units of fining-upward sands with bases channelled into underlying clays suggest to us that a meandering river depositional model is more likely for this sequence. Little is known of the Lappathorn Member mottled clays and sands owing to lack of exposure, and consequently their depositional environment is uncertain; a fluvial, probably meandering stream, origin seems most likely. The mottles may be related to soil-forming processes in oxidising conditions during low groundwater levels.

Rootlet horizons indicating sub-aerial exposure with some *in-situ* plant growth have been recorded in boreholes and some pit sections through the clay-sand lithofacies. They have been noted in the Ringslade Member, Stover Member, Great Plantation Member and Bovey Heath Member, but none have been definitely seen in the Abbrook Member. The Parkes Seam at the base of the Stover Member contains vertical rootlets; elsewhere it contains breccias comprising clasts of grey laminated clay in a grey clay matrix, probably indicating a widespread episode of subaerial exposure.

Alluvial fans

The few available sections of sands in the upper Bovey Formation (mainly in the Stover Member) are interpreted as having formed mainly on alluvial fans prograding into floodplain clays. The gravelly sands, sandy gravels, and sands of the Stover Member show well-developed gravel-filled channels, erosional surfaces and cross-bedding (Fig. 23) and are interpreted as the deposits of high-energy braided streams. The finer-grained, massive, very poorly sorted, thickly-bedded sands and sandy pebble gravels (Fig. 24) show bedding indistinctly picked out by impersistent clay laminae. Certain of these massive relatively structureless sands may have been deposited by some type of sediment gravity flow.

Sands in the Stover Member of the western Bovey Basin are probably the result of deposition on alluvial fans. Intercalated units of grey to brownish-grey clay with rootlet horizons suggest subaerial exposure of floodplain surfaces, indicating interdigitation of the fan deposits with more basinal alluvial floodplain deposits. Also in the north-west of the basin**,** poorly sorted, medium- to coarse-grained, locally gravelly, clayey sands of the Bovey Heath Member were deposited rapidly, possibly on alluvial fans; they extend basin-wards and interdigitate with probable floodplain sequences. The presence of coarse-grained 'granitic sand' indicates direct derivation from weathered Dartmoor Granite.

Cross-bedding and channel structures in the Woolley Member indicate a fluvial, possibly braided stream origin. The coarse-grained sediments of the Staplehill Member were probably also deposited by high-energy, possibly braided, rivers at the southern margin of the basin.

Petrockstowe Basin

The Petrockstowe Basin in north Devon (Fig. 33), lies in a topographical depression trending northwest-southeast, a few kilometres south of Great Torrington, flanked and cut internally by elements of the Sticklepath Fault Zone. A total of about 760 m of Bovey Formation strata has been proved in the basin; one borehole penetrated the base of the Bovey Formation into the underlying Bude Formation (Upper Carboniferous), at 661 m depth. The Bovey Formation sediments range from almost sand-free, kaolinite-rich clays to cobble gravels. Natural exposures of the beds are extremely rare, most of the available data coming from open pits, mines and boreholes.

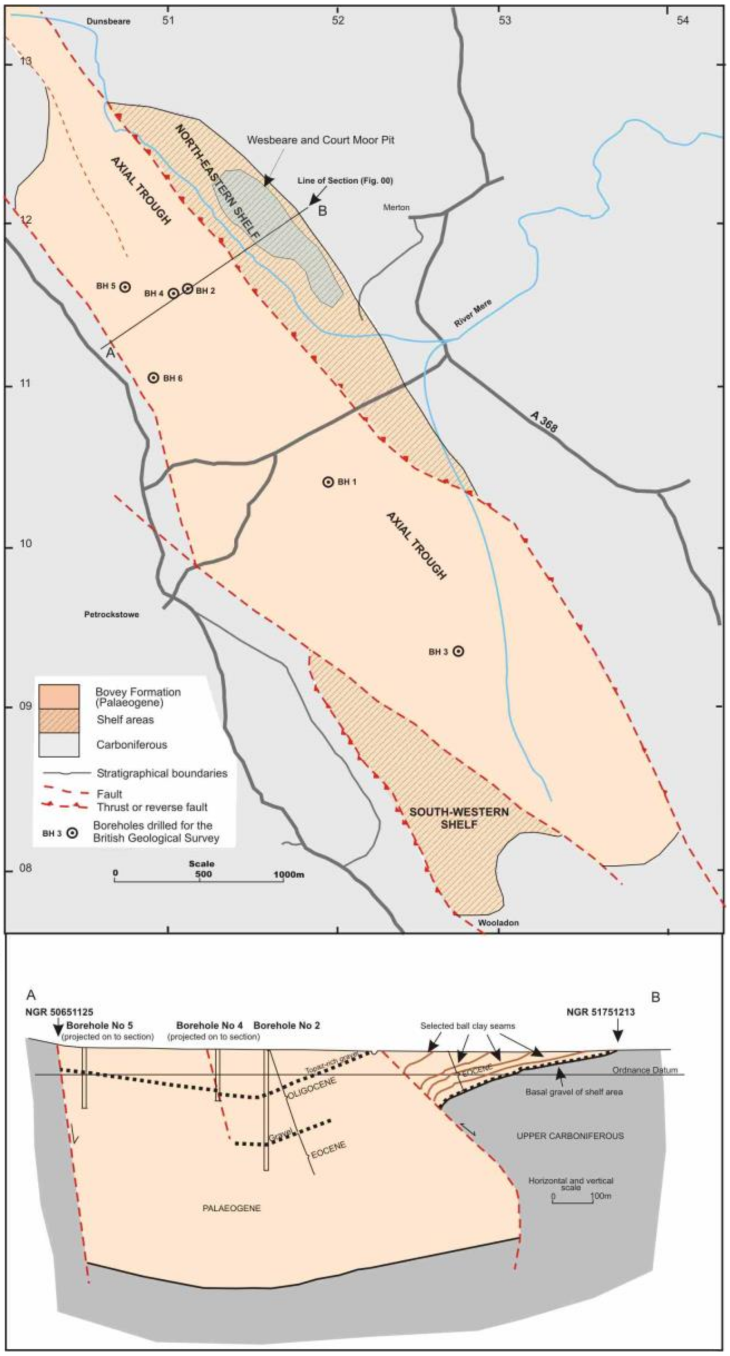

Figure 33. *Geological map (a) and cross-section (b) of the Petrockstowe Basin.*

Lithology

Clay. This, the commonest lithology in the Petrockstowe Basin, is commonly very sandy and forms part of a continuous sequence which passes into clayey fine-grained sands. Sharp contacts between different lithologies are uncommon, except for certain horizons which are the erosive bases of depositional cycles. Within such cycles, clay, which is dominantly kaolinite, may form between 8 per cent and 55 per cent of the material, while quartz in the form of fine-grained sand and silt varies between 8 per cent and 70 per cent, and clay micas between 10 per cent and 38 per cent. The kaolinite is crystallographically disordered and is very fine grained. Smectites are occasionally present in small quantities, particularly in the more carbonaceous clays.

Most of the clays show little internal structure, although in places a crude irregular banding is seen, especially in the carbonaceous brown clays where there can be signs of burrowing. The seat-earth types of clay commonly show brecciation, besides containing rootlets. However, polygonal desiccation cracks filled with either sand or sandy clay are common, and in places the polygons may be over 1 m across with the cracks over 1 m deep.

In the north-eastern part of the axial trough finely laminated reddish brown 'varved' clays are present. The laminae, which are in the order of 1–10 mm thick, show a distinct grading from very sandy clay just above a sharp, slightly erosive base to a less sandy top. These clays are also characterised by the presence of well-preserved whole-leaf fossils.

Sand and silt. Sands and silts in the basin usually contain high proportions of clay. Grain-size distributions show most of the sands are divisible into two main populations; the coarser sands, with a grain size greater than 0.085 mm, are relatively well sorted and were probably transported by saltation, while the finer sands, with grain sizes less than 0.085 mm, are poorly sorted and were probably transported in suspension. The sand- and silt-grade particles are almost wholly quartz and are subrounded to sub-angular with some almost spherical transparent grains. Like the clays, most of the sands show little internal structure, but in one of the few exposures of sand in the axial area of the basin, and in some borehole cores, there is some lamination and cross-lamination. Lamination is also present in sands which contain brown organic matter; these sands show irregular pale fawn and deep reddish-brown-coloured laminae ranging in thickness from 1 to 20 mm. Small scour channels are commonly present as well as abundant micro-faults.

Other well-laminated sands and silts are those associated with the finely-laminated clay mentioned above. They show the same features as the clays and there is usually a gradation from one to the other. As might be expected, the erosional features at the base of each sand lamina are more strongly developed than at the base of the sandy clay laminae. Clay pellets are common within the sands, especially near the erosional base of a sand unit. In some cases larger disrupted clay masses are present in the sands, but this is commonly associated with large-scale disruption and brecciation of unconsolidated strata, perhaps involved in contemporaneous tectonic movement.

Gravel. Pure gravel is very rare, most of the sediment being very sandy gravel or gravelly sand. The gravels consist almost entirely of sub-rounded pebbles of vein quartz, with some flints and rotten green Carboniferous sandstone up to 10 cm in size. Flint and sandstone pebbles are particularly common in the basal gravels of the Bovey Formation. In the one exposure of gravel in a stream diversion channel [SS 514117], rough bedding, wedge bedding and channelling were recorded.

Lignite. There is little lignite in the Bovey Formation of the Petrockstowe Basin in comparison with the Bovey Basin. It occurs both as fragmented lignite or as very lignitic clay in which the organic matter is present in a finely divided form making up to 80 per cent of the sediment. Beneath each lignitic horizon there is normally a rootlet bed which indicates the former presence of an *in-situ* cover of vegetation.

Structural framework

The deposition and preservation of the Bovey Formation strata in the Petrockstowe Basin are due mainly to their involvement in the Sticklepath Fault Zone, which is up to 800 m wide and made up of several individual faults which vary in importance along their length. Post-Permian dextral movement of about 3 km, as indicated by the displacement of the New Red Sandstone in the Crediton Trough, is considered to be responsible for the development of a downwarp between elements of the Sticklepath Fault Zone to provide a sink for the deposition of the Bovey Formation sediments. Holloway and Chadwick (1986) disputed this interpretation and considered that the Paleogene movement was sinistral.

A north-west–south-east section along the basin shows a broad asymmetrical synclinal structure with the deeper part (about 780 m) towards the north-western end. This asymmetry is also indicated by the position of the residual gravity anomaly, the stratigraphy, and the sedimentology of the deposits.

A section across the north-western basin (Fig. 33b) shows a deep fault trough flanked by a shelf on its north-eastern side. In the shelf area, monoclinal folds were commonly seen in old ball clay mines, especially those driven south-westwards towards the large internal north-west – south-west fault that bounded the shelf. The clay seams roll over from a dip of around 10° to dips of over 45°. Each of the monoclines probably formed in response to the presence of a small subsidiary basement fault occurring approximately parallel to the shelf margin fault. The miners found that in tunnels approaching this fault the seams steepened to 60° or more, and mining became impractical. This fault was originally considered to be a normal fault, although gravity data (Freshney *et al*., 1979) indicated that it was a reverse fault and this has now been confirmed by drilling which shows Paleogene sediments below Carboniferous rocks (G. Witte, *pers. comm.*).

In the south-western Woolladon area, excavation and drilling (Bristow *et al*., 1992) have shown that the western marginal fault is reverse, with Carboniferous rocks thrust over Paleogene sediments. These reverse faults were probably active during sedimentation, when masses of weathered Carboniferous rock were shed from an active fault scarp into the Paleogene clays. Bristow and Robson (1994) suggested that the faulting responsible for the sedimentation and deformation of the Petrockstowe Basin occurred in two phases. The first consisted of oblique extension producing a pullapart basin at rightoffset en echelon dextral strike slip faults, and the second was a later transpression phase in which marginal thrusting took place.

The presence of a broad fold in the axial trough of the basin can be deduced from the correlation of strata in boreholes. The fold trends north-west–south-east and its axis passes west of Petrockstowe Station [SS 517105]; its eastern limb dips 15–20° south-west in the north and 10° west in the area around IGS Borehole No.1, while the western limb dips 8–10° east. In the south-east of the basin, drilling and quarry operations have shown the presence of many faults and a monocline. Here, there is also evidence that the eastern marginal fault is reverse (Bristow and Robson, 1994).

Stratigraphy

A section constructed from Borehole No.1 (Fig. 33), near the deepest part of the basin shows the following generalised stratigraphy: a mainly argillaceous section, with abundant brown clay and lignite, occurs down to a depth of about 135 m, below which the beds are greyer and sandier down to 316 m. A band of gravel and sand occurs immediately below this and, in turn, overlies a sequence of sandy clay and clayey sand (which is deeply red-stained between 564 m and 601 m). The lowest part of the succession consists of lignitic laminated sand underlain by sands and gravels which are coarser at the base, at a depth of 660.5 m. A correlation based on topaz-rich sand bands and pollen analysis (C. Turner, *pers. comm.*) shows that the youngest strata (Oligocene) occur in the northern half of the basin, a few hundred metres to the north-west of Borehole No 1.

North-eastern marginal shelf area. In the north-eastern marginal shelf area, the succession is between 70 and 122 m thick and consists of nine fining-upward cycles of sandy clays with abundant seams of brown lignitic, almost sand-free, clays. Coarse-grained sands and gravels are present only in the basal few metres. The succession probably correlates with beds between 110 m and 385 m depth in Borehole No. 1 (C. Turner, *pers. comm.*).

South-western shelf area (Woolladon). The small shelf area in the south-western (Woolladon) part of the basin is comparable in many respects to the north-eastern marginal shelf, with a succession, only 65 m thick, that is similarly made up of several fining-upward cycles containing relatively sand-free brown lignitic clays. Its correlation with other areas is doubtful. However, strong overlap of strata occurs from the centre of the basin towards the southern margin, which makes it unlikely that the base of the deposit near Woolladon is the same age as the base in Borehole No 1. The base of the Bovey Formation succession was formerly exposed in the south-western part of Woolladon Pit [SS 529078]. There, stained sandy clay rested on laterally impersistent fine quartz gravel; resting in turn on Carboniferous mudstone and sandstone which were intensively weathered during the early Paleogene, so that the sandstone now appears as soft green sand and the mudstone as soft bluish-grey, rather kaolinitic, clay (Bristow, 1968). Excavation of the pit at various times uncovered channel structures, one of which, filled by a mixed sequence of sand and clay, was so large that only one side was exposed. In another, the exposed channel was 2 m wide and 1.5 m deep and filled only with fine-grained sand.

South-eastern marginal area (Meeth). The stratigraphy in this area is less well defined than that in the north-eastern marginal shelf area. There are fewer obvious marker bands, and the presence of folding, faulting and sand-filled channels which trend northwest-southeast makes for difficult interpretation. This succession, shown in the table below (B.L. Jones, *pers. comm.*), is comparable with that in the north-eastern area, especially in the presence in the productive sequence of a similar number of cycles, but this south-eastern succession differs in being much sandier and containing almost no lignite or lignitic clays.

Lithology	Approximate thickness (m)
Mainly clayey sand and sandy clay with thin beds of silty clay; red and yellow staining common; rare carbonaceous bands	30
Productive ball clay sequence: up to 12 fining-upward cycles; sand generally clayey and fine grained, locally with lignitic fragments; rare bands of quartz gravel; ferruginous staining in some cycles; clay usually pale grey, rarely carbonaceous	120
Sand and very silty clay, usually with red and yellow ferruginous staining; spherulitic siderite common; poorly defined contact with underlying very weathered Bude Formation sandstone and shale	30

Table 3. *Succession of the Bovey Formation in the south-eastern area of the Petrockstowe Basin.*

Palaeobotany and age

Pollen analysis of the Petrockstowe sequence (Turner, *in* Freshney *et al.*, 1979) suggests an age range from Eocene to Oligocene. The total thickness of the strata obtained from BGS Boreholes No 1 and No 2 is about 760 m, the age of the topmost 260 m being Oligocene and the strata below 260 m being Eocene (C. Turner, *pers. comm.*). The dating of the basal deposits is very doubtful owing to their unsatisfactory yield of pollen and spores, but it is possible that they are as old as early Eocene.

