

A NEW LOOK AT THE POST-VARISCAN EVOLUTION OF SOUTH-WEST ENGLAND

JOHN C. W. COPE



Cope, J.C.W. 2004. A new look at the post-Variscan evolution of south-west England. *Geoscience in south-west England*, **11**, 00-00.

The post-Variscan history of south-west England may be pieced together by using evidence provided by a series of outliers of rocks that indicate former extensive outcrops, and from derived materials in coarse clastic rocks. Other evidence may be deduced from the outcrop pattern of the area, that indicates areas of extensive post-Variscan folding and faulting; these are of various discrete ages. Offshore, extensive outcrops of Mesozoic and Cenozoic sediments are preserved and from their structure and disposition, further indications of the missing cover of south-west England emerge. The offshore outcrops often preserve relatively complete successions that demonstrate that south-west England has been significantly exhumed at various stages in its post-Variscan history and affected by the Late Cimmerian, Laramide and Alpine movements. Offshore magnetic data indicate a large positive gravity anomaly to the immediate northwest of Devon; its source is a large Palaeogene basaltic intrusion that must have impacted upon the adjacent areas, resulting in new drainage directions.

*Department of Geology, National Museum of Wales, Cathays Park, Cardiff, CF10 3NP, U.K.
(E-mail: John.cope@nmgw.ac.uk).*

INTRODUCTION

South-west England has a geology that is unique in the United Kingdom. Not only are the Devonian rocks largely in marine facies, but the succeeding Carboniferous rocks are in deeper water facies than their correlatives farther north. The effects of the Variscan orogeny are more profound in south-west England than elsewhere in the United Kingdom and the overlying Permian and Triassic red-bed sequence provides the best exposures of these rocks in the UK. Tantalising glimpses of the peninsula's post-Triassic history are provided by small exposures of Cretaceous, Palaeogene and Neogene rocks in a series of small outliers.

It is now recognised that, following the Variscan orogenic episode and the emplacement of the granites, there have been several periods when the Cornubian peninsula has received significant sedimentary cover, but such episodes have been interspersed with intervals of tectonic activity including uplift, strike-slip faulting and considerable erosion. In common with other western parts of Britain the area underwent major Palaeogene inversion and exhumation that largely stripped off its veneer of Mesozoic sediments (Roberts, 1989).

Examination of the geological map of the area that encompasses the offshore geology (British Geological Survey, 1991) shows that the onshore area has been significantly exhumed when compared to the offshore areas, which are dominated by Cretaceous or younger rocks. But even offshore there has been significant exhumation, as demonstrated, for example, by over-compaction of the sediments. Hillis (1995) showed that much of the offshore Chalk exhibited over-compaction suggesting that it had been exhumed by some 1 – 1.2 km; similar figures seem likely for some, at least, of the onshore area. This paper attempts to reconstruct what the pre-exhumation cover may have been, its thickness, and its erosional history.

SW ENGLAND AT THE END OF THE VARISCAN CONVERGENCE

By the end of the Variscan orogenic episode, south-west England had been folded and thrust into a series of E-W oriented folds and thrusts; at various points these were cut by NW-SE

trending fault systems. The surface geology consisted entirely of Devonian and Carboniferous rocks; the former being in all probability underlain directly by a Neoproterozoic basement of low grade schists and volcanic rocks (Cope, 1988; Cope and Bassett, 1987). The development of these Variscan structures was to have a profound affect on sedimentation and tectonics throughout the Permian and the Mesozoic. Initially the post-orogenic sedimentary basins that were formed in the initial phase of post-tectonic extension would have been aligned in intermontane troughs whose margins were in large measure delineated by fold- or fault-defined topographic lows. Structural highs, on the other hand provided the initial sediment sources; these highs were progressively overlapped during the Permian and Mesozoic. Reactivation of Variscan thrusts has been documented extensively in offshore areas. For example, in the Bristol Channel, the Central Bristol Channel Fault Zone is a reactivation of a Variscan thrust (Brooks *et al.*, 1988). In the Western Approaches Basin Hillis and Chapman (1992) found that the structural trends of the Permian and Mesozoic basins paralleled those of the Variscan basement and they could identify where basin development ensued from posthumous reactivation of Variscan thrusts in the Late Jurassic and Early Cretaceous. It is therefore important to recognise the nature of the Variscan basement to understand the development of the post-Variscan geology which overlies it (Figure 1).

PERMIAN AND TRIASSIC

The granites of Cornubia are included here, as these late Variscan intrusions have been dated as lying around the Carboniferous-Permian boundary. The granite bosses dominate the peninsula and extend from Dartmoor in the east, *via* the Land's End granite to the Isles of Scilly and form part of a single batholith. Farther to the west is the granite of Haig Fras that comprises a separate batholith.