Work by Chaanda *et al.* (2023) using carbon isotope data has provided important new evidence for the dating of the Bovey Formation of the Petrockstowe Basin. In borehole 1B, a carbon isotope excursion with a magnitude of −2.5 ‰ was identified at 586 m depth with $\delta^{13}C_{TOC}$ values reaching a minimum of −28.6 ‰ with the entire excursion occurring over a thickness of about 19 m (at a depth of 586–605 m). The magnitude of this excursion is within the lower limit of that associated with the PETM, which ranges from -2.4 to 6.3 ‰, and could be related to that event, dated at about 56 Ma. However, the event could alternatively be identified with one of the other transient carbon isotope shifts that occurred after the PETM, for example the ETM2, dated at about 54 Ma. If the event is the PETM it suggests that the Paleocene–Eocene boundary is present in the Petrockstowe basin, with about 56 m of Paleocene strata present between the PETM at a depth of 586–605 m and the base of the sequence resting on Carboniferous rocks at 661 m depth.

Derivation of the sediments

The fining of grain size north-westwards along the axis of the basin suggests that the river depositing the sediments flowed from the south-east. The heavy minerals present in the sands are for the most part probably reworked from rocks ranging between Carboniferous and Cretaceous in age. They consist of well-rounded zircon, some zoned tourmaline, heavily abraded staurolite, apatite, brookite, etc. Some of the well-rounded zoned zircons may have originated directly from exposed areas of the Cornubian Batholith, but it is more likely that they are reworked from the New Red Sandstone. There are, however, a number of distinct horizons where relatively unabraded topaz crystals occur with large unabraded fragments of reddish-brown to green zoned tourmaline. In places this material occurs in such abundance that it is almost certainly directly derived from aplitic or pegmatitic bodies associated with the Dartmoor granite. The most prominent horizons are in the basal gravel of Petrockstowe and at about 300 m depth in Borehole No 1. The gravel, containing mostly vein quartz, comes from the ubiquitous veins which occur in the Carboniferous rocks. The fine-grained sand and silt are derived from the fine-grained silty sandstone of the Carboniferous succession, and the kaolinite and illitic clay minerals from the illite and chlorite assemblages of the Carboniferous shale. Almost all the sediments in the basin are derived from the reworking of Carboniferous sandstone and shale, with perhaps some New Red Sandstone and Mesozoic rocks. During the Paleogene, these older rocks were deeply weathered in subtropical to tropical conditions, as shown by the deep weathering profile seen in boreholes which have penetrated below the bottom of the basin (Bristow, 1968).

The Dartmoor origin of the heavy minerals suggests that the river depositing the sediments flowed from the south-east towards a marine area in the outer Bristol Channel and Celtic Sea *via* the area of the Stanley Bank Basin, which is of the same age. Most of the sediments in the basin, however, were derived from the local Carboniferous rocks.

Ball clays

The ball clays of the Petrockstowe Basin are characterised by very fine-grained, highly disordered kaolinite, reflecting their derivation predominantly from weathering mantles developed on Carboniferous rocks. These clays are stronger and more plastic than most Bovey Basin ball clays but tend to fire cream or pale grey.

Two main types of ball clay have been distinguished in the Basin (Watts Blake Bearne, 1984). Both types are kaolinitic, but Type 1 clays also contain appreciable amounts of montmorillonite; Type 2 clays have relatively little montmorillonite. The presence of montmorillonite is to some extent the reason for the inherent high strength and plasticity of the Petrockstowe Basin ball clays. The distinction between Type 1 and Type 2 clays is locally blurred by the presence of very siliceous clays occurring in association with both types. In 2024 there was one ball clay pit (North Devon Quarry – formerly Westbeare and Courtmoor quarries, now combined) in the Petrockstowe Basin, at Merton, operated by Sibelco.

Depositional environments

The cyclical nature of the Bovey Formation in the Petrockstowe Basin is a notable feature of the sequence, in which the sediments are prominently arranged in a number of fining-upward cycles (Fig. 34) (Freshney, 1970). Probably most of the cyclicity in the basin resulted from the normal action of a meandering river, but it is likely that some of the broader cyclicity was caused by tectonic control of subsidence and sedimentation.

The base of each cycle in the axial part of the basin is erosive and commonly channelled, succeeded by coarse-grained, locally gravelly, sand which fines upwards into sandy clay. The top of the cycle may be smooth to slightly sandy clay which can be very lignitic in shelf areas of the basin. Beneath the topmost clay, rootlets are commonly developed in a seat-earth, which shows the development of various iron compounds, dependent on water-table level and the effect of the organic content of the seat-earth on the overlying sediment at the time of deposition. In swamps containing much organic matter, the iron mineral formed is marcasite which is generally finely divided. Where the water table is low, and the soil is well-aerated, red and yellow oxides of iron form. In some cases, marcasite formed first in swamps and, following uplift, oxidation resulted in red and yellow staining of the clays.

Cycles in the north-eastern shelf area of the basin (Fig. 34) differ from those in the axial area in showing a general reduction in mean grain size. Although the base of each cycle

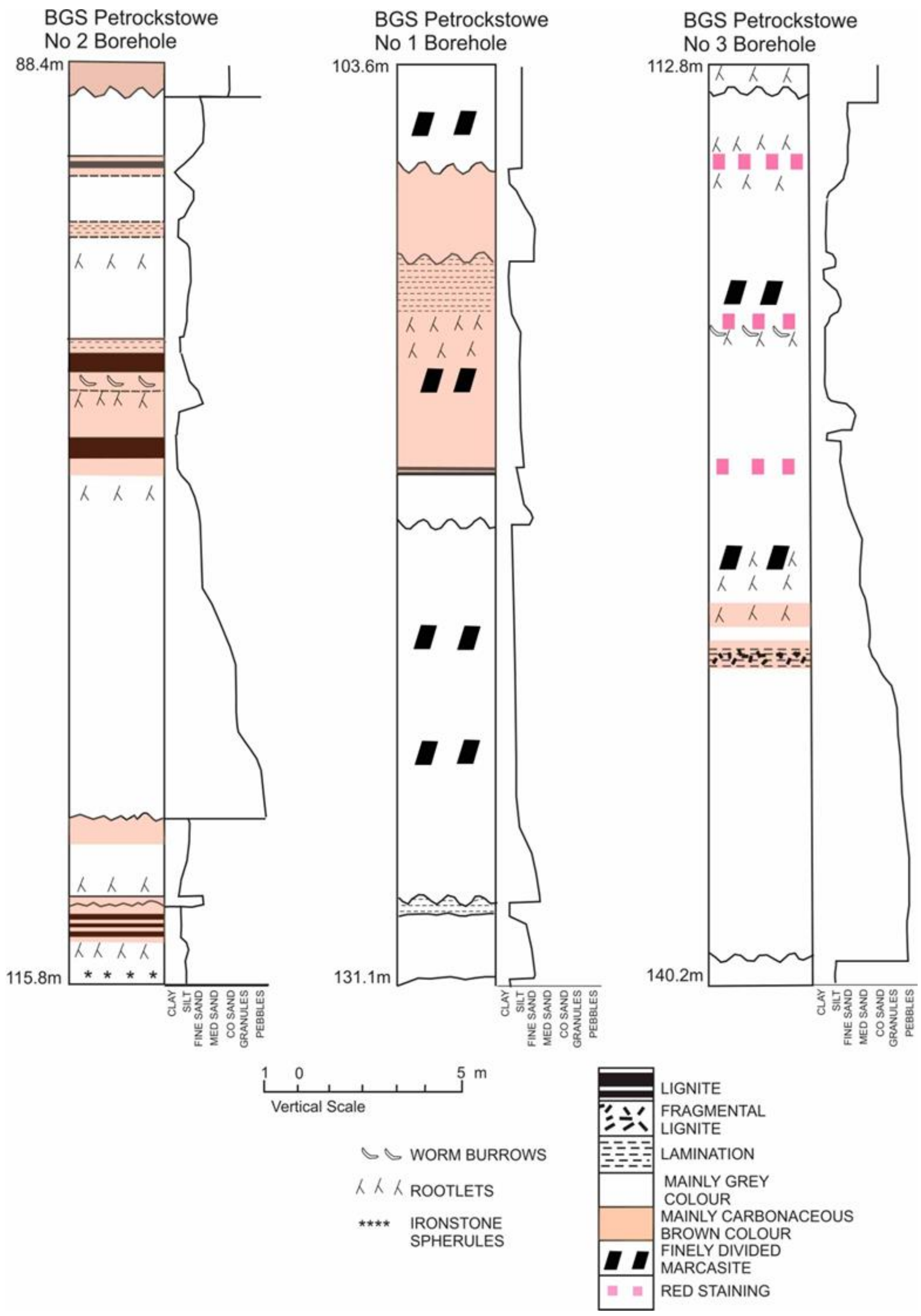

Figure 34. *Sedimentary cycles in the Bovey Formation succession of the Petrockstowe Basin (after Freshney* et al., *1979).*

is still erosional, there is less evidence of channelling and fine-grained silty sand is generally present at the base of each cycle. In addition, clays above the sea-earth are often almost sand-free and commonly very lignitic, particularly immediately above the seat-earth. Such clays represent the main commercial ball clays of the Petrockstowe Basin.

The type of cyclicity seen in the Bovey Formation of the Petrockstowe Basin and the lateral variability seen in the elongate basin, strongly suggest that most of the deposit was laid down in a meandering river system. The axial zone consists dominantly of point-bar sediments together with levée, crevasse splay and some overbank floodplain sediments, while the shelf areas are mainly of floodplain and swamp origin. The presence of rootlet and other soil profile indicators, such as sulphide and iron oxide staining and spherulitic siderite, point to periodic uplift and oxidation of the sediments. The occurrence of some thicker beds of gravel in the axial zone may suggest periods of higher sediment input and higher energy flow when the meandering river style may have changed to a braided river style. The presence of well laminated clays in the north-western part of the basin suggests that a temporary lake had formed in the axial zone of the basin, with a considerable diminution of flow both in and out of the basin.

The finely laminated clay and silty sand appear to form a very distinctive group of pelagic character, and the graded nature of the laminae and the un-abraded leaf remains suggest deposition in a lake, or certainly in ponds of water that persisted longer than the duration of the normal overbank flood. Notably, these sediments are restricted to the north-western axial area of the basin, which is also the area with the maximum thickness of strata and largest residual gravity anomaly. Thus, although fault movements and related subsidence of the basin were usually just enough to maintain either fluvial sedimentation or non-deposition, there were times when this subsidence was sufficient in the north-west to allow the development of temporary lakes.

Features of the basin, such as the reduction in grain size from axial to marginal (shelf) areas, the gradual reduction in grain size north-westwards along the axis of the basin, and the presence of the fining-upward cycles described above, all indicate sedimentation from a river that flowed along the basin towards the north-west. The river system was differentiated into an axial zone which contains mainly channel deposits and some overbank sediments, and flanking (shelf) areas where the sediments were laid down almost entirely in overbank and backswamp environments. At times the overbank area was fairly dry, with growth of a vegetation cover and oxides forming the soil profile, while at other periods it was very swampy with much development of marcasite.

The weathering profile, up to 30 m thick, in the Carboniferous rocks below the Paleogene deposits shows an upward diminution in the amount of original illite, chlorite and sodic plagioclase, and an increase in the proportion of kaolinite. Most of the kaolinite is fine-grained and crystallographically disordered and is identical to that found in the overlying Paleogene clays. The topmost kaolinite in the weathering profile is, however, better ordered and this has been attributed to resilication of bauxite minerals during diagenesis of the overlying sediments. The profile can be subdivided into an upper iron-rich zone underlain by mottled and pallid zones. The ubiquitous fine-grained sand of the basin is the same grain size as that within the Carboniferous sandstones, and the quartz in the Paleogene gravels is mainly vein quartz similar to that found within the structurally deformed Carboniferous rocks. Where seen at outcrop, Paleogene weathering has reduced the hard folded Carboniferous sandstones and mudstones to soft greenish-grey sand and bluish-grey clay respectively.

Most of the sediments in the basin were deposited by rivers that flowed through an area of relatively low relief. The flora includes such plants as palm trees and magnolia that suggest a subtropical climate. Weathering mantles in which kaolinite is produced from chlorite and illite also suggest subtropical or tropical conditions. The plant cover included conifers on the higher ground, with ferns and swamp-loving plants growing near the river and feeder streams. Animal fossils are entirely absent, probably due to acidic conditions in the sediments after deposition, but it is inconceivable that mammals, birds and insects were not abundant in this environment. Structures described as 'worm burrows' are recorded, mainly in brown or greyish-brown clays, and are distinguished by infillings of clay of a slightly different colour from that of the surrounding clay (Freshney *et al*., 1979).

Stanley Bank Basin

The offshore Stanley Bank Basin, situated to the east of Lundy Island (Fig. 2), is the largest in outcrop area of the Cenozoic basins sited along the course of the Sticklepath Fault Zone. It was discovered by a seismic reflection survey (Fletcher, 1975), and a subsequent borehole (73/36; Fig. 3) penetrated 33.85 m of Bovey Formation strata comprising grey clay (locally red-mottled), lignitic clay and silt, with lignite beds up to 5 m thick. Later seismic refraction work suggested a maximum basin depth of 340 m (Brooks and James, 1975). Dips shown on The BGS 1:250 000 Series Lundy Sheet (1983) are consistently to the west or south-west at between 2 and 3° over most of the outcrop, except in the far south where dips are 1–2° degrees to the north-west. The outcrop is bounded on the west side by an extension of the north-west - south-east-trending Sticklepath Fault Zone. On the east side the deposit rests unconformably on Devonian (Pilton Shale), Triassic and Jurassic rocks.

Stratigraphy and depositional environments

Three Paleogene units were distinguished seismically within the Stanley Bank Basin by Davies (1987), but the uppermost is now thought to be of Pleistocene age (Tappin *et al*., 1994). A basal unsampled unit of 'hummocky clinoforms' (Facies B in Fig. 3) is probably fluvial (braided channel) in origin. The overlying unit, with parallel reflectors dipping towards the faulted western margin of the basin (Facies A in Fig. 3), forms a major part of the succession. Boreholes show it to be mainly clays and lignites (up to 5 m thick). The clays are grey and brown, locally red-mottled, silty and sideritic, with interbedded sandstones; rootlets and plant fragments are present. The sequence probably formed as a distal-floodplain deposit laid down in a backswamp or shallow lagoon (Boulter and Craig, 1979; Davies, 1987). Limited marine influence is indicated by the presence of microplankton in a borehole (73/36) in the north of the basin, indicating the proximity of a shoreline. Drainage of the floodplain was probably to the north-west (Davies, 1987), continuing the direction indicated at Petrockstowe (Freshney, 1970).

Age

Boulter and Craig (1979) examined pollen and spores from three boreholes (73/35, 73/36, 73/58 (Fig. 3)) and concluded that a Middle Eocene age was indicated. The section in borehole 73/36 was assigned by Wilson (1996) to her assemblage zones P1, P2 and P3 which were dated successively as Rupelian, early Chattian and late Chattian. King (2016), however, has pointed out that the occurrence of *Boehlensipollis* in P2 and P3 indicates that these zones are also Rupelian.

A Chattian age was suggested by Evans *et al*. (1991) who recorded the '*verus-vestibulum*' association. However, the presence of *Boehlensipollis* throughout the section in borehole 73/36 (Boulter and Craig, 1979, table 2) indicates that the sequence is entirely Rupelian (King, 2016). Marine microplankton were recorded by Wilson (1996) from several levels in borehole 73/36, including *Areoligera semicirculata* (Rupelian – early Chattian). Thus, although King (2016) concluded that the entire known cored sequence was Rupelian, other sources indicate that Chattian strata may also be present.