The generation and emplacement of the granites may in part be related to the same post-Variscan extensional episode that generated the early Permian sedimentary basins. The initial basins would have been predominantly intermontane basins and the earliest sediments within them could have been of

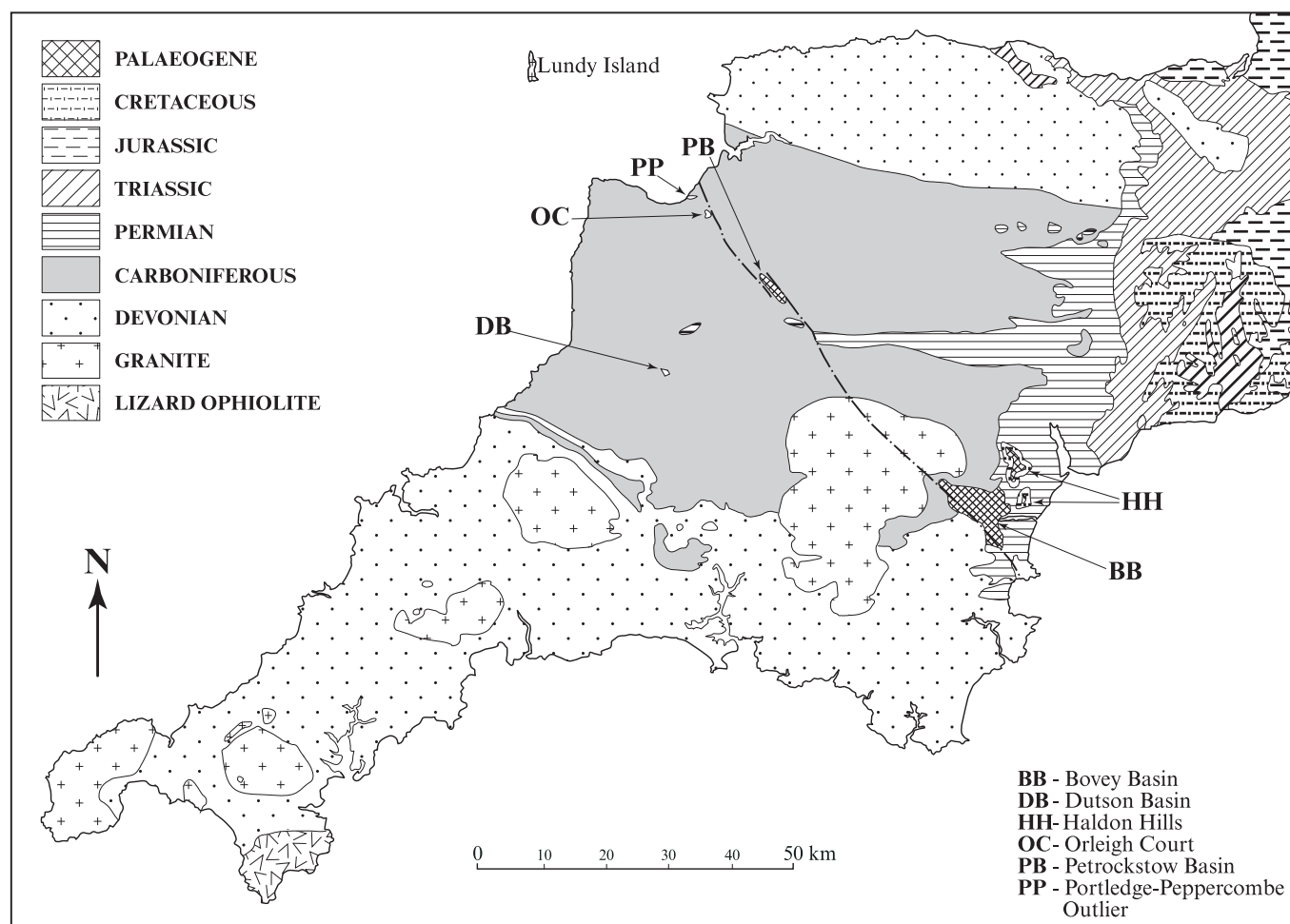


Figure 1. Geological map of south-west England indicating the position of smaller outcrops referred to in the text.

latest Carboniferous (Stephanian) age. However, larger basins, such as the offshore Plymouth Bay Basin, may incorporate some early Permian sediments. Many of these early-formed basins were probably lost to erosion early on as progressive uplift ensuing from the granite emplacement continued. One notable exception to this, the Crediton Trough, has been preserved; its preservation may be due to its position being just to the north of the influence of major uplift from Dartmoor.