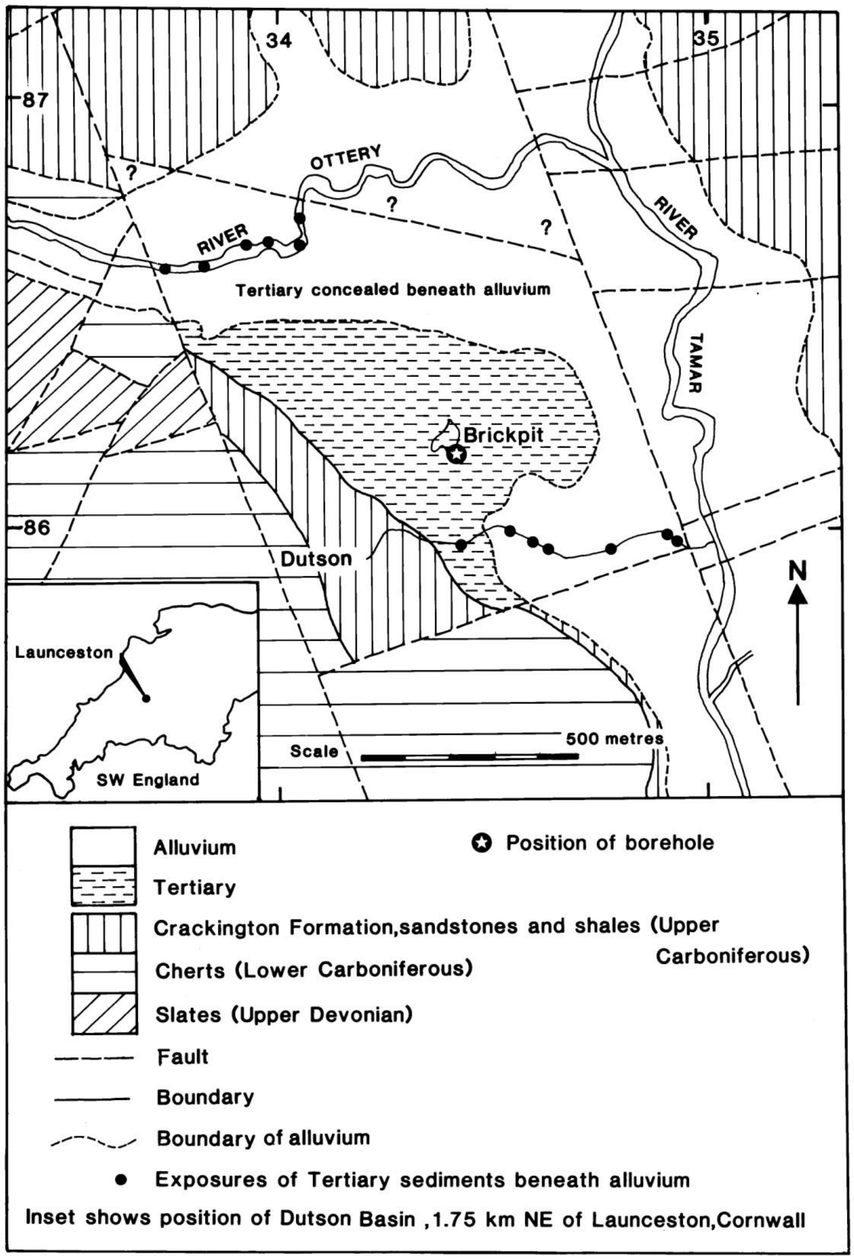

Figure 35. *The geology of the Dutson Basin (after Freshney* et al., *1982, fig. 1). Reproduced with permission of the Geologists' Association.*

Dutson Basin

About 1.75 km north-east of Launceston, Cornwall, a small (*c.* 0.5 km^2) probably wholly fault-bounded pull-apart basin (Fig. 35) lies along a north-west – south-east-trending strike-slip fault zone, the Tamar Fault Zone. Small outcrops of Bovey Formation-type clays are visible beneath alluvium in the banks of rivers in the vicinity, but the presence of the formation was established by a 9.35 m-deep borehole drilled in 1977 by the authors (Freshney *et al.*, 1982), in which the sequence comprised about 2.3 m of grey, very sandy clay, resting on 3.6 m of brown clay with a bed of black lignitic clay, on 3.4 m of grey sand-rich clay and clay-rich fine-grained sand. Rootlets were recorded from one level. The clays were briefly worked in the 1920s for the manufacture of bricks (Bristow, 2004); as far as is known no ball clays were produced.

One borehole sample yielded a pollen and spore assemblage indicating a late Eocene (Bartonian) age, based on taxa including *Nudopollis* and *Plicatopollis*. The sequence probably corresponds in part to the lower Bovey Formation in the Bovey Basin, to shelf and lower axial-trough sequences in the Petrockstowe Basin, and possibly to part of the lower sequence in the Stanley Bank Basin. In the same sample, 68% of the specimens were fern spores and 15% conifer pollen, an unusual characteristic for Tertiary assemblages from the western British Isles (Wilkinson and Boulter, 1980). The assemblage suggests poor soils and lack of a tree canopy, and indicates a mean annual air temperature of 15° C.

Mineral assemblages of quartz, kaolinite, illite, mixed-layer minerals and smectites, typical of immature tropical and sub-tropical weathering profiles, probably developed on Upper Palaeozoic rocks. The deposit was probably laid down by a river flowing south from the central upland area of Cornwall. Owing to the strong control that north-west–south-east faults were likely to have had on drainage patterns, there was probably no connection with any rivers flowing into the Bovey or Petrockstowe basins.

Lamerton

Gravity surveys between Dartmoor and Bodmin Moor (Rollin, 1988) showed a small local closure at *Lamerton*, north-west of Tavistock, interpreted as either a Cenozoic basin with about 150 m of infill, or a small granite cupola extending from the roof-region of the granite at about 2 km depth. A piston core borehole [SX 4532 7593] drilled by the authors to a depth of 15.4 m proved head or landslip deposits of mainly yellowish-brown gritty, silty, sandy clay with ferruginous concretions and angular clasts of slate, chert and possible volcanic rock. No deeper borehole has been drilled to investigate the supposed deposit and the presence of a Cenozoic basin remains unproved.

Bristow (1989) noted that gravity lows at least as large as that at Lamerton had been identified during a gravity survey over the southern half of Goss Moor, north of the St Austell Granite. These had originally been modelled as cusps of granite, probably kaolinised, which reached up to within 100 m of the surface. On drilling, however, the anomalies were found to be caused by about 200 m of completely kaolinised slates impregnated with sulphite blebs. There appeared to be a causal relationship between the very deep kaolinisation of the country rock and the mineralisation, acids produced during weathering of the sulphide having accelerated kaolinisation of the slates. Possibly the situation at Lamerton is similar to that found by Bristow beneath Goss Moor.

Orleigh Court

A unit of clay and sand overlying the flint gravels at Orleigh Court (Fig. 2), about 5 km south of Bideford, was proved by test-pitting (Cope, 2007); it may represent a previously unrecorded former cover of Bovey Formation, of unknown extent. An excavation about 115 m south-west of Orleigh Court showed 3.2 m of white and yellow clay on 0.4 m of dark and pale grey laminated clay.

The dark laminated clays yielded a very sparse *in situ* flora that contained *Baculatisporites primarius* (an *Osmunda*-type fern), ?*Tricolpites* cf. *hians* (a plane or *Cercidiphylum*-type angiosperm) and ?*Inaperturopollenites dubius* (probably Cyperaceae pollen). The assemblage indicated a probable Paleogene age; if it had been younger than early Miocene it would be expected that it would contain at least some Poaceae or Asteraceae pollen instead of the fern that was found.

Analysis of the clay shows some similarities to Petrockstowe ball clays, except that the Orleigh Court sample contains feldspar (17%), not found in the Petrockstowe clays. The Orleigh Court deposit lies close to the course of the Sticklepath Fault and may have been influenced by movements along that fault. The extent of the hypothetical large 'lake' shown by Cope (2007, fig. 3) is based on the present 90 m contour and does not consider any post-depositional tectonics.

Cadham Farm

Near Cadham Farm [SS 584 030] (Fig. 2) a patch of quartz gravels, silts and plastic clays were included in the Bovey Formation by Edmonds *et al*. (1968). Resistivity and seismic surveys indicated a thickness of up to 12 m at the eastern end of the deposit. East of the Beckamoor Brook the deposit is mainly quartz gravel. About 140 m north-west of Lower Cadham, quartz gravel with clasts up to 5 cm overlies yellow and white silt and fine gravel [SS 5830 0309]. A pit at Lower Cadham showed the following section:

?Pleistocene (5th Terrace)
- **Gravel**, coarse, with boulders and cobbles of granite and Carboniferous rocks — 0.6 m

?Bovey Formation
- **Gravel**, quartz, fine, ferruginous — 1.8 m
- **Silt**, yellowish-brown — 0.6 m
- **Sand**, grey, clayey — 0.15 m

In a small pit [SW 5766 0320] fine quartz gravel contains flints up to 15 cm across. On Lower Cadham Moor [SW 5765 0292] pale grey plastic clay was proved beneath head. No stratigraphical order could be assigned to the fragmentary exposures noted above. The deposits are situated between faults near the course of the Sticklepath Fault, and their deposition and preservation are probably related to movements along that fault zone.

Sandypark

Three old pits, reputedly dug for tin, near Sandypark, Chagford (Fig. 2), are located at Bradford Pool [SX 700 910], Great Tree Farm [SX 705 906] and Parford Wood [SX 713 902] (Edmonds *et al*., 1968).

At Bradford Pool pale grey clays and weathered granite are present on the south-west side. Analysis by Coque-Delhuille (1987) showed that the clays were dominantly kaolinitic (90%), with quartz forming most of the sandy fraction, together with small amounts of potassium feldspar and brown-black. At Great Tree Farm the bottom of the pit shows pale, ochre-mottled sandy clay and on the north-east slopes pale grey clayey sand is present. At Parford Wood, near the entrance [SX 7140 9000], blocks up to 0.6 m across of quartz-tourmaline conglomerate and 'quartz grit' with a chalcedonic cement are present in the head. A section [SX 7133 9034] at the north end of Parford Wood shows about 3 m of head overlying a 1 m-thick bed with blocks of iron-stained 'quartz grit' and conglomerate. Owing to the lack of exposures it is uncertain if the three workings are separate or part of a single linked outcrop.

White plastic clays were recorded from Bradford Pool and the other workings by Blyth (1962) who suggested that they might represent faulted remnants of a more extensive sheet of Bovey Formation clays. The quartz-tourmaline conglomerate and 'grit' from Parford show lithological similarities to the Woolley Member of the Bovey Formation near Bovey Tracey. Edmonds *et al*. (1968) noted that a specimen of 'grit' from Parford was a 'quartz-grit' with a chalcedonic matrix, containing subrounded quartz clasts up to 1 cm across, tourmaline and small patches of white clay minerals, together with small amounts of feldspar, biotite and muscovite. This specimen was indistinguishable from a specimen [SW 7923 8101] of 'grit' from the Woolley Member. These and other lithological similarities indicate that the Sandypark deposits represent a facies of the Bovey Formation.

Court Barton Farm

A deposit of sands and clays described by Coque-Delhuille (1987) is present at Court Barton Farm [SX 8306 8571], Christow (Fig. 2). A shallow borehole [SX 8320 8568] in the centre of an old claypit showed the following sequence, recorded by Coque-Delhuille (1987, fig. 133) and summarised below:

- **Soil** — 0.4 m
- **Clay**, blue, becoming sandier with depth — 0.2 m
- **Sand**, yellowish-brown, coarse-grained — 0.7 m
- **Sand**, yellow, fine-grained — 0.75 m
- **Clay**, blue — 0.15 m

Bottom of borehole at 2.20 m depth.

The sands are granitic in origin and the clays rich in kaolinite, which is a mixture of a fine-grained, low-crystallinity type, characteristic of derivation from local Devonian and Carboniferous rocks by weathering, and a higher crystallinity type probably derived from hydrothermally altered granite. Some clays in the Bovey Formation of the Bovey Basin have a similar composition. The Court Barton deposit lies close to a north-south-trending fault, to which it may owe its deposition and preservation. The clay mineralogy and association with deep tropical weathering of the Court Barton deposit suggest that it is probably of Bovey Formation age, although no carbonaceous clays are present to allow dating by palynomorphs.

A borehole drilled by the authors adjacent to the deposit penetrated nearly 7 m of soft, highly altered dolerite, high in kaolinite (30-50%) with even higher levels of smectites (20-70%). The dolerite probably underlies the Bovey Formation deposit and has been deeply weathered, probably in a subtropical climate.

Beacon Cottage Farm (St Agnes)

The deposits that form an arcuate outcrop around the northern margins of St Agnes Beacon, Cornwall (Fig. 36) were formerly grouped together as the 'St Agnes Beds' (Pryce, 1778) and first classified as 'Older Pliocene' by Reid (1890). The deposits are now believed to form two separate outliers: the *St Agnes Outlier*, of Pliocene age, and the *Beacon Cottage Farm Outlier*, of Oligocene age (Walsh *et al*., 1987). Work by Jowsey *et al*. (1992) has indicated that the two outliers are separate

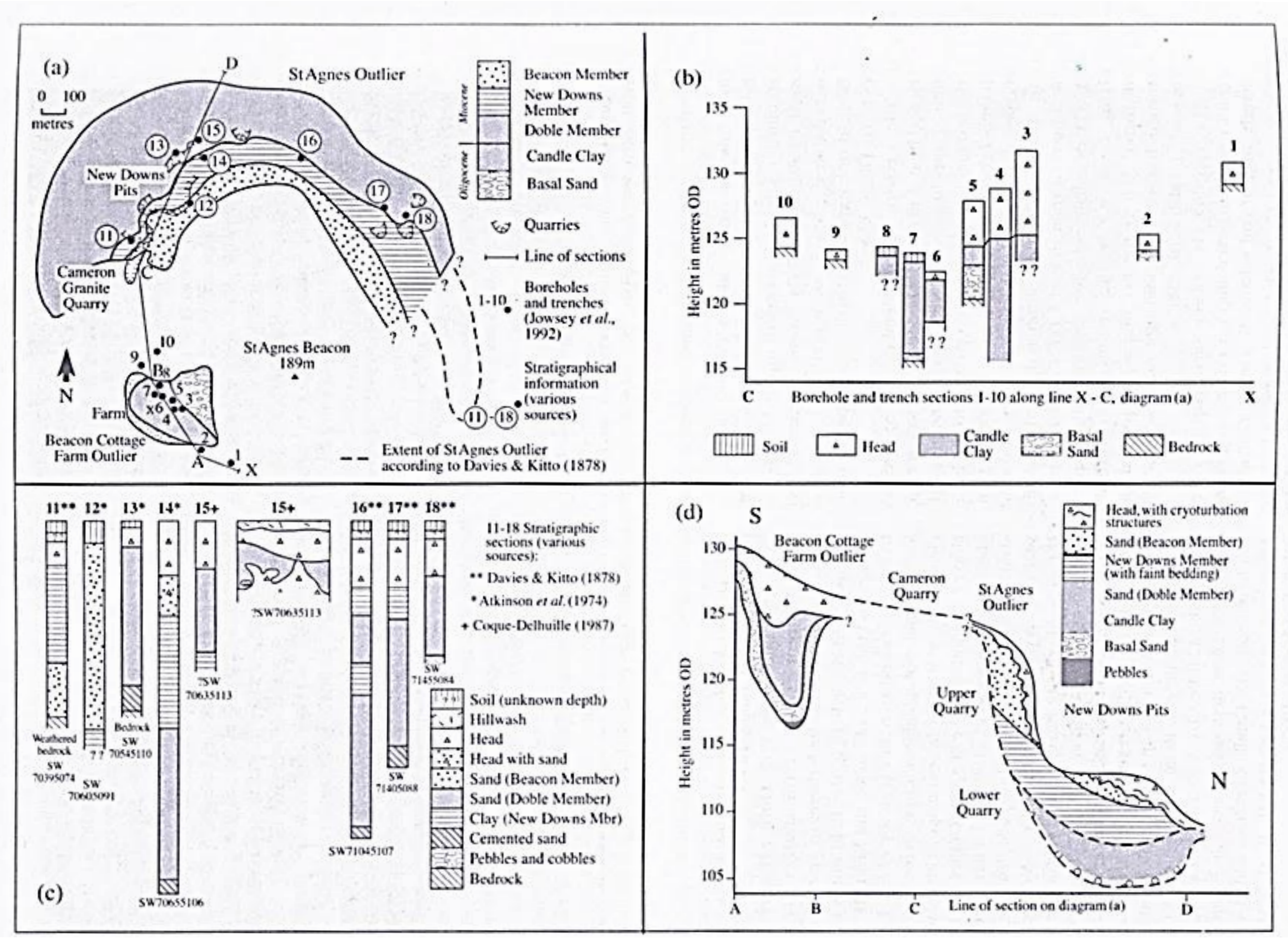

Figure 36. *(a) A revision of the St Agnes and Beacon Cottage Farm outliers by Jowsey* et al. *(1992). (b) Borehole and trench sections along line X-C (diagram a), adapted from Jowsey* et al. *(1992). (c) Stratigraphical sections along line D-C (diagram a), compiled from various sources. (d) Schematic reconstruction of the Beacon Cottage Farm and St Agnes outliers, based on Jowsey* et al. *(1992). After Campbell* et al. *(1998, fig. 3.7).*

(Fig. 36), with no overlap as was previously thought by Walsh *et al*. (1987).

The Beacon Cottage Farm Outlier sequence is up to 8.9 m thick, and this most westerly representative of the Bovey Formation has been divided into two members by Jowsey *et al*. (1992): a Basal Sand Member and overlying Candle Clay Member.

The Basal Sand Member, 1.5 to 2 m thick, consists of orange-brown or buff (locally white, ranging through yellow and orange, to red), fine- to medium-grained quartz sand. Sub-horizontal bedding is locally indicated by thin beds of silt and pebbles. Most of the sands are very well sorted except the basal 60 cm which are less well sorted and generally coarser grained.

The Basal Sand Member is sharply overlain, possibly unconformably, by the Candle Clay Member. The name derives from the former use of the clay to fix candles to tin miners' helmets or to the walls of underground workings. The member, about 4 m thick, is mainly pale grey sandy silt, locally coloured brownish grey, purplish grey, medium grey or mottled pinkish grey (the latter can probably be identified with the 'Red Blush' clay described in H. Dewey's 1932 field notebook, in the BGS archive). Various subdivisions into thinner units recorded by earlier workers and H. Dewey were not recognised by Jowsey *et al*. (1992), who regarded the member as generally uniform in character. The lithology and age determinations (see below) indicate that the deposit should be included in the Bovey Formation.

The base of the deposit, investigated using borehole data by Jowsey *et al*. (1992), is uneven, forming an irregular shallow depression ranging in elevation from about 116 m to 132 m OD. On the north-east side the unconformity is bordered by scarp-like features, locally over 6 m high. The sub-Oligocene floor was much more irregular than the sub-Miocene floor beneath the nearby St Agnes Formation which apparently rests on part of the 130 m platform (the Reskajeage Surface) of north and west Cornwall.

In 1932, H. Dewey of the Geological Survey collected a sample (BGS code MR 10401) from the lower part of the Candle Clay in the Beacon Cottage Farm claypits [SW 7049 5088], described in the BGS database as 'black pottery clay', but referred to as 'lignite' in Jowsey *et al*. (1992). The precise nature of the sampled level is uncertain. Although both Ussher (1879) and Dewey noted that the lower levels of the Candle Clay were dark (lignitic), Jowsey *et al*. (1992) found no further examples of lignitic clay despite extensive sampling. Local information suggested that the lignitic clays may have occurred as discrete isolated bodies. Dewey noted the presence of 'black clays' in the lower levels of the Farm excavations and also, in the openworks of Wheal Coates Mine, 'a bed of laminated clay with obscure remains of plants'.

The single sample from the Beacon Cottage Farm deposit is crucial to the dating and understanding of the deposit and it is therefore important to have confidence in its provenance and location. Coque-Delhuille (1987) rejected the Oligocene dating of the deposit on the grounds that: a) it was based on only a single sample; b) the provenance of the sample was uncertain; and c) the Oligocene date was not compatible with her assessment, on geomorphological grounds, for a Pliocene age.

Walsh *et al*. (1987) noted that they initially doubted the authenticity of the MR 10401 sample and the validity of the results. However, examination of H. Dewey's notebook, a consideration of the possibility of mislabelling at the Geological Museum and a re-examination of the pollen led them to conclude that there was no error in the sampling or analysis of the flora. The good state of preservation of the microflora and the presence only of Oligocene forms indicates that the sample is unlikely to have been derived.

This carbonaceous or lignitic clay sample (MR 10401) was prepared by W.A. Watts in about 1965 for palynological analysis at the Institute of Geological Sciences, and preliminary determinations of the microflora indicated an Oligocene age, referred to in Mitchell (1965). The slides were re-examined, and new preparations made at NE London Polytechnic (now University of East London) (Atkinson *et al.* 1975), resulting in a Middle to Upper Eocene age attribution. Further work (Walsh *et al.* 1987) confirmed the original taxonomic identifications by Mitchell (1965) and Atkinson *et al.* (1975) for sample MR 10401. King (2016) noted that the occurrence of *Cicatricosporites paradorogensis* (typically Priabonian and Rupelian) and *Boehlensipollois hohli* (Rupelian) indicates an early Oligocene, Rupelian, date. Such a date is comparable to the age of the middle and part of the upper Bovey Formation of the Bovey Basin (Edwards and Freshney, 2023).

Jowsey *et al.* (1992) considered, on the evidence of grain-size analysis and the presence of sand grains interpreted as aeolian, that the Basal Sand Member formed as aeolian dunes banked against the lower slopes of a proto-Beacon; the coarser-grained, locally pebbly, lowest part of the member was thought to represent aeolian sands mixed with locally-derived coarser fluvial sediment.

The palynological studies of Boulter (*in* Walsh *et al.* 1987) suggest that the lignitic clay of sample MR10401 was deposited in a low-energy environment. The presence of palm pollen, *Monocolpopollenites tranquillis,* suggested frost-free winters, and the general floral assemblage indicates a mean annual lowland air temperature of about 12^{o} C. Jowsey *et al.* (1992) suggested that the generally structureless nature of the Candle Clay Member indicates a polygenetic accumulation deposited in part in water and possibly mixed with wind-blown dust. The sediments were possibly derived mainly from local masses of rotted Devonian country rock ('killas'). Small temporary ponds in which carbonaceous sediment accumulated may have formed on an uneven slopewash sheet, and sample MR 10401 may have accumulated in one of these temporary ponds. Although the Beacon Cottage microflora differs significantly from those in the Bovey and Petrockstowe basins, its undoubted Paleogene age indicates that the deposits are a local representative of the Bovey Formation.

Crousa Gravel

Lizard Peninsula

The Lizard Peninsula is notable for the presence of a widespread, remarkably planar surface, part of the Reskajeage Surface, which slopes southwards over several kilometres, from about 110 m to 75 m OD, and cuts across all the underlying rock types. Coque-Delhuille (1987) distinguished northern and southern elements of the plateau. The northern part was at elevations of about 110 m OD; the southern part was some 10-20 m lower. However, it is uncertain, without further study, to be sure if this distinction is real or whether both supposed elements are simply part of a single southward-sloping surface. The northern surface was considered by Coque-Delhuille (1987) to be 'continental' in origin and part of the 'Devon-Cornwall' (Reskajeage) Surface; it was distinguished by the presence on it of the ***Crousa Gravel***. The southern part was thought by Coque-Delhuille (1987) to be a marine Pliocene surface, but this interpretation is now open to question.

At Crousa Common (Fig. 2), about 2 km south-west of St Keverne, the Crousa Gravel (Fig. 37) lies on this surface at an elevation of about 110 m OD, almost on the summit of the common, and has an outcrop that extends for 1.5 km from east to west and 0.6 km from north to south. The Crousa Gravel

Figure 37. *Crousa Gravel at Crousa Common [SW 7723 1983], May 2009. The field of view is about 1 m across (photograph by R.A. Edwards).*

was considered by most authors (*e.g.*, Milner,1922; Boswell, 1923; Flett, 1946), to be a marine gravel of Pliocene age resting on a marine-cut platform. Coque-Delhuille (1987) suggested, however, that the Crousa Gravel was a fluvial deposit of 'Mio-Pliocene' age. A fluvial origin was also suggested by Hendriks (1923) and Guilcher (1949). However, the gravel has since yielded dateable palynomorphs that suggest a Paleogene age (Scourse, 1985).

The presence at several localities on the Lizard plateau of rounded quartz pebbles indicates that the current outcrop on Crousa Common is probably the erosional remnant of a formerly more extensive spread of the gravels. Rounded pebbles of white quartz from 2.5 cm to 15 cm or more in diameter were noted by Flett (1946) from Goonhilly Down and are not uncommon on 'Kynance Down' (an area shown on figure 4 of Flett (1946) occurring north of Kynance Cove and approximating to the 'Lower Predannack Downs' of modern Ordnance Survey maps). Rounded quartz pebbles are common in the banks of small streams draining the downs and were probably transported there from former outcrops of the Crousa Gravel at higher levels. They have also been recorded in the coastal head and underlying raised beaches between Coverack and Leggan Cove on the east side of the Lizard. About 1 km south of St Keverne, south of Trebarveth Farm [SW 7955 1990], at between 75 and 91 m OD, Coque-Delhuille noted pebbles of quartz and Lizard Complex rocks (mainly gabbro). About 3.5 km SW of Crousa Common, at about 80 m OD, Coque-Delhuille (1987) recorded a scatter of gabbro pebbles east of Gwenter Farm [SW 7462 1785]. In the south of the peninsula, Coque-Delhuille (1987) recorded, north of Trethvas Farm [SW 7100 1380], at around 75 m OD, well-rounded pebbles of quartz as well as flint (not present at Crousa) and Lizard Complex rocks.

The deposit was noted by De la Beche (1839) and Budge (1843). Flett (1946) described the gravels in some detail at a time when only one pit was in operation. Walsh *et al.* (1987) sank five pits along the eastern margin of the Crousa Gravel outcrop in 1981 (see below). Leake *et al.* (1992) carried out an exploration for enrichment of vanadiferous magnetite and ilmenite in the Lizard ophiolite complex, including drilling of power auger holes in the Crousa Gravel (see below). The gravels have been widely worked in the past for road mending and paths before the mid-nineteenth century, but the only current exposure of about 2 m of gravel is at [SW 7723 1983], about 2 km south-west of St Keverne (Fig. 37).

Flett (1946) noted that the level surface underlain by the Crousa Gravel contrasts with the surrounding area which is littered with numerous large blocks of gabbro (known locally as 'crusairs') (Fig. 38) so that the boundaries of the gravels can be fairly easily determined despite the lack of exposures. Ealey *et al.* (1999) noted that the Soil Survey map (Staines, 1984) probably shows most accurately the distribution of the Crousa Gravel.

Figure 38. *Large blocks of gabbro ('cruisars') on Crousa Common (photograph by R.A. Edwards).*

The only extant exposure of the Crousa Gravel is in a small pit [SW 7723 1983] (Fig. 37) which shows yellowish brown unbedded gravel with a silt and clay matrix. The chief clasts, ranging between 2.5 and 15 cm in diameter, are vein quartz, the smaller clasts being well rounded and the larger subrounded to angular (Flett, 1946). Coque-Delhuille (1987) noted that the median size of the quartz pebbles was 3–4 cm. Clasts of dark grey or blue quartz-tourmaline rock are uncommon, and very weathered pebbles of granite are rare. Clasts of dark chert have been noted. Flint pebbles are apparently absent. Between 30 and 198 ppm of the heavy mineral cassiterite have been recorded. Flett noted that quartz veins are very rare in the Lizard rocks (locally present in the mica schists and more rarely in the hornblende schists), and thus the source of the quartz pebbles in the Crousa Gravel is most likely to have been the Devonian rocks north of the Lizard boundary. Walsh *et al.* (1987) noted that the nearest likely source of quartz pebbles was the Gramscatho-type conglomerates, located 4 km north of the Crousa Gravel outcrop. The granite and quartz-tourmaline rock pebbles and the cassiterite were probably sourced from the Carnmenellis Granite and its margins, north of the Helford River. The heavy minerals (abundant tourmaline, epidote, zircon, anatase, rutile, topaz and andalusite) support a derivation from the Carnmenellis granite and its aureole (Coque-Delhuille, 1987). The Helford valley probably did not exist or was infilled at the time of formation of the Crousa Gravel to allow transport of detritus from north of the current valley.

Flett (1946) noted thicknesses of the Crousa Gravel of between 3 and 5 m. The extant exposures show generally structureless gravel (Fig. 37), but Flett noted that the lower part of the deposit was bedded, with thin locally impersistent layers of yellow sand and white clay. The upper levels of the gravels were affected by (?Devensian) periglacial processes producing disturbed bedding planes and pebbles with vertically aligned long axes. The 'cross-bedding' noted in one pit by Milner (1922) may in fact be periglacial in origin. A BGS photograph (P200621) of a pit, taken in 1907, shows involuted pockets of loess up to about 2 m deep extending down into the gravels (Ealey, 2012).

Five trial pits across the eastern end of the outcrop were dug in 1981 by Walsh *et al.* (1987) (locations on Fig. 39), and showed evidence of intense post-depositional weathering. All the pits reached 'gabbroic bedrock' which was very decomposed, consisting either of growan-like rotten rock in two of the pits, or mottled clay with relic crystal structures in the remaining pits. There was no clear junction between the rotted gabbro and the 'Crousa Gravel', and the top of the bedrock surface was taken at the lowest level with quartz pebbles. The surface lies at a level close to 103 m OD in four

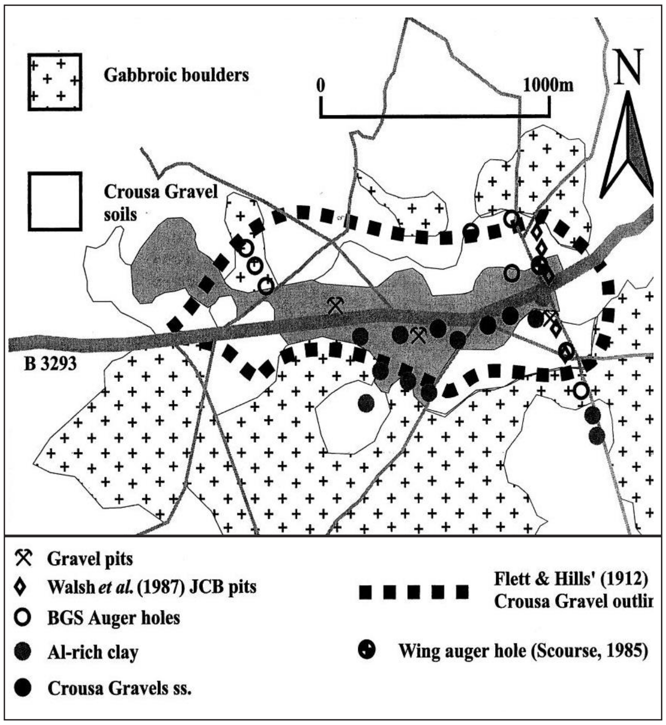

Figure 39. *Distribution of the Crousa Gravel, and sites mentioned in the text. After Scourse and Furze (1999, fig. 49). Reproduced with permission of the Quaternary Research Association.*

of the trial pits, descending to 98 m OD in the southernmost of the trial pits. Bedding was evident in only one pit.

As part of an exploration for vanadiferous magnetite and ilmenite in the ophiolitic Lizard Complex, together with a search for possible placer concentrations of Fe-Ti oxides and other heavy minerals in the Crousa Gravel, Leake *et al.* (1992) drilled several power auger holes to depths of 3 to 12 m over the gravel outcrop (locations on Fig. 39). Crousa Gravel was proved in three holes to depths of between 4 and 9 m. The gravels were considered to form a channel deposit 'several metres thick and a few tens of metres wide', extending east-west for at least 1 km to the west of St Keverne Beacon. A deposit up to 12 m thick of kaolinite-rich material enriched in Al and relatively depleted in Ti and Zr (Fig. 39) was also penetrated in auger holes over a wider area.

Sn concentrations in the gravels were relatively high (30 to 198 ppm). Additionally, grains of tourmaline and/or quartz-tourmaline were recovered. Since Sn and tourmaline are not known from the Lizard Complex, they must have been derived from the granites and their aureoles to the north or west.

Leake *et al.* (1992) recorded rounded boulders of fresh gabbro assocated with the clay-rich material. Such boulders were not considered to be associated with the underlying rock which in some cases was gabbro of different composition and also deeply weathered and soft. The large boulders in a clay matrix were interpreted by Leake *et al.* (1992) as glacial till originating as sea-bed sediment pushed up onto the Lizard plateau together with boulders of gabbro from the exposed coast at the base of a sheet of sea ice. The gravel was interpreted as a fluvial sub-ice meltwater channel. The date of the supposed glacial event was not clear but the loess overlying the gravels is considered to be late Devensian in age; Wintle (1981) suggests a 'relatively early glacial event'. However, the attribution of the Crousa Gravel to a possible Cenozoic date (Ealey *et al.*, 1999) suggests that this glacial hypothesis is untenable (*see below*).

Flett (1946) and Walsh *et al.* (1987) recorded deeply weathered gabbroic bedrock beneath the Crousa deposit. The material underlying the Crousa Gravel is more likely to be a deeply weathered layer formed during a period of subtropical weathering. The plastic clay with a high alumina and low titania content recorded by Leake *et al*. (1992), which they interpreted as exotic material, is more likely to be a subtropical weathering product of the gabbro.

The gravels were originally assigned a Pliocene age and considered to rest on a marine surface (Flett, 1946), but no fossils had hitherto been recorded so that the age of the deposit was uncertain. Ealey *et al*. (1999), however, sampled the deposit by wing auger at the crossroads [SW 776 200] (location shown on Fig. 39), providing the following section, from which palynomorphs were recovered:

- 0-15 cm. **Topsoil**.
- 15-45 cm. **Clay**, blue-brown, mottled, with vein quartz pebbles (5 – 100 mm).
- 45-60 cm. **Clay**, grey-white, with smaller clasts than above.
- 60-90 cm. **Clay**, white, with angular quartz sand and granules.