This uplift caused rapid erosion above the granites and their early exhumation. Thus, there is evidence that Dartmoor, at least, was partially unroofed within the latter part of the Permian Period, as volcanic clasts from Upper Permian breccias appear to have been derived from a granitic magma of Dartmoor affinity (Awad *et al.*, 1996). The extension of the Early Permian gave way in the mid-Permian to crustal shortening and strike-slip faulting (Shail and Alexander, 1997). The granites are connected to form a single batholith and the occurrence of this relatively light crustal material along the length of the peninsula must have played a significant role in the post-Variscan history of Cornubia, buoying up the spine of the region.

The Culm tract of North Cornwall and central Devon shows outcrops of Permian rocks, contiguous with the main outcrop, running from the east Devon coast northwards towards the Bristol Channel. Further westwards extend a series of outliers of Permian rocks, the most westerly of which is on the shores of Barnstaple Bay in the Portledge-Peppercombe outlier (Figure 1). This outlier was the subject of study by Burley and Cornford (1998) who showed that formation of its cements occurred at some 70° C, implying that cementation took place under a cover some 1 km thick. The offshore map (BGS, 1991) shows that the whole of Cornubia is surrounded by Permian and Triassic

rocks, though in some areas these have been overstepped by Lower or Upper Cretaceous rocks and do not crop out on the sea-bed. Small outliers of Permian breccias occur in east Cornwall associated with early Permian rhyolites in the Cawsand area, and farther to the east around Withnoe; these testify to the former extension of the Permian rocks well to the north of their present offshore occurrence. Outside of these areas where former extension of the Permian outcrop can justifiably be extrapolated, there is significant reddening of the Devonian-Carboniferous Variscan basement in many areas (noted already by De la Beche, 1839), suggesting that the Permian and Triassic outcrop was formerly more extensive.

Some considerable insight into the likely former extent of Permian rocks over Cornubia may be gained by looking at the outcrop pattern of the Permian rocks over other areas of England. A relevant example is the Cheshire Basin, which persisted as a basinal area through Triassic times and probably also through much of the Jurassic (Cope, 1998). Here the Permian outcrop is largely confined to the northern edge of the basin. Its outcrop is partially concealed by overlapping Sherwood Sandstone Group Triassic sediments and, significantly, there are few outliers of Permian rocks on the underlying Carboniferous rocks of the area. Those that do exist are small and close to the existing Permian outcrop. The Cheshire Basin demonstrates one of the characteristic features of the distribution and extent of Permian and Triassic rocks of England: that Permian outcrops are of limited extent when compared to those of the overlying Triassic and are frequently overlapped by them. Within the Triassic, the Sherwood Sandstone Group is often overlapped by the Mercia Mudstone Group, so that the latter often oversteps directly onto the eroded Variscan basement, as in the Mendip Hills or in South Wales.

Thus, it is unusual in England to find a series of Permian outliers extending any distance from the principal outcrops and this implies that the Permian cover of the Culm tract of central Cornubia was formerly far more extensive than that preserved at present. The corollary of this, in the context of the regional geology of Britain, is that there was formerly an extensive Triassic cover over the area too. The Triassic Sherwood Sandstone Formation could have been expected to have overlapped the Permian outcrop, onlapping farther onto the Variscan basement and, in turn, this would have been overlapped by the Mercia Mudstone Group which may have overstepped a considerable distance onto the basement. These conclusions are at odds with those of most recent Permian and Triassic palaeogeographical reconstructions of the area (e.g. Smith and Taylor, 1999; Warrington and Ivimey-Cook, 1999), but seem inescapable. They imply that much of the Cornubian peninsula, from Exmoor southwards, had an extensive red bed cover. That Permo-Triassic red-bed sediments were formerly far more extensive than the present outcrops would suggest, is supported by independent evidence provided by a series of N-S veins with associated mineralisation within the area; these are of Mid - Late Triassic age (Scrivener *et al.*, 1994).

Viewed in a wider context, during Permian and Triassic times, Cornubia was essentially an uplifted area lying between the basinal areas of the Bristol Channel Basin (Brooks and Al Saadi, 1977), that extends westwards into the South Celtic Sea Basin, and the Plymouth Bay Basin (Evans, 1990). Basinal extension during the Permian and Triassic periods produced a series of N-S fractures that cut across the E-W trending metallic sulphide ore veins of Cornwall and Devon. Shepherd and Scrivener (1987) were able to determine, from evidence provided by fluid inclusion analyses and REE analyses of the host fluorites, that the fluids invading these N-S veins were low temperature brines derived from the nearby basinal areas. Scrivener *et al.* (1994) dated this mineralisation by selecting for analysis samples from veins in the Tamar Valley region, as they were relatively remote from the Cornubian granites. They concluded that the mineralisation took place at 236 ± 3 Ma; this places the event just below the Ladinian-Carnian stage boundary of the Middle and Upper Triassic. Scrivener *et al.* (1989) postulated that the metallic minerals were derived, at least in part, from stratiform metalliferous Devonian and Carboniferous host rocks, and consideration of the Permian and Triassic succession of the whole region suggested to Scrivener *et al.* (1994) that the earliest Triassic Aylesbeare Group mudstones, lying above permeable Permian sandstones, would have prevented further upward migration of the mineralising fluids. These veins are widespread beyond the present boundaries of the Permian and Triassic sediments and their distribution over significant parts of the outcrop of Devonian and Carboniferous rocks of the area provides strong support for a former extensive Permian and Triassic cover.