The clay between a depth of 15 and 45 cm was sub-sampled and yielded a palynomorph assemblage dominated by triporate grains resembling *Corylus*. Further examination identified these as *Engelhardia*. In addition, a grain of *Eucalyptus* was seen. Other taxa included Gramineae and spores of Polypodium and undifferentiated Filicales. Ealey *et al*. (1999) suggested that the dominance of *Engelhardia* indicated a Cenozoic rather than a Pleistocene age, but clearly further sampling is necessary to be confident of this dating.

The gravels are generally poorly sorted but bedded in their lower levels with impersistent interbeds of sand and clay. These features suggest a fluvial origin, in agreement with the view of Coque-Delhuille (1987). As noted above, the included clasts and the presence of Sn and tourmaline indicate source areas to the north or west. The gravels represent the eroded remnants of a formerly extensive sheet of fluvial gravels, possibly deposited by braided streams on an extensive braidplain. The Helford Valley was unlikely to have existed at the time of deposition since it would have formed a barrier to transport of material from northern sources. The presence beneath the gravels of deeply weathered material formed in a tropical weathering environment suggests a relatively old, possibly Paleogene age.

?Start Peninsula

About 100 km east of the Lizard, on the southern part of the Start Peninsula of south Devon, Coque-Delhuille (1987) noted a well-developed horizontal surface, divided into three elements by the Kingsbridge ria and the Lannacombe valley. It has an altitude of 130–133 m OD to the west, 137–138 m OD towards East Prawle, and 122 m OD to the east. Coque-Delhuille (1987) recognised supposed 'marine' deposits on this surface:

- South-west of Marlborough, very well-rounded quartz pebbles 3–4 cm in diameter were recorded in fields [SX 695 3860] east of Bolberry Down, at an altitude of about 130 m.
- North of Prawle Point, Coque-Delhuille (1987) recorded numerous pebbles, especially west and north of East Prawle, at [SX 7763 3644] (*c*. 130 m OD) and [SX 7800 3755] (138 m OD). Pebbles were also noted north-west of Lannacombe Bay, in fields [SX 7930 3765] between Higher Borough and Lannacombe Barn, at about 130 m OD.
- At these three sites quartz pebbles make up 75 to 95% of the total clasts, with in addition flint, shale and scarce Devonian quartzitic sandstone. The average clast size is 3 to 5 cm, with a maximum of 10 cm.

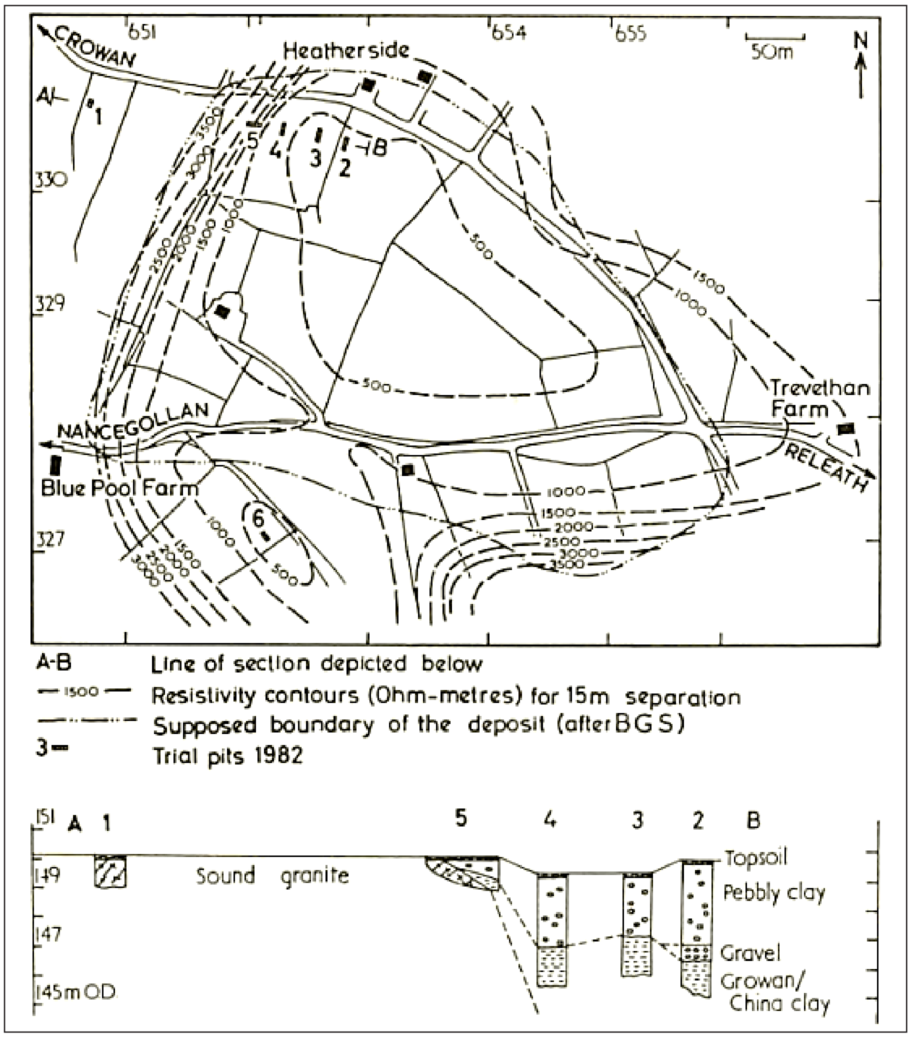

Figure 40. *(a) Profile of the northwest corner of the Polcrebo Downs Outlier, based on trial pits. (b) Resistivity contours derived from a 15 m separation Wenner survey. Pit 6 proved only growan-china clay to a depth of 3 m (partly after BGS sources). After Walsh* et al. *(1987, fig. 11). Reproduced with permission of the Geological Society of London*.

- On the Start Point platform, very well-rounded quartz pebbles and granules were recorded at a locality [SX 8170 3750] near Start Farm, at an elevation of about 130 m OD.

These quartz pebbles occur only as remanié scatters on the Start surface and no exposures of thicker deposits are known. Their lithology and position on a probable subaerial surface invite comparison with the Crousa Gravel, and they may have originally formed part of an extensive sheet of Paleogene fluvial gravels. In accordance with her understanding of South-West England landscape evolution, Coque-Delhuille (1987) interpreted the Start surface as a Pliocene marine platform, but it is here considered to be a subaerial surface forming an element of the Reskajeage Surface.

Polcrebo

At Polcrebo Downs [SW 6530 2201] on the west side of the Carnmenellis Granite, Cornwall (Figs 2, 40), the ***'Polcrebo Gravels'*** occur on a bench-like feature at an elevation of about 147 m OD and have an outcrop area of about 10 ha (BGS Geological Sheet 352). Like the Crousa Gravel, with which it has been compared, the Polcrebo deposit is an erosional remnant, and Everard (1977) regarded its survival as dependent on its watershed location. There are no current exposures of the deposit and no fossils have been reported.

The deposit was examined by Walsh *et al.* (1987) in five trial pits dug along the north-west corner Fig. 40). In pits 2, 3 and 4 it was up to 3.3 m thick (in pit 2) and consisted of greyish-white, pebbly, clayey, coarse-grained sand, the term 'Polcrebo Gravels' of the BGS map and Lexicon being a misnomer. The deposit is generally unbedded except for a few poorly defined lines of pebbles and some colour-banding in the clay matrix. Any original sedimentary features have probably been obscured by post-depositional rotting. The clasts are rounded and subrounded and consist predominantly of vein quartz and tourmalinised Mylor Slate Formation rocks. Very few non-quartz clasts were noted by Walsh *et al.* (1987). Scourse and Furze (1999) thought it probable that the deposit was originally an oligomictic gravel with dominant locally derived granite clasts which have been subsequently broken down by intensive post-depositional rotting. The base of the deposit on growan is not clearly defined and was taken by Walsh *et al.* (1987) as the deepest isolated vein quartz pebble in any pit (succeeded by at least 60 cm of non-pebbly material).

In pit 5, at the western end of the line of section, the deposit and growan wedge out against unweathered granite, the junction being inclined at about 30° ESE. Walsh *et al.* (1987) suggested that this was evidence that the form of the deposit was controlled by a pre-depositional basin excavated in kaolinised granite. There is no direct evidence of age, but the lithological similarity to the Crousa Gravel and indications of intensive sub-tropical weathering, as at Crousa, suggest that the Polcrebo deposit is Paleogene in age.

Neogene Deposits: Miocene

During the Neogene, relative sea levels fell around South-West England and the outline of the British Isles began to resemble that of the present day. There was a cooling trend, which culminated at the start of the succeeding Quaternary with the development of glacial and periglacial conditions (Fig. 1). Neogene deposits are poorly represented in the British Isles, but in south-west England fragmentary deposits of Miocene and Pliocene age are present in Cornwall, although dating evidence for many of the small, isolated deposits is lacking.

On-land Miocene deposits in Britain are very poorly represented. The deposits at St Agnes, Cornwall, described below, are the only Miocene sediments recorded in South-West England. In Derbyshire, the Brassington Formation fills solution cavities in Carboniferous Limestone, and Miocene sediments also occupy solution pipes on Anglesey. Outcrops of gravel and sand in Cornwall, at Trewirgie, Camborne, Porkellis and Pendarves, are also believed to be Miocene, but there is no definite fossil dating evidence. In the Bovey Basin, the Great Plantation and Bovey Heath members of the upper Bovey Formation are undated. They may be Rupelian or younger; a Miocene age cannot be entirely ruled out.

St Agnes

At St Agnes Beacon in Cornwall, sands and clays form an arcuate outcrop wrapping around the eastern, northern and western sides of the Beacon. They have long been recognised since Pryce referred to the 'St Agnes Beds' in 1778. Their age and origin have been the subject of much speculation, and until recently they were considered to be equivalent to the St Erth Formation, resting on a Pliocene marine platform and of Pliocene age. They are now regarded as Miocene in age (Walsh *et al.*, 1987).

The St Agnes deposits are now regarded as consisting of two distinct outliers: the *St Agnes Outlier* which wraps around the northern side of the Beacon; and the *Beacon Cottage Farm Outlier* to the west of the Beacon (Fig. 41). The St Agnes Outlier is included in the ***St Agnes Formation*** and the Beacon Cottage Outlier is included in the Bovey Formation. Although almost contiguous, the deposits have been assigned different ages, the Beacon Cottage Farm deposit (described above) being dated as probably early Eocene (Rupelian) whereas the St Agnes Formation to the north has been dated as Miocene, equivalent to Zone SP9 or younger, based on analysis of pollen samples from carbonaceous clays in the *New Downs Member* (see below) (Walsh *et al.*, 1987).

The St Agnes Formation rests on the 130 m platform of West Cornwall (the Reskajeage Surface) and has an outcrop area of about 1.6 km^2. The deposit is up to about 12.5 m thick and gently inclined (<10^o) northwards. Some sections are still visible in New Downs Sandpits [SW 706 509], but these vary according to the state of the workings; most of the exposures described by earlier authors are currently overgrown.

There was an early recognition by De la Beche (1839) of the tripartite subdivision of the formation into upper and lower sands with an intervening clay unit. He recorded the following section in the St Agnes Formation on the north-east of the Beacon:

Head 3 ft

Yellow sand 2 ft
Brown sand, possibly cross-bedded 11 ft

Light-coloured clay 2 ft
Blue clay 9 ft

Yellow sand 4 ft
White sand 4 ft
Yellow sand 3 ft

Pebbles, resting on an uneven surface of Devonian slate

Walsh *et al.* (1987) examined discontinuous sections in the New Downs Sandpits [SW 706 509] (also known as Doble's Sandpits), together with auger holes in adjacent fields, and confirmed the basic tripartite stratigraphy of de la Beche (1839). They formally designated the deposit as a formation, subdivided into (in ascending order) the Doble, New Downs and Beacon members, summarised below. The outcrops are shown on Figure 41. Coque-Delhuille (1987, fig. 140) described the sequence in detail from exposures in the Doble pits but did not formally name the subdivisions recognised in her figure (Coque-Delhuille, *op. cit.* fig. 140).

- ***Beacon Member***: (3.0 m). Yellow and orange, cross-bedded fine- to medium-grained sand.
- ***New Downs Member***: (3.5 m). Pale grey, micaceous silty clay with sporadic dark grey and brown lignitic clay; locally sandy with isolated vein quartz pebbles.
- ***Doble Member***: (6 m). Yellow or buff, fine-grained

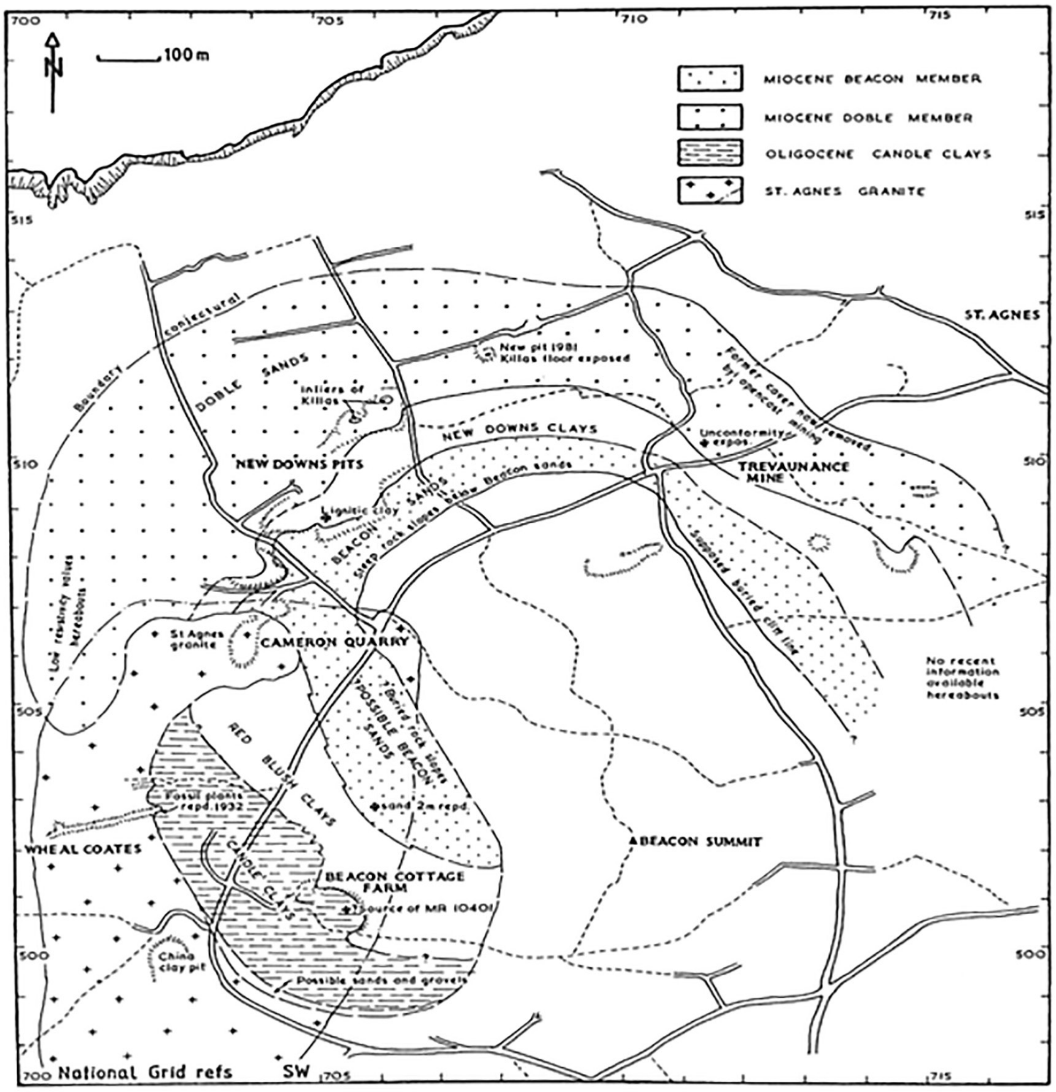

Figure 41. *Geology of the St Agnes and Beacon Cottage Farm outliers. The interpretation of the area between Cameron Quarry and the Beacon is problematical. Resistivity surveys indicate the presence of a thin cover of Cenozoic sediments but thick overlying Head precluded augering. After Walsh* et al. *(1987, fig. 2). Jowsey* et al. *(1992) considered that the St Agnes Outlier and the Beacon Cottage Farm Outlier were not contiguous. Reproduced with permission of the Geological Society of London.*

silty sand with a local basal pebble bed.