Onshore, the thickest development of subsequently eroded Permian and Triassic rocks is likely to have been over what is now the Culm tract of North Cornwall and central Devon. There, away from the buoyant granite masses, accommodation space would have been more readily provided within any basins. How thick these sediments were over north Devon is more conjectural. Within the Bristol Channel, borehole evidence suggests that Permian rocks may well be developed in the axial part of the basin. Whittaker (1985, map 4) showed an area of Permian rocks more than 400 m thick in the area extending into the Bristol Channel from the onshore region of the Brent Knoll Basin; thus Permian rocks are present in some thickness in at least the eastern part of the Bristol Channel Basin. Within this basin, overlap of the Permian rocks by the Sherwood Sandstone Formation seems likely; in boreholes around Brent Knoll, Whittaker (1985, map 6) recorded more than 100 m of the Sherwood Sandstone Group. On the north side of the Bristol Channel Basin post-Variscan sedimentation did not resume until the late Triassic, so that the Mercia Mudstone Group is seen to rest directly on an eroded surface principally of Carboniferous rocks, but in some places on Old

Red Sandstone and locally, as around Cardiff, on Silurian rocks. On the west Somerset coast, Whittaker (1985, map 8) recorded a maximum of over 600 m of Mercia Mudstone Group rocks in the axial region of the syncline extending westwards into the Bristol Channel. North Devon lies therefore between the Bristol Channel and central Devon, two essentially basinal areas where the succession is likely to have been thicker, and may thus have received a more attenuated Permian and Triassic succession, perhaps similar to that of South Wales. It is interesting to note here that this distribution suggests that sedimentation patterns were structurally controlled to produce E-W trending basinal areas, suggesting that the Variscan basement was playing an active role, perhaps through posthumous movement along Variscan faults. Such movement has been demonstrated in the inner Bristol Channel by Miliorizos *et al.* (2004).

JURASSIC

The marine transgression that heralded the Jurassic Period commenced in latest Triassic Penarth Group times. Sea-level rise took place gradually, with landmasses being progressively inundated. The London-Brabant landmass shows progressive onlap of its margins during the earliest Jurassic (Donovan *et al.*, 1979) so that, for example, at the western end of that landmass in the Oxford area, the Lower Pliensbachian Jamesoni Zone rests directly on the Old Red Sandstone (Sumbler, 1996, fig. 10). However, the area remained essentially land through most of the Jurassic (Figure 2). In the Vale of Glamorgan and in the Mendip Hills littoral facies were developed around an archipelago of islands that display their progressive inundation during the earliest Jurassic (Trueman, 1922) although it was not until the late Bajocian that all the Carboniferous Limestone of the Mendips was inundated. What is clear about looking at the distribution of Jurassic rocks around Britain is that basinal successions are frequently developed where there were Triassic basinal successions: where the Triassic is well developed, so is the Jurassic.

For south-west England we must thus consider a position somewhat analogous to that of the London-Brabant landmass and conclude that the area was in part inundated by the Jurassic seas, but that some areas of the south-west were likely to have remained as land during the whole of the Jurassic Period. The most persistent land area is likely to have been the area around the granitic 'spine' of Cornubia; its buoyant crust maintaining much of it as land. However, it is quite possible that the more south-western areas of the peninsula, including the more south-westerly granites, could have received a modest Jurassic cover at times of high Jurassic sea-levels. Members of the Lower Jurassic formations of Dorset display westward thinning and the proximity of land is indicated by the occurrence of insects and land reptiles such as scodosaurs, suggesting that Cornubia may have been their source. It should not be overlooked, however, that the London-Brabant landmass and even the significant Armorican landmass were not all that distant. It is likely, however, that north of the granites of Cornubia, a significant Jurassic succession was deposited. This is likely to have been thickest over north Cornwall and central Devon, perhaps somewhat thinner over north Devon, and thickening northwards into the Bristol Channel-South Celtic Sea basins.