The St Agnes Formation rests on Devonian slate (Gramscatho Group: Porthtowan Formation), or the St Agnes granite. The nature of the sub-St Agnes Formation floor has been discussed by Walsh *et al*. (1987). They note that the floor has been exposed in the lower levels of New Downs Pits, where it was apparently sub-horizontal over an area of about 1000 m^2, and in the openworks of Trevaunance Mine [SW 7121 5128]. However, to the south, at the base of the Beacon, it appears that the formation wedges out against a stepped rock wall with an overall gradient of 45° or more. Davies and Kitto (1878) noted a 4.8 m high 'buried sea cliff' on the east side of the Beacon. Its *c*. NNW–SSE trend is similar to that of many strike-slip faults in south-west England and the 'cliff' may be a fault feature. However, Walsh *et al*. (1987) note 'clear evidence of rock cliffs and pinnacles in the New Downs area' and the 'buried sea cliff' east of the Beacon was regarded as a non-faulted junction.

Rapid thickness and facies variations are characteristic of the St Agnes Formation (Walsh *et al*., 1987). The Doble Member is probably the most restricted of the three members and was probably deposited in localized rock basins. It was probably overlapped at the south end of the New Downs Pits. The granite at Cameron Quarry [SW 7038 5065] (Fig. 41) probably projected through the sheet of Doble sands. The Doble Member is reportedly pebbly on the east side of the Beacon. Apart from a small lignitic lens in New Downs Pits (Fig. 41), the New Downs Member is the most laterally persistent and uniform of the three members. Davies and Kitto (1878) distinguished a 'candle clay' from a 'fireclay', the latter apparently restricted to the north and west of the outcrop. Where both types of clay were present, the fireclay was the uppermost of the two. The same authors noted 'candle clay' containing a bed of sand 1.5 m thick south-east of Polberro Mine. Details of the Beacon Member east and west of the New Downs Pits are not known, but the member is considered to overlap older sediments against a rising floor of Devonian rocks (Walsh *et al*. (1987).

Doble Member

The pebble bed at the base of the Doble Member, recorded by Reid and Scrivenor (1906), was not seen by Walsh *et al*. (1987), who noted that the contact with the underlying Devonian rock was marked by a layer of iron-cemented, non-pebbly sand, extending for about 50 m in the floor of the pits. This basal 'hardpan' varies from a few millimetres to 2 m thick, with an average of 0.5 m (Atkinson, 1975). The colour varies from black, through dark blue and brown to yellow. Concentrations of tubular structures up to 2 m long and 0.3 m wide occur in the hardpan and contain unconsolidated yellow sand (Atkinson, 1975). Most of the tubes are subhorizontal and trend 35-215°. The hardpan is Bed 2 of Coque-Delhuille (1987, fig. 140).

Above the basal hardpan, the bulk of the Doble Member consists of yellow or buff (typically 5 YR 6/10) fine-grained silty sand, 5–6 m thick according to Walsh *et al*. 1987 (Beds 3, 4 and 5 of Coque-Delhuille (1987, fig. 140) 3–4.5 m thick). In the upper levels of the member, the sands become pale yellow and there is a gradational junction with the overlying clays of the New Downs Member. Epsilon-type planar cross-bedding is common; individual units reach about 1 m thick, but are mostly thinner. Paleocurrent measurements in the new Downs Pit suggest a sediment source to the north-west, but foreset bedding in the sands of the New Pit (Fig. 41) indicates paleocurrent flow from the south-east.

Grain-size analysis by Walsh *et al.* (1987) and Coque-Delhuille (1987) showed that the Doble sands are well-sorted fine- to medium-grained, with a median between 0.27 and 0.34 mm (Coque-Delhuille, 1987). One sample from 5 m above the base of the member was less well-sorted owing to the inclusion of silt (less than 15 %) and a small proportion of coarse-grained sand (more than 0.6 mm) (Walsh *et al.*, 1987).

The sands are predominantly composed of quartz grains (95-99%) with 1-3% feldspar. Brown or yellow tourmaline is present in all samples at 1 to 3%. The heavy minerals (haematite, tourmaline, zircon, rutile, kyanite, andalusite, topaz and cassiterite) are all of local origin, derived from granites or their metamorphic aureoles.

Walsh *et al.* (1987) carried out scanning electron microscope (SEM) analysis of three samples of Doble Member sand from different levels. The combination of low-medium relief, mainly subrounded and rounded grains and dish-shaped concavities (63 %) was considered strongly indicative of aeolian transport. Post-depositional chemical alteration of grain surfaces would have obliterated any other less frequent surface textures that might have elucidated the transport history.

Coque-Delhuille (1987), however, concluded that a marine origin with secondary aeolian influence was more likely. The proportion of 'blunt-shiny grains' ('émoussés-luisants') always over 30%, was interpreted as evidence for a marine origin, but with secondary aeolian influence. SEM analysis was also considered to suggest a mainly marine origin, but the presence of 'croissant de choc ou V éoliens' (shock or wind crescents) indicated aeolian influence subsequent to marine polishing.

About 1.8 m above the base of the Doble Member, Walsh *et al.* (1987) recorded a 10 cm-thick bed of pebbles and cobbles. Coque-Delhuille (1987) noted a similar bed (Bed 4 in Fig. 42) but recorded as about 3 m above the base of the member. The clasts are of local origin, ranging from large, angular, stained fragments of slate to small, well-rounded pebbles of vein quartz and sandstone. Long-axis trend analysis for 107 elongate pebbles and cobbles showed a clear preferred NW–SE alignment (Walsh *et al.*, 1987, fig. 5).

New Downs Member

The Doble Member passes up into the overlying New Downs Member, which is a pale grey (typically 7.5Y 7/1), almost structureless, silty, locally sandy clay. Coque-Delhuille (1987) measured thicknesses of 2.5–3.0 m (Bed 6 in Coque-Delhuille, 1987, fig. 140); Walsh *et al.* (1987) recorded 3.4 m of the member in boreholes in the New Downs Pits. The base of the member is gradational, but the top is sharply demarcated and may represent a minor erosion surface. Isolated vein quartz pebbles have been recorded in the upper levels of the member. The New Downs Member is generally structureless, but there are locally indications of indistinct bedding which dips uniformly northward at 3–8° Although Walsh *et al.* (1987) noted the absence of burrows and desiccation cracks, Coque-Delhuille (1987) recorded 'numerous traces of burrowing animals', but no further description is given.

Walsh *et al.* (1997) noted early reports of carbonaceous sediments in the New Downs Pits (*e.g.*, Hawkins, 1832). Dewey (1932, field notes) recorded:

> 'dark grey, current-bedded [sic] drab clays... (with) numerous remains of plants, carbonaceous stems, leaves and twigs, but not determinable'.

Dark-grey and brownish lignitic clay (10YR 3/1) was exposed 'about 20 m SE of the drying plant (SW 7049 5088)'. This bed, 22 cm thick, was intermittently exposed in a small drainage channel, but the exposure was not clear enough to determine its relationship to the non-carbonaceous clays, except that it occurs in the upper half of the New Downs Member. The lignitic clay lies about 1.3 m below the base of the Beacon Member.

Grain-size analysis of the New Downs Member (Walsh *et al.*, 1987) shows that it is mainly silt (51.1%) and sand (28.3%), with a relatively small (20.6%) clay fraction. Coque-Delhuille (1987) analysed the mineralogy of the sand fraction, as follows:

At 0.63 mm		**At 0.31 mm**
82%	Quartz	92-94%
7%	Feldspars	3-4%
10%	Contact aureole	1-2%
0%	Tourmaline	1%
1%	Other heavy minerals	1%

X-ray diffraction (XRD) of the clay fraction (Walsh *et al.*, 1987) shows (by mass): 19% kaolinite, 36% mica, 22% quartz, 7% tourmaline and the remainder amorphous.

Beacon Member

In New Downs Pits, Walsh *et al.* (1987) recorded about 3 m of cross-bedded, fine- to medium-grained, very well sorted, yellow and orange sands (7.5YR 6/10) overlying the New Downs Member. The sands were locally iron-cemented, especially above silt beds, and some sections show irregular lenses of green silty sand. Periglacial processes have produced contorted bedding, but where relatively undisturbed, foreset bedding dips to the south-south-east or south. Coque-Delhuille (1987, fig. 140) measured a similar thickness (3 m) of sand (Beds 7, 8, 9 and 13), but Macfadyen (1970) recorded up to 7.3 m of Beacon-type 'brown sand' in the New Downs Pit. Dewey (1932, field notes) recorded the Beacon Sands thinning against a steadily rising floor of Devonian rock.

SEM analysis of two samples from the Beacon Member by Walsh *et al.* (1987) showed surface textures comparable to those from the Doble Member, with mainly rounded to subrounded grains, medium to high relief and ubiquitous dish-shaped concavities (50%). As for the Doble Member these textures were interpreted by Walsh *et al.* (1987) as evidence for an aeolian origin.

Depositional environments

Interpretations of the origin of the St Agnes Formation have varied widely. Walsh *et al.* (1987) considered three possible depositional environments: 1). Marine; 2). Fluvial; and 3). Aeolian.

1. Marine. In favour of a marine origin is the supposed 'buried sea cliff' recorded by Davies and Kitto (1878) on the east side of the Beacon and the presence of basal gravels (possibly beach deposits). The location of the formation on a supposed marine planation surface would support a marine origin, but this surface (the Reskajeage Surface) is now considered to be of subaerial origin.

   Coque-Delhuille (1987) favoured a marine origin for the Doble Member, based on the shape of sand grains and analysis of surface textures by SEM. However, there was also evidence of 'croissant de choc ou V éoliens' (shock or wind crescents) subsequent to 'marine polishing'. This would suggest reworking at some stage of the supposed marine sands by wind. On the other hand, Walsh *et al.* (1987) considered that the grains from both sand members of the St Agnes Formation show 'clear evidence of aeolian action', and 'none of the quartz sand grains from any sample show surface textures normally associated with marine action'. No glauconite, a possible indicator of a marine origin, has been recorded from any sands in the St Agnes Formation. The absence of dinoflagellate cysts in samples from the New Downs Member suggests that that sequence is non-marine.

   The thin pebble beds in the Doble Member were interpreted by Coque-Delhuille (1987) as marine, on the basis that the pebbles show 'un net aplatissement marin' ('a clear marine flattening'), but it is doubtful whether this feature is sufficiently diagnostic of a marine origin. The pebble beds were thought by Walsh *et al.* (1987) to represent a fluvial incursion into the aeolian dune belt.

2. Fluvial. A fluvial explanation for deposition of the St Agnes Formation would envisage river-laid sands (Doble and Beacon members) separated by a flood-plain sequence. In this scenario, the basal pebble bed and pebble beds within the Doble Member would be the product of high-energy fluvial traction flow. However, Walsh *et al.* (1987) argued against a fluvial origin for the following reasons: a) there is no evidence from quartz-grain surface textures for fluvial transport; b) grain-size analysis of the New Downs sediments show them to be 'quite untypical of floodplain deposits'; c) a fluvial interpretation for the St Agnes Formation 'would require a complicated post-Miocene physiographic inversion, for which there is no structural evidence' (Walsh *et al.*, 1987). On the other hand, the presence in the New Downs Member of dark grey clays with plant remains suggests a terrestrial (fluvial) origin.
3. Aeolian. Walsh *et al.* (1987) preferred a model in which the two sand members of the St Agnes Formation were aeolian, with the intervening New Downs Member a 'colluvial slope-wash deposit'. In support of this hypothesis, they noted that the quartz grains in the sands show 'clear evidence of aeolian action'. Coque-Delhuille (1987) also supported an aeolian origin for the Beacon Member, in contrast to the supposed predominantly marine origin for the Doble Member, argued by the same author. SEM analysis showed 'très forte éolisation', with the surface of quartz grains showing numerous fresh traces of wind friction.

   The very well sorted nature of the sands favours an aeolian origin. The sporadic pebble layers in the Doble Member may record minor incursions of streams into sand dunes.

   In the New Downs Member, Walsh *et al.* (1987) noted a mixture of aeolian-type grains, together with edge abrasion, suggesting a period of weathering followed by restricted downslope movement. The grain size of the New Downs Member was considered to be compatible with that of modern subtropical colluvium (Goudie and Bull, 1984).

   Alternatively, the New Downs Member could represent an interdune fluvial incursion.

The present height of the St Agnes Formation at *c.* 131 m OD suggests a pre-uplift sea level of 40 m above present levels (Westaway, 2010) for the Mid-Miocene, assuming a marine origin for the formation. This may be related to elevated sea levels around the Middle Miocene Climatic Optimum (MMCO) (Fig. 1), at around 14–17 Ma (Zachos *et al.*, 2001; Steinthorsdottir *et al.*, 2021). Hart *et al.* (2011, fig. 4) constructed a paleogeography of south-west England based on a sea level of 131 m. This scenario would suggest a widespread inundation of South-West England, including much of Cornwall and South Devon. However, there is no evidence for marine Miocene sediments in these areas. Moreover, as noted above, this model does not take into account the likely amount of post-Miocene uplift that has occurred; Westaway (2010) estimated uplift of 90 m since the MMCO which would indicate a figure of 40 m above present levels for the mid-Miocene, suggesting a much less widespread inundation of South-West England, on the assumption of marine origin.

Samples collected by Walsh *et al.* (1987) from the carbonaceous clays of the New Downs Member have yielded a Miocene pollen assemblage indicating a subtropical Mediterranean climate with a typical European vegetation of conifer forest and mixed woodland and shrub. They noted that the assemblage (Table 4) is similar to the inland conifer forest (*Pinus*-like species, Taxodiaceae, etc.) from upland vegetation and mixed angiosperm and conifer forest perhaps from less elevated surfaces (tricolpates and conifers). In addition, shrubland and heathland type vegetation may be represented by forms such as *Polyvestibulopollenites vestibulum*, *P. versus* and *Erecipites*. The absence of palm pollen may mean that winter temperatures fell below 0 °C, and the absence of dinoflagellate cysts confirms that the lack of marine influence.

Bryophytes: *Stereisporites stereoides*

Ferns: *Laevigatosporites haardti*

Conifers: *Pinus* haploxylon-type. *Pinus* sylvestris-type. *Tsugaepollenites* canadensis-type.

Cedruspollenites. Abiespollenites. Sciadopityspollenites serratus. Sequoiapollenites.

Inaperturopollenites dubius.

Deciduous forest—mixed woodland: *Tricolpopollenites liblarensis. T. microhenrici. T. Henrici.*

T. ipilensis. Trivestibulopollenites betuloides.

Shrub-heath: *versus. Triporopollenites. Porocolpopollenites vestibulum.*

Ericipites.

Table 4. *Dispersed pollen and spore form genera identified from the October 1983 sample from New Downs Pit, St Agnes (Walsh* et al., *1987, table 2). Reproduced with permission of the Geological Society of London*

Seven earlier samples of carbonaceous clay from the New Downs Member proved barren apart from fragments of indeterminable carbonaceous debris about 10–40 µm in size, but an eighth sample collected in April 1983 yielded additionally pollen and spores. A further sample in October 1983 yielded a similar assemblage. At least 19 species were identified. Conifer pollen is most abundant and angiosperm taxa are represented by only one or two specimens.

Comparisons with other northwest European microfloras indicate that the assemblage is of a Neogene age, most likely Miocene, and all the taxa occur in terrestrial sediments of this age. There are no Palaeogene forms, and European Pliocene assemblages do not contain taxa such as *Monocolpopollenites* and *Porocolpopollenites vestibulum*.

Neogene deposits: ?Miocene

Trewirgie

Temporary sections [SW 696 409] at a cricket ground at **Trewirgie**, Redruth, Cornwall exposed sands and gravels. A possible Miocene age has been suggested (Camm and James, 1999). The deposit is situated at about 145 m OD on a spur cut into Devonian rocks (Mylor Slate Formation: Famennian).

Camm and James (1999) identified the following lithological units, shown on Figure 42:

- Unit 1. **Soil**
- Unit 2. **Head** 0.5 m
- Unit 3. **Sand**, well sorted, fine- to medium grained. Occasional vertically-inclined angular clasts of slate in the upper part (probably derived from Unit 2 (Head)). Fractured ferricrete and manganese pan near the base up to 1.2 m
- Unit 4. **Gravel**, with lenses of sand and sandy clay. Clasts of rounded vein quartz, slate, hornfels, rounded clasts of microgranite and a single clast of fine-grained basic igneous rock. Large, rounded cobbles of slate and weathered coarse-grained granite occur scattered through the eastern end of the unit. Unit 6 is a 0.2 m-thick bed of **clay** between units 5 and 4 average 0.5 m
- Unit 5. **Pebbles and sand**, manganese-coated, thin, laterally persistent, overlying an irregular highly weathered surface of Devonian bedrock (Mylor Slate Formation) with a relief of about 0.7 m maximum 0.05 m
- Unit 7. **Slate**. Mylor Slate Formation (Devonian: Famennian).