In the Bristol Channel Basin, evidence of land in the vicinity is first apparent during the Middle Jurassic. The Aalenian and Bajocian rocks south of the Pembroke ridge are siltstones and clays and in the St George's Channel and Cardigan Bay areas is a thick (c. 250 m) succession of sandstones, siltstones and mudstones, quite unlike either the oolitic limestone shoals of the Cotswold Hills, where the thickness is usually less than 100 m, or the attenuated ferruginous limestone succession of Dorset and Somerset where thicknesses are frequently less than 10 m in total. Clearly Wales, at least, was contributing clastic sediment into its marginal basins; it is likely that swell areas in Cornubia were also emergent. Further emergence of Wales does not become apparent until the Oxfordian and the

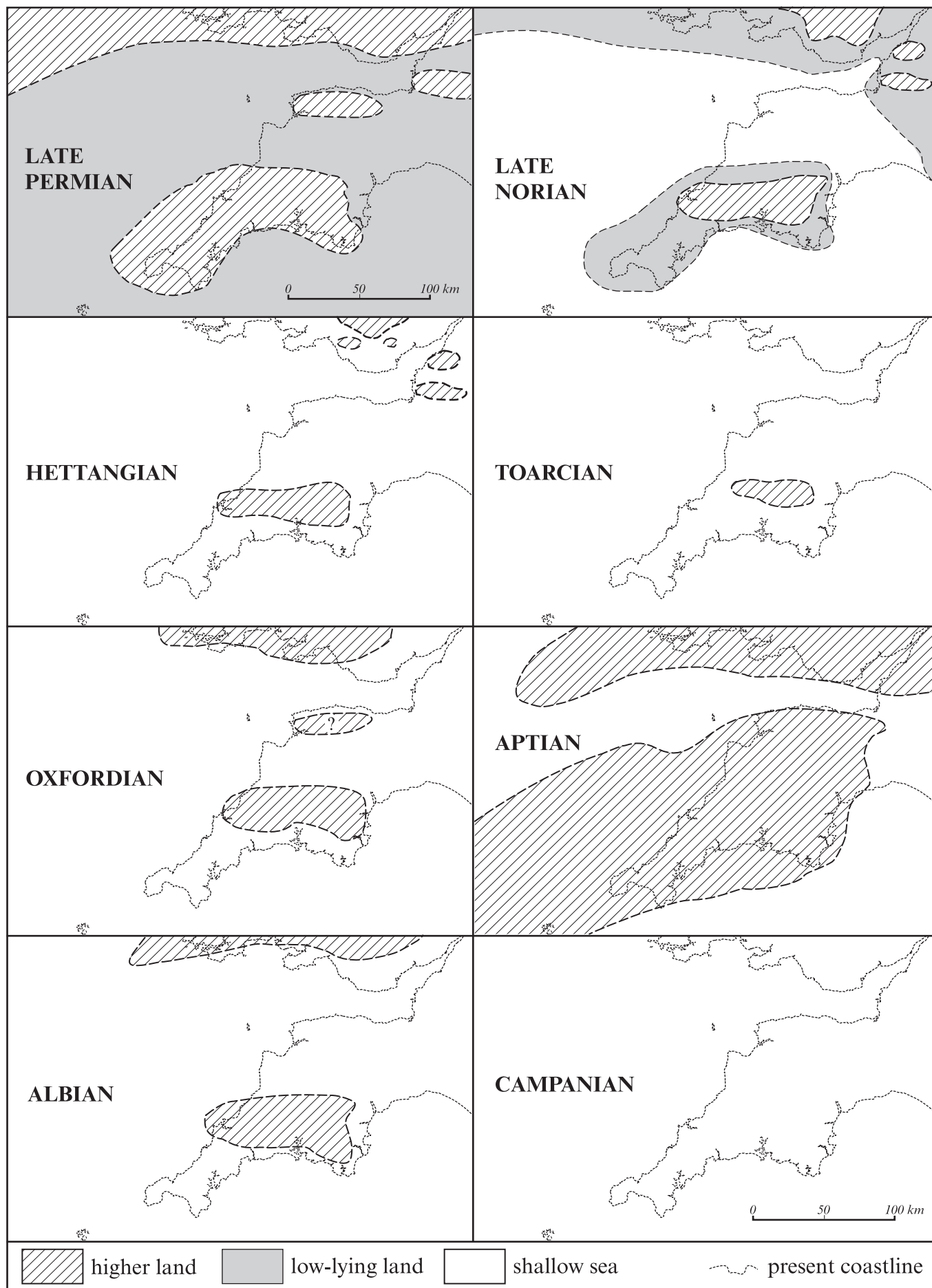


Figure 2. Selected palaeogeographical reconstructions for the period between the Late Permian and near-latest Cretaceous in the Cornubia region, working from the basis of more extensive red bed cover in the area and its consequences.

underlying succession is apparently complete in the Bristol Channel and Cardigan Bay basins (Figure 2). There is thus no reason to suppose that the Jurassic succession, up to that point, was not essentially complete over central Devon and north Cornwall. In the Oxfordian some 520 m of sandstones with glauconite and lignite accumulated in the Bristol Channel Basin (Evans and Thompson, 1979); this is the thickest development of these rocks in Britain and clearly reflects rapid subsidence in the Channel and a local sediment source. Whether this source was over north Devon or South Wales is not known, but it is at least possible that north Devon was a contributor to these rocks, perhaps stripping off some of the earlier deposited Mesozoic rocks.

The overlying Kimmeridge Clay represents offshore clay facies with oil-shales in the Bristol Channel Basin showing no evidence of any nearby land (Evans and Thompson, 1979), although to its north, in the St George's Channel Basin a largely freshwater succession contains land-derived material (Millson, 1987) but the source of this material was probably the Irish massif. In general sea levels during Kimmeridge Clay times (Kimmeridgian and Bolonian stages) were probably the highest since the Toarcian (Cope *et al.*, 1999) and it thus seems probable that Kimmeridge Clay was deposited over much of south-west England, except for the highest parts of the peninsula.

The top Bolonian zone, however, the Fittoni Zone, is known only from south Dorset (Cope, 1978, 1980) and this reflects a sea-level fall, with sedimentation ceasing and erosion ensuing, even in some basinal areas. The succeeding Portland Beds are only known onshore from southern Britain, but they are known offshore from the Celtic Sea basins and from the St George's Channel Basin and the Bristol Channel Basin, in both the latter cases some 45 m of Portland Beds, consisting predominantly of mudstones and siltstones, crop out (Tappin *et al.*, 1994; Evans and Thompson, 1979). As the Portland Beds are so restricted on land over southern Britain, it seems highly unlikely that Portland Beds, or their equivalent, were ever deposited over south-west England and the end-Jurassic to late Early Cretaceous interval seems unlikely to have been represented by any sediments there.

THE LATE CIMMERIAN UPLIFT

In East Anglia and Lincolnshire there is an incomplete and very condensed record of marine sedimentation from the late Bolonian into the Lower Cretaceous (Casey, 1973) and a less complete record on the Yorkshire coast. Outside of these areas no marine sediments are known between the Portlandian and Aptian in Britain and non-marine sediments represent most of that interval in southern and south-east England (Figure 2). In the Bristol Channel Basin and the St George's Channel Basin the Portland Beds are succeeded by Purbeck Beds and then a succession of Wealden type sediments. Palaeogeographically these have usually been linked through to the Weald Basin of southern and south-eastern England (e.g. Rawson, 1999), but there seems little reason why the sediment transport direction should not have been westwards, with currents directed towards the South Celtic Sea Basin. In the Western Approaches Basin, Wealden type sediments have been proved in several boreholes with drainage almost certainly directed to the south-west and open sea (Rawson, 1999, map K1). No sediments of this age are believed to have been deposited on what is now south-west England. Indeed it is likely that this time interval was one of active uplift and erosion over the region, with sediment eroded being transported by drainage into the surrounding basins. This uplift, erosion, and significant earth movement continued through the Aptian stage, by which time a marine transgression had restored marine conditions over the areas of Wealden sedimentation, but did little more than flood those areas of previously non-marine sedimentation (Rawson, 1999, map K2a).

Regression at this time is a widespread phenomenon over the British area and is usually referred to as the Late Cimmerian

period of uplift and erosion. Such uplift in south-west England is supported by apatite fission track analysis on the Carnmenellis granite (Chen *et al.*, 1996). These workers recorded a fast cooling effect, reflecting major regional uplift, which they dated as at c. 137–155 Ma. The earlier of these dates (Mid Callovian) appears to be somewhat earlier than that which is indicated by regional stratigraphical considerations, which would suggest that the onset of this uplift was more likely to have been around 141 Ma (mid Bolonian), whilst the date of 137 Ma correlates with the later part of the Portlandian, when uplift would have been pronounced, with very restricted basinal deposition (Cope *et al.*, 1999, maps J11c–d).

Examination of the latest-Jurassic to earliest Cretaceous uplift by McMahon and Turner (1998) shows that the Late Cimmerian episode of uplift, folding and faulting is in fact divisible into two separate components. These authors identify an earlier episode of uplift that peaked in the Berriasian Age; this is evidenced by pronounced Berriasian thickening in the Wealden Group and they identify this uplift in all the basins surrounding the Cornubian Platform. The earliest stratigraphical evidence for this uplift seems likely to have been in the Fittoni Zone of the Bolonian (see above); above this, sediments coarsen upwards. The second Late Cimmerian event was dated by McMahon and Turner (1998) as occurring during the Aptian, when further uplift, folding and faulting occurred. Erosion of these uplifted areas is likely to have continued through to the later part of the Albian Stage at around 100 Ma. Such erosion is demonstrable onshore in areas to the immediate east of Cornubia, in Dorset, where Gault of mid-Albian age rests on horizons from the Lower Jurassic to the Wealden Group.