Camm and James (1999) interpreted the unit (5) of pebbles and sand overlying Devonian bedrock as a possible marine beach gravel. The overlying deposits all show evidence of reworking and cryoturbation and were considered to be soliflucted from higher ground during the Pleistocene. Unit 4 was interpreted as head. The well-sorted sands of unit 3

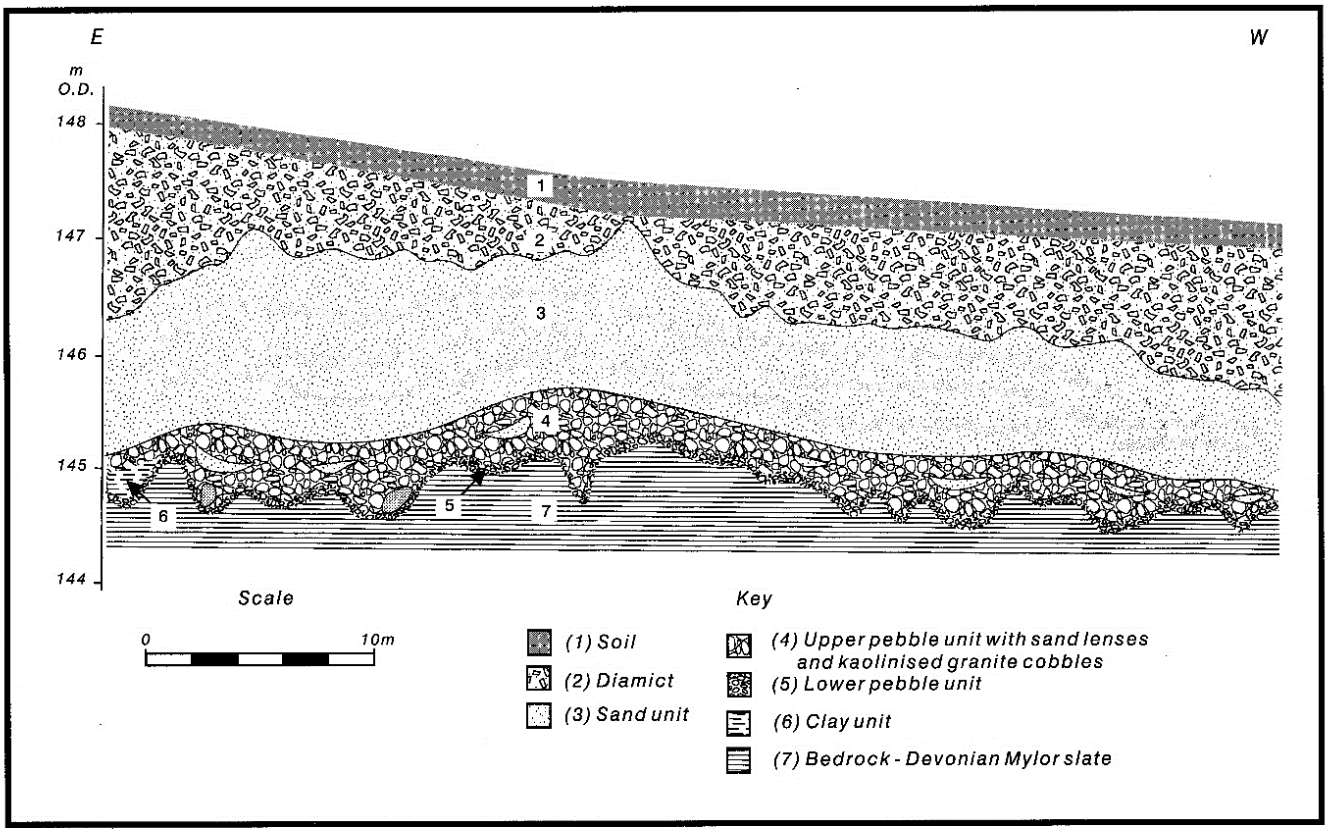

Figure 42. *Cross-section of the Trewirgie deposit, Redruth. After Camm and James (1999, fig. 4).*

are probably aeolian, but the presence of angular clasts of Devonian rock in their upper part suggests that they too have been soliflucted. The source of the sands is conjectural, but Camm and James (1999) noted that the only record of a similar deposit at a comparable height is the Beacon Member of the St Agnes Formation.

The unit (Unit 6) of sandy clay within Unit 4 (Fig. 42) yielded pollen. Camm and James (1999, page 387) noted that:

'The presence of Cedrus pollen in the clay infill of Unit 6, if not reworked, would indicate a pre-early Pliocene age, while the presence of Gramineae pollen and Compositae (Ligulifiora) further suggests a post Oligocene age since they evolved in the Late Oligocene. Hence a Miocene date would therefore be appropriate.'

The pollen assemblage indicated a grassland environment with some evidence for open ground with some wet areas.

Camborne

Camm and James (1999) noted a deposit [SW 6530 3964] at ***Camborne***, about 6 km south-west of Trewirgie, first reported by A.J.J. Goode. An exposure showed 2 m of slaty head resting on 2 m of yellow sand, but bedrock was not seen. The deposit lies at an elevation of about 140 m OD, similar to that of the Trewirgie deposit.

Porkellis

Three small deposits centred on [SW 6870 3430], north-west of ***Porkellis*** village on the Carnmenellis Granite, were discovered during drilling investigations for placer cassiterite (Camm and James, 1999). A basal 2 m-thick cobble bed consists of abundant well-rounded granite cobbles up to 0.2 m across, in a matrix of orange ferruginous clay and silt. The cobble bed was adjacent to a 'cliff-like' erosional feature at an elevation above 130 m OD. The Porkellis deposit was interpreted by Camm and James (1999) as representing possible beach gravels adjacent to a degraded relic cliff line. The deposit was similar to that described from Goss Moor on the St Austell Granite, where beach gravels at about 130 m OD were inferred by Camm and Hosking (1985) to be present adjacent to a degraded cliff line.

Pendarves

Leveridge *et al*. (1990) recorded an exceptional thickness of 30 m of 'superficial deposits' in boreholes at ***Pendarves*** [SW 650 377], near Camborne, Cornwall, apparently preserved against an erosional feature at about 85 m OD. No detailed section is given, but these authors noted that the deposit includes head, and minor sand and gravel and may in part represent a residual Cenozoic deposit.

Neogene Deposits: Pliocene

The only definite marine Paleogene or Neogene deposits in south-west England are those of late Pliocene age located in Cornwall at St Erth [SW 556 352], but additional small outcrops at Splattenridden [SW 535 358 and SW 536 363], Tregurtha Farm [SW 530 317] and Angew Farm [SW 5910 4085] are shown on the BGS Penzance 1:50 000-scale sheet (351/358) and were also included by Goode and Taylor (1988) in the St Erth Beds [Formation]. Additional small deposits at Varfell and Penhallow are of uncertain, possibly Pliocene age (Camm and James, 1999).

St Erth

Seas around the South-West England Peninsula rose in the late Pliocene to deposit the highly fossiliferous ***St Erth Formation***, named from the village of St Erth [SW 556 352] near Hayle, Cornwall. The formation was formerly exposed from about 1834 in pits that produced high-quality foundry moulding sands at an elevation of 30–37 m OD. From about 1881, pits were opened for the working of clays which locally cap the sands and which were used in the construction of a dry dock in Penzance Harbour.

The formation differs from other Cenozoic deposits in the region in yielding from the clays a rich and diverse fauna of molluscs and ostracods, together with benthic and planktonic foraminifera, pollen and spores, and dinoflagellates. Studies of the benthic (Mitchell, 1973) and planktonic foraminifera (Jenkins, 1982; Jenkins *et al*., 1986; Jenkins *et al*., 1989; Roe *et al*., 1999; Hart *et al*., 2026) have indicated a late Pliocene age (*Globorotalia inflata* Zone).

The 'St Erth Sand Pits' were designated in 1986 as a Site of Special Scientific Interest (SSSI) for the sequence of Late Pliocene marine sediments containing an exceptionally diverse fossil fauna, especially macrofossils, as well as evidence for the geomorphological evolution, former sea levels and palaeoenvironments of South-West England. There are no current exposures in the pits.

Whitley (1882) described the deposit as 'tough boulder clay, with marine shells'. The discovery of ice-deposited boulder clay on the Isles of Scilly (Mitchell and Orme, 1967) prompted the re-examination of the St Erth deposit by Mitchell and coworkers. A detailed study of the formation was carried out by Mitchell (1973). The deposits at St Erth have been worked from several pits, all now overgrown, named from north to south Moor Meadow Pit, Trenhayle Pit, Vicarage Pit (north and south) and Harvey's Pit (Fig. 43); the history of the workings has been described by Roe *et al*. (1999).

The north face of the northern Vicarage Pit was excavated for a length of 25 m (Mitchell, 1973) then a trench was dug through the clay thus exposed, into the underlying sand (Fig. 44). Seven detailed sections were recorded, and Figure 45 is based on these. Augering of the sand showed a thickness of more than 4.8 m. The top of the sand was irregular and contained small, rounded pebbles in the top 30 cm. Overlying the sand were up to 4 m of very fossiliferous, brown-weathering, blue marine clay, originally calcareous, and locally sandy. This clay is the source of the rich molluscan and foraminiferal faunas for which St Erth is celebrated. The highest surviving level of the clay is at 35 m OD. The clay is overlain by a variety of head deposits.

The generalised sequence in the northern part of Vicarage Pit [SW 5570 3536 to 5574 3535] can be summarised as follows:

- **Head** — about 2.0 m
- **Sand**, coarse-grained — up to 0.5 m
- **Clay**, leached, marine, highly fossiliferous, with lenses of calcareous brown clay and blue clay — up to 4.0 m
- **Sand**, fine-grained. Very irregular upper contact. Small rounded pebbles in the top 0.3m — about 4.5 m

On the east side of the south Vicarage Pit, Mitchell (1973) cleared a 20 m-long section. The clay was absent in this section, and head rests directly on fine-grained sand. The pit to the south of the Vicarage Pit was first known as 'Harvey's Pit'. Bell (1898) recorded mottled clay which is probably leached shelly clay. The pit was extended eastwards as the 'Cornish Sand Company' Pit'. Milner (1922) recorded 0.6–1.2 m of head and soil resting on 1.2–7.2 m of sand, on an eroded floor of Devonian slate with an elvan dyke.

Heavy minerals in the sands of the St Erth Formation were studied by Boswell (1923), Milner (1922) and Groves (1931). Boswell suggested a derivation mainly from granites. Groves supported Milner's analysis and suggested an easterly source. Detailed mineralogical and grain-size analyses of the St Erth sands are given in Mitchell (1973, p. 12–18).

Mitchell (1973) noted that the St Erth Formation rests on a subaerially eroded rock surface at an elevation of 30–37 m OD, but Roe *et al*. (1999) considered that the clays and associated sands appear to rest on erosion surfaces that are about 16 and 28 m above OD. The higher level was considered to have been cut in the Early Pliocene (about 3–4 Ma) while the lower Late Pliocene level (about 2 Ma) suggests that sea level during sequence TB3/3.8 (Haq *et al*., 1987, 1988) was about at 35–45 m above present levels. This surface is at a considerably lower level than the supposed Pliocene marine platform at *c*. 130 m OD, widely present in West Cornwall, which Walsh *et al*. (1999) considered more likely to be part of an early Miocene subaerial surface.

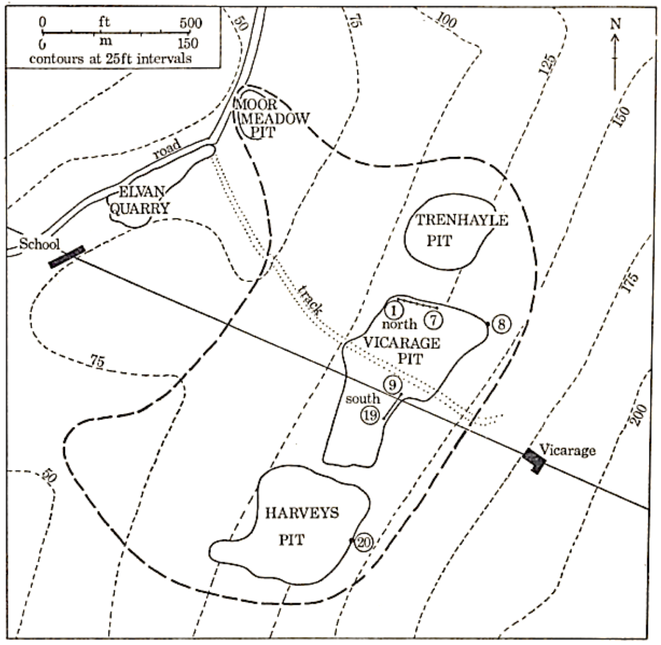

Figure 43. *Location of the sand pits in the St Erth Formation. After Mitchell (1973, fig. 5). Reproduced with permission of the Royal Society.*

The St Erth Formation may have originated as a series of coastal sand dunes which were overwhelmed by beach sand deposited by rising seas. Deposition then continued in shallow lagoons, which deepened and were occupied by an abundant fauna, with the clay being laid down in perhaps about 10 m of water (Mitchell, 1973). Hart *et al*. (2011, 2026), however, considered this estimate too shallow, and the relatively rare planktic foraminifera are shallow-water species normally associated with waters <50 m deep.

Palynological analysis (Head, 1993) suggests that the marine clays at St Erth were deposited in the warm shallow waters of an inlet or embayment during a probable high stand in sea level. The scarcity of planktic foraminifera suggest a lack of open marine waters more than 50 m deep (Hart *et al*., 2011). Palaeotemperatures were in the range of 10–18 °C, based on stable isotope analysis of the planktic foraminifera (Jenkins, 1982).