Further support for erosion in this time interval was provided by Psyrillos *et al.* (2003), who deduced that kaolinization of the St Austell granite had occurred immediately prior to its unroofing in the Late Jurassic to Early Cretaceous. They suggested that fluids for the kaolinization could have come either from the nearby Permo-Triassic rocks of the Plymouth Basin, the formation waters of which were geochemically capable of that process, or from highly evolved meteoric waters circulating through the sediments directly enclosing the pluton.

The major transgression that occurred in mid-late Albian times cut across the uplifted and eroded margins of the Aptian marine basins (Figure 2). In south-western parts of England folding had produced significant E-W oriented fold axes, including such structures as the Bristol Channel syncline (extending onshore into the Glastonbury Syncline), succeeded southwards by the Somerton anticline and the Vale of Marshwood anticline. In the Weymouth area the folding was particularly intense in the Ringstead-Poxwell area, where the Late Cimmerian Upton syncline, with Wealden Beds in its core, is overlain unconformably by Gault Clay, allowing precise dating of the folding. Towards Cornubia, a gentle eastward regional dip had been applied to the Permian to Middle Jurassic rocks of the Devon and Dorset coasts, reflecting probable greater uplift and erosion on the Cornubian highlands than in the surrounding basinal areas. After this folding and warping a significant period of erosion ensued; there can be little doubt that erosion took place as uplift proceeded along anticlinal areas, but some of the Late Cimmerian basinal areas have also been considerably eroded. As an example of this latter phenomenon, the Bristol Channel syncline has a clear westward plunge that was clearly imparted during the Cimmerian movements. Thus its youngest pre-Late Cimmerian core of Wealden-type sediments is only preserved at the western end of the syncline. Farther east a varying amount of Jurassic cover has been eroded, so that in the eastern Bristol Channel the Lias Group is at outcrop and younger rocks are only preserved as local outliers, such as the diminutive cap of Inferior Oolite on the top of Brent Knoll in north Somerset. Erosion is likely to have occurred in the Plymouth Basin too, so that there the Albian sediments are seen to rest directly on Permian or Triassic rocks and any Jurassic rocks that had been deposited in this region were totally removed.

CRETACEOUS

Across the region this eroded surface was transgressed by the mid-Albian sea and upon it was deposited a cover of Gault (in the east) overlain by Upper Greensand, during the mid- and Late Albian. Westwards from Dorset, the Gault passes laterally into Upper Greensand facies. The progressive westward overstep at the base of the Middle Albian can be traced right across south-western Britain, so that on the Dorset-Devon boundary the Upper Greensand rests on the lower part of the Lias Group, in east Devon it oversteps onto the Triassic and then onto the Permian west of Exeter in the Haldon Hills. In the area around Newton Abbott the Upper Greensand rests directly on Culm or Devonian rocks (Selwood *et al.*, 1985).

Thanks to the preservation of these western outliers we have a good idea of where the western shoreline of the Late Albian sea lay (Figure 2). Indeed the sediments of the Newton Abbot area have characteristics of near-shore deposits and the coral bed of the Greensand of the Haldon Hills (Selwood *et al.*, 1985) is also believed to be an indicator of a near-shore position. Westward projection from these south Devon areas suggests that the Late Albian coastline must have lain on the eastern flanks of Dartmoor. But how far did this sea transgress onto the northern side of Cornubia? On the basis of the arguments marshalled herein, it seems probable that those areas of Devon that have outliers of Permian upon them at the present day, (which it is argued also had substantial Triassic and Jurassic cover, largely removed during the Late Cimmerian period of uplift and erosion), had a cover of Upper Greensand. Thus similar marginal facies of the Upper Greensand would be expected to have originally extended westwards along the northern flank of Dartmoor and continued farther westwards to link up with known sediments on the shelf south of the South Celtic Sea Basin.

Upper Greensand was succeeded by Chalk across the British area. It has long been accepted that Cornubia had a cover of Chalk as patches of flint gravels occur above the Upper Greensand of the Haldon Hills, and also around Orleigh Court near the shores of Bideford Bay (Rogers and Simpson, 1937; Edmonds *et al.*, 1979). Hancock (1969) was able to show, by simple arithmetical calculation that, by taking the present height of the top of the Upper Greensand that underlies the Haldon Gravels, adding the likely thickness of Chalk formerly deposited over the area and the likely depth of the Chalk sea, the Upper Cretaceous Campanian sea-levels were likely to have engulfed the highest point of Dartmoor, even though it were possible that the depth of water might have been insufficient to allow deposition of Chalk there (Figure 2). Some idea of part of the cover may be gained from outliers of younger rocks of the area. The gravels of the Haldon Hills of eastern Devon, largely composed of flints derived from the former Chalk cover of the area, were well described by Hamblin (1973). Hamblin (1973) showed that the succession consists of two quite separate formations. The older Tower Wood Gravels represent largely *in situ* weathering of Chalk, leaving angular flints with a clay matrix. The overlying Buller's Hill Gravels, in contrast, are reworked flints, together with Variscan rocks, whose origin can be ascribed to fluvial processes. The flints of the Haldon gravels contain fossils representing all of the zones of the Chalk from the early Coniacian to the late Campanian; the lack of Turonian fossils may be due to the lack of flint in Chalk of that age, whilst the Cenomanian is also likely to have been free of flint, but it is in part represented by the youngest Upper Greensand on Haldon. Maastrichtian and even Danian Chalk, both known offshore of Cornubia, may have been deposited over the area if the rocks did not include flints. Of these two stages, however, only the early part of the former is known anywhere onshore in the United Kingdom (in Norfolk and Northern Ireland), but in Cotentin, only 150 km to the south-east, Upper Maastrichtian sediments rest on Precambrian basement, showing that the Late Cretaceous transgressions persisted right to the end of the Cretaceous in Northwest Europe (*contra* Hancock and Kaufmann, 1979). In view of