Based on the present elevation of the sub-St Erth Formation surface at 16–28 m OD, combined with an estimated water depth of 50 m, Hart *et al*. (2011, 2026) suggested that the Late Pliocene sea level during deposition of the formation

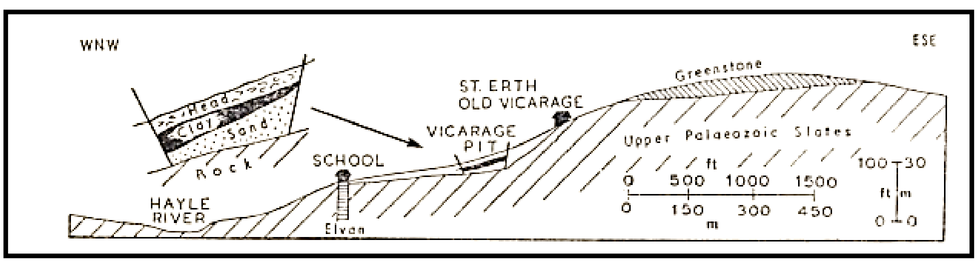

Figure 44. *Cross-section through the Vicarage Pit and surrounding area. After Mitchell (1973, fig. 2). Reproduced with permission of the Royal Society.*

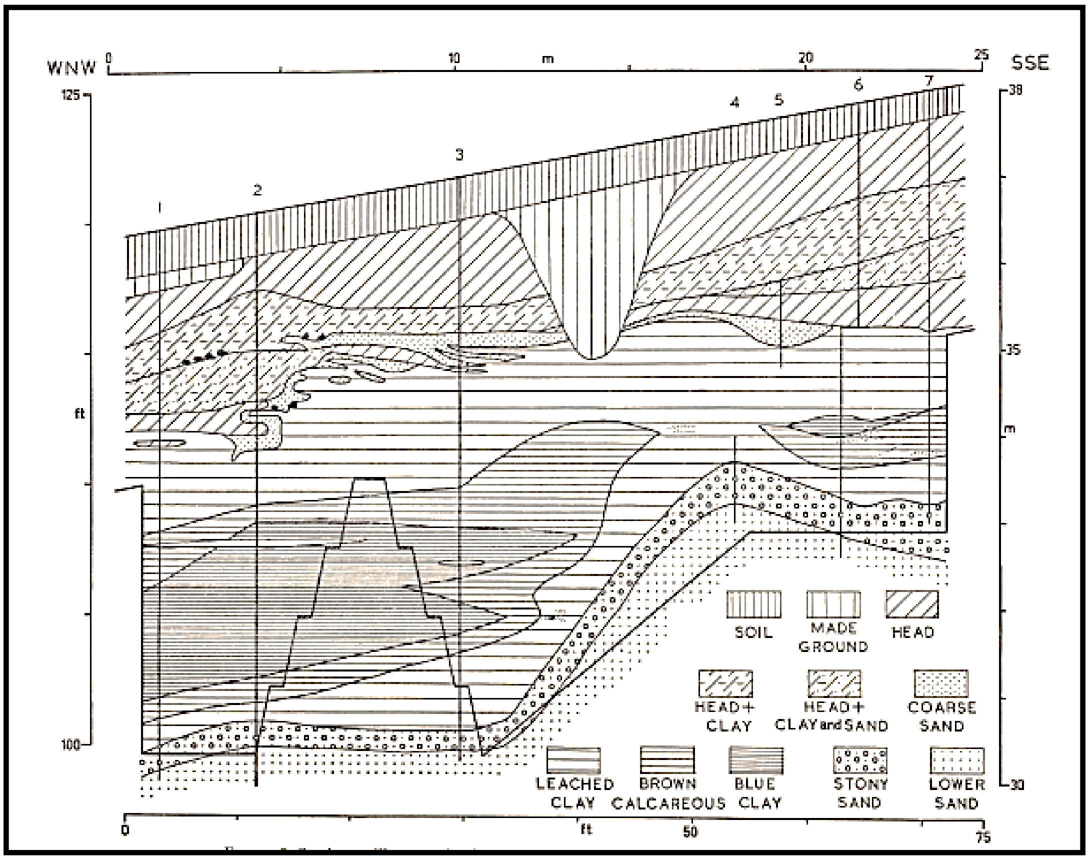

Figure 45. *Section through the St Erth Formation in the northern part of the Vicarage Pit. After Mitchell (1973, fig. 7). Reproduced with permission of the Royal Society.*

may have been between 66 and 78 m above that of today. A figure of 70 m, at the lower end of this range, was indicated by the palynomorph evidence (Head, 1993, 1999). A map plotted using this sea level value (Hart *et al.*, 2011, fig. 3) shows South-West England with a very indented coastline with several islands adjacent to the mainland. In such a scenario, land would have been near enough to provide the mixed palynological assemblage recorded by Head (1993). However, these calculations do not take into account the subsequent uplift of south-west England (Westaway, 2010). An estimated post-Early Pleistocene uplift of 55 m in west Cornwall suggests that sea level at the time of deposition of the St Erth Formation was in fact 25 m above present-day levels.

- **Molluscs**. The molluscan fossils in the clays from St Erth (selected examples are illustrated in Fig. 46) were first noted by Whitley (1882) who described 10 species. Kendall and Bell (1886) described two further sections and listed 72 species of mollusc. McMillan (*in* Mitchell, 1973) identified 55 marine species (35 of gastropods and 20 of bivalves), and one species of freshwater bivalve (*Pisidium henslowanum*). Full lists are given in Mitchell (1973).
- **Planktic foraminifera**, represented by a limited number of simple globigerine taxa are fairly scarce at St Erth, but provide the most precise dating for the formation. Jenkins *et al*. (1986) described 15 species of planktic foraminifera and placed the age of the fauna in the *Globorotalia inflata* Zone, Late Pliocene, between 2.09 and 2.0 Ma.
- **Benthic foraminifera**. The foraminifera in the marine clays at St Erth were first studied by F.W. Millett in a series of papers between 1886 and 1902; 138 species and varieties were listed. Margarel (*in* Mitchell, 1973) identified over 100 species of benthic foraminifera,

Figure 46. *Molluscan fossils from the clay unit of the St Erth Formation (Pliocene). Scale bar: 1 cm. Collections of fossils from St Erth are on display in the Royal Cornwall Museum, Truro. (Photograph by Cornwall Geoconservation Group).*

mostly belonging to the families of Miliolidae, Glandulinidae, Discorbidae and Elphidiidae, but very few species were common. The characteristic species of the deposit are *Quinqueloculina cliarens*, *Q. seminula*, *Monspeliensina* sp., *Ammonia* sp., and *Faujasina subrotunda*. Agglutinating forms were represented only by a single species, *Textularia deperdita*. The Lagenidae and the Glandulinidae are represented by numerous species, and the most frequent forms were *Lagena sulcata*, *Fissurina lucida*, *F. orbignyana*, *Oolina lineata* and *O. squamosa*. *F. cornubiensis* is a form that is, apparently, restricted to St Erth. Margarel (2023) has provided a monographic treatment of the Lagenidae, some of which came from St Erth.

- **Dinoflagellates**. Dinoflagellate cysts were first reported by Watts (*in* Mitchell, 1965). Head (1993) reported a moderately diverse assemblage of 21 taxa. An updated list was given by Head (*in* Scourse and Furze, 1999).
- **Ascidian spicules**. Messenger *et al*. (2005) recorded, and illustrated, well-preserved small, spinose, calcareous microfossils of uncertain affinity, found in the 250 m size fraction. They were previously present in samples collected by Millett but not described in the literature. At first sight they are comparable to bolboformids (though actually much younger than 'normal' bolboformids) or to the calcareous cysts of dinoflagellates, or to some other unidentified fossil grouping. In a subsequent investigation, Hart *et al*. (2026) have now identified these microfossils as the spicules of ascidians ('sea squirts').
- **Pollen and spores**. Mitchell (1973) noted that the content of macroscopic and microscopic plant debris in the St Erth clay was very small, and mostly in very poor condition. Of 2500 pollen grains counted, 58% was tree pollen, 21% Ericales, 17% Chenopodiaceae, 2% Gramineae, 1% Cyperaceae, and all others 1%. The following identifications (many tentative), and associated environments were made, variously based on achene, bud, caryopsis, calyx, colony, fruit-stone, megaspore, oospore, pollen, seed, spore, thorn, or utricle.

- Estuary and salt-marsh. Evidence comes from the presence of *Armeria* sp., Chenopodiaceae and *Zostera noltii* (or *Z. noltei*). No complete fruits of *Z. noltii* were recorded, but there were many fragments, representing at least 20 fruits. In the British Isles today (including in Cornwall), *Z. noltii* is an inter-tidal form of seagrass. Pollen of Chenopodiaceae indicates saltmarsh in the vicinity, and the *Armeria* may also have grown in a salt-marsh.
- Fresh water. *Chara* sp., *Pediastrum* sp., *Potamogeton* sp., *Typha* sp.
- Damp soil. Cyperaceae, *Filipendula* sp., *Juncus* aff. *Balticus*, *Selaginella selaginoides*
- Woodland and dry soil. *Alnus* sp., *Artemisia* sp., *Rubus* cf. *idaeus*, *Corylus* sp., cf. *Cerastium* sp., *Spergula* sp., *Ilex* sp., Compositae, *Urtica* cf. *dioica*, *Salix* sp., cf. *Draba* sp., *Ulmus* sp., Gramineae, *Hedera* sp., *Ranunculus* cf. *flammula*. *Corylus* and *Alnus* were the most prominent of the deciduous trees in the vicinity with *Salix* and *Ulmus* also present, and *Ilex* and *Hedera* less common. The shrubs and herbs are wide-ranging taxa.
- Coniferous woodland, heath and bog. *Abies* sp., *Calluna* sp., *Sphagnum* sp., *Betula* sp., *Empetrum* sp., *Picea* sp., *Erica* cf. *tetralix*, aff. *Adiantum* sp., *Pinus* sp., *Erica* sp., *Osmunda* cf. *regalis*, *Tsuga* sp., cf. *Vaccinium* sp., *Pteridium* sp. *Pinus* is the dominant pollen (47% of total pollen; 81% of all tree pollen) and Ericales 21% of all pollen. *Empetrum* and *Erica* were represented among the Ericales pollen, but preservation was poor. Amongst other conifers represented by pollen are *Picea* and *Tsuga*, and some damaged grains suggested Cupressineae and Taxus. Four leaves and 15 leaf fragments of heather were clearly *Erica*, possibly *tetralix*. *Sphagnum* was represented by some leaf-fragments and spores, and unidentified spores of other mosses. Ferns were represented by spores of type, spores of regalis-type *Osmunda*, and spores of *Pteridium*.

Mitchell (1973, p. 33) summarises, as follows:

> 'If there were sand dunes or other sandy deposits in the vicinity of the site as the sedimentological report suggests, there will have been sandy soils, and these may well have developed podsols with mor surfaces beneath pine and occasional other coniferous trees and heathers in the field layer. This mor will have been full of carbonized plant debris, damaged pollen of local origin and fungal sclerotia, and when sea level rose, allowing clay to be deposited on top of sand, the waves will have eroded the soil, and its contained vegetable debris will have been secondarily deposited in the clay. Fossils of such provenance dominate the plant list, which merely indicates that there was a conifer-heath association in the immediate vicinity of the site, and does not give any general picture of the surrounding countryside as a whole. None the less the total absence of the pollen of such late Pliocene forms as *Sequoia*, *Taxodium*, *Sciadopitys*, *Liquidambar* and *Nyssa* is remarkable.'

- **Ostracods**. Whatley (*in* Mitchell, 1973) reported briefly on ostracods from the St Erth Formation and noted that as many as 100 species may be represented. The fauna includes the following forms: *Aurila convexa*, *Cnestocythere truncata* (Reuss), *Cytheropteron datum*, *Leptocythere pellucida* and three other species, *Loxoconcha elliptica, L. rhomboidei*, *Neocytherideis complicata*, *Paracytheridea triquetra*, *Paradoxostoma*, 3 spp. *Semicytherura*, 5 spp. Maybury and Whatley (1986) and Wood *et al*. (2011) reported in more detail on the ostracod fauna, with 378 species representing the most diverse assemblage described from a single deposit. The overall aspect is that of a warm-water environment. The high diversity may be explained by favourable preservation, the possible mixing of warm and slightly cooler-water species, a variation in salinity, the wide variety of available niches and considerable allopatric speciation.
- **Other animal fossils**. Mitchell (1973) compiled a list of other animal fossils recorded from the St Erth formation, as follows (the nomenclature for older records may be outdated):
- PORIFERA: *Cliona* sp., *Leucandra caminus, Leuconia Johnstonii*. COELENTERATA: *Alcyonaria* sp., *Melobesia* sp. BRYOZOA: *Cellaria crassa*, *Hornera striata*, *Lepralia pallasiana*, *L.* (*Microporella*), *L. violacea*, *Melicerata Charlesworthii*, *Pustulopora clavate*. *ANNELIDA: Eunicidae*. CRUSTACEA: *Balanus* sp. (? *bisulcatus*), *Carcinus* sp., *Maenas* sp., *Gonoplax rhomboides*, *Macropipus* cf. *puber*, *Maia squinado*, *Portunus corrugatus*, *P. holsatus*, *P. marmoreus*, *P. pusillus*, *Xantho floridus*. ECHINODERMATA: *Cucumaria dubiosa*, *Echinus esculentus*, *E. etheridgeii*, *Spatangus purpureus*. TUNICATA: *Leptoclinum tenue*. PISCES: *Anarrhicas lupus*, *Galeus canis*. There are also various unidentified bones, vertebrae, jaws and otoliths (fish stato-acoustic organs).

Neogene Deposits: ?Pliocene

Wilson (1975) and Goode and Taylor (1988) mapped and described two closely adjacent small outcrops at

Splattenridden [SW 535 358 and SW 536 363], about 2 km north-west of St Agnes, which they included in the St Erth Formation. In the southern outcrop, surface debris forming bands parallel to the contours of the hill slope indicates that the lowest beds consist of gravels with locally-derived pebbles, passing upwards into pebbly sandstone and sandstone. Grain-size analysis of the sandstones suggests an upward passage from alluvial deposits into beach sands.

Pebble and cobble gravel, and coarse-grained and pebbly sandstones with a ferruginous cement, occur as surface debris on the northern outcrop. The gravel consists of locally-derived rocks, including granite, and occupies the western and northern part of the outcrop while coarse-grained sandstones and pebbly sandstones are present over the south-eastern part. The Splattenridden sediments were correlated by Goode and Taylor (1988) with the pebbly deposits and sands at St Erth and similarly indicate a marine transgression.

The deposits at **Tregurtha Farm** [SW 530 317] about 4 km south-west of St Agnes, were attributed by Goode and Taylor (1988) to the St Erth Formation. A 1901 shaft section [SW 5274 3165] showed up to 6 m of 'stiff brown clay'. A generalised borehole section [SW 5300 3169] showed:

- **Head** 2.30 m

St Erth Formation
- **Clay**, sandy, and **sand** 1.3 m
- **Clay** (possibly cryoturbated) with some sand and silt; locally laminated 3.1 m
- **Sand**, coarse-grained, with fine-grained sand and clay 0.8 m
- **Gravel and sand**, angular and rounded, with silty matrix, passing down into coarse-grained sand 1.0 m
- **Sand**, coarse- and medium-grained, with some fine gravel 2.20 m

Another borehole section [SW 5242 3167] showed:

- **Head** 2.0 m

St Erth Formation
- **Sand**, fine- and medium-grained, with clay laminae 3.95 m
- **Sand**, fine- and medium-grained, micaceous 0.5 m
- **Sand** with clay laminae 0.15 m
- **Sand**, fine- and medium-grained, micaceous, becoming clayey downwards 0.5 m
- **Clay** with silt and sand laminae 3.65 m
- **Sand**, coarse-grained, clayey, ferruginous, with some gravel 0.4 m

Goode and Taylor (1988) reported that many of the medium- and coarse-grained sand grains were well rounded and polished; a marine origin was supported by the sparse presence of glauconite. However, at the base of the Tregurtha Farm succession the coarsest material was poorly sorted and interpreted as fluviatile; rounded grains with frosted surfaces near the base of the section may indicate aeolian influence.

The succession resembles that at St Erth in passing upwards from coarse-grained sand and gravel into clays and fine-grained sands. No fossils were reported from either section.

At **Angew Farm** [SW 5910 4085], Gwithian, 2.13 m of 'buff clay' and 3.05 m of 'candle clay' were recorded in 1906 from a well [SW 5910 4085]. On the basis of its lithology and height of about 45 m OD, Goode and Taylor (1988) included the deposit in the St Erth Formation.

Near **Varfell Farm**, Penzance, two test pits [SW 505 330] on either side of the A30 road showed rounded cobble and sands just above 25 m OD.

The section in the pit east of the A30 road was:

- **Soil** 0.3 m
- **Head**, angular, subangular and rounded cobbles in a clay matrix 2.8 m
- Sand, buff, coarse-grained 0.6 m
- **Gravel and sand**, ferruginous and manganiferous, dark brown to black, with well-rounded clasts up to 0.15 m of hornfels, metadolerite and rare granite 0.2 m seen

The Varfell deposit lies at an elevation just above 25 m OD. Camm and James (1999) regarded it as a littoral deposit situated at similar elevation to the Pliocene St Erth Formation deposits at Splattenridden and Tregurtha Farm.

At **Penhallow** [SW 769 511] about 5 km east of St Agnes, Leveridge *et al*. (1990) mapped a small area of gravel-rich soil with pebbles and cobbles of locally-derived sandstone, vein quartz and exotic quartzite and mica schist. The deposit lay at a height of between 45 and 50 m above OD and was interpreted as a Cenozoic deposit on the basis that it occurs at a similar height to the late Pliocene St Erth Formation and may be of the same age as that formation.

Acknowledgments

This account is an updated version of unpublished drafts for: 1. A proposal (1994–2002) for a 2nd edition of the *Geology of Devon* book (first published in 1982 by the University of Exeter Press); 2. A proposal (2008–2017) for a new (5th) edition of the British Geological Survey *British Regional Geology* guide for South-West England; and 3. A renewed proposal (2017–2023) for a 2nd edition of the *Geology of Devon* book. We have taken this opportunity to considerably expand and update our original accounts. Some of the results relating to the Bovey Basin have been published in an article in *Geology Today* (Edwards and Freshney, 2023), and these have been incorporated for completeness in the present study.

We thank Fred Locke of Imerys who has been most supportive, facilitating access to Newbridge/Twinyeo Pit (Bovey Basin) and providing many images, borehole logs and samples relating to the geology of the Bovey Basin. Gordon Witte and Chrisha Calunod of Sibelco guided us on a visit to Southacre Pit (Bovey Basin) and provided invaluable additional information and images. Dirk Knaust of Equinor ASA is thanked for examining images of the trace fossils from the Newbridge/Twinyeo Pit and providing his expert opinion on their origin.

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