the high sea-levels persisting to the end of the Cretaceous it seems likely that Upper Maastrichtian chalks may have been deposited over much of Britain, including south-west England.

PALAEOGENE

Over much of southern Britain end-Cretaceous (Laramide) movements caused broad uplift and in south-east England rapid local erosion occurred before the deposition of the earliest Palaeogene sediments, of late Palaeocene age (Curry, 1992). In the Eocene, major uplift of the whole of the north-western margin of the European plate, related to the Icelandic plume, is generally held responsible for rapid exhumation of that margin. However, evidence is now emerging of earlier localised uplifts on the western margin of Britain, that had significant regional effects. Thus uplift centred in the Irish Sea area was caused by a hot-spot or underplating of that area probably in earliest Palaeogene times (Cope, 1994, 1995, 1998). Although this predates the major Palaeocene-Eocene volcanicity, several intrusions, including those of the Fleetwood dyke in the Irish Sea have yielded radiometric dates of from 65.5 to 63 Ma (Arter and Fagin, 1993), giving a likely maximum age to that uplift. Erosion of the Chalk proceeded rapidly from the centre of the Irish Sea and spread outwards (Cope, 1994). On the margin of Cornubia lies the granitic Lundy Island. Brooks and Thompson (1973) showed, however, by means of a gravity survey that Lundy lies in the midst of a major intrusion of basic magma that was intruded at high crustal levels. This intrusion covers some 1500 km² in the area around Lundy and extending across Barnstaple Bay and is up to 4.5 km thick west of Lundy (Figure 3). The Sticklepath-Lustleigh Fault was found to have a profound effect on the intrusion; to its north-east it appears much thinner. Whether this is due to vertical displacement of the intrusion by the fault, or whether the fault plane itself had an influence on the distribution of the intrusive rocks was not determined (Figure 3). Lundy Island itself is largely composed of granite, derived from partial melting of continental crust due to underplating by mantle melts (Thorpe *et al.*, 1990). The age relationship of the basic intrusion and the granite is not clear, but as Lundy lies in the midst of the area of intrusion it seems probable that the two events are connected and the granite may just post-date the basic intrusion. The granite has been dated at 52 Ma (Thorpe *et al.*, 1990) and the basic intrusion may therefore be slightly older than this and an appropriate age might be around 53-55 Ma.

Such an intrusion of such a volume of basaltic rocks, at high crustal levels must have caused uplift. In turn, the uplift would have caused doming and rapid erosion; under the then tropical climate, the Chalk cover would have been quickly stripped from the region and its erosion products (flints) carried away from the area. One direction of transport would have been approximately south-eastwards and rivers flowing in this direction could well have produced the higher gravels of Haldon. The latter have been dated as of early Eocene age, around 55 Ma, and contemporary uplift to the north-west would provide a suitable trigger for high-energy rivers to distribute swathes of gravels such as the Buller's Hill Gravels of Haldon (Hamblin, 1973). With an appreciation of the likely uplift of the Lundy area, it now becomes apparent that the Orleigh Court gravels of the Bideford area (Edmonds *et al.*, 1979) may well have been derived from Chalk in Barnstaple Bay, rather than from the Cornubian highlands, as hitherto supposed. Once the Chalk had been removed from the area, isostatic readjustment would have occasioned further uplift over the north-western side of Cornubia, progressively stripping off the underlying Mesozoic rocks and locally exposing the Variscan basement. On Dartmoor, after removal of the Chalk, erosion proceeded on the underlying granite, and there is evidence of Dartmoor-derived heavy minerals from early Eocene sediments lying in the English Channel, to the south-east of Dartmoor (Murray, 1999). Around Lundy itself, the erosion ensuing from the up-doming has produced a circular outcrop of Devonian-Carboniferous rocks on the sea-floor (BGS, 1991).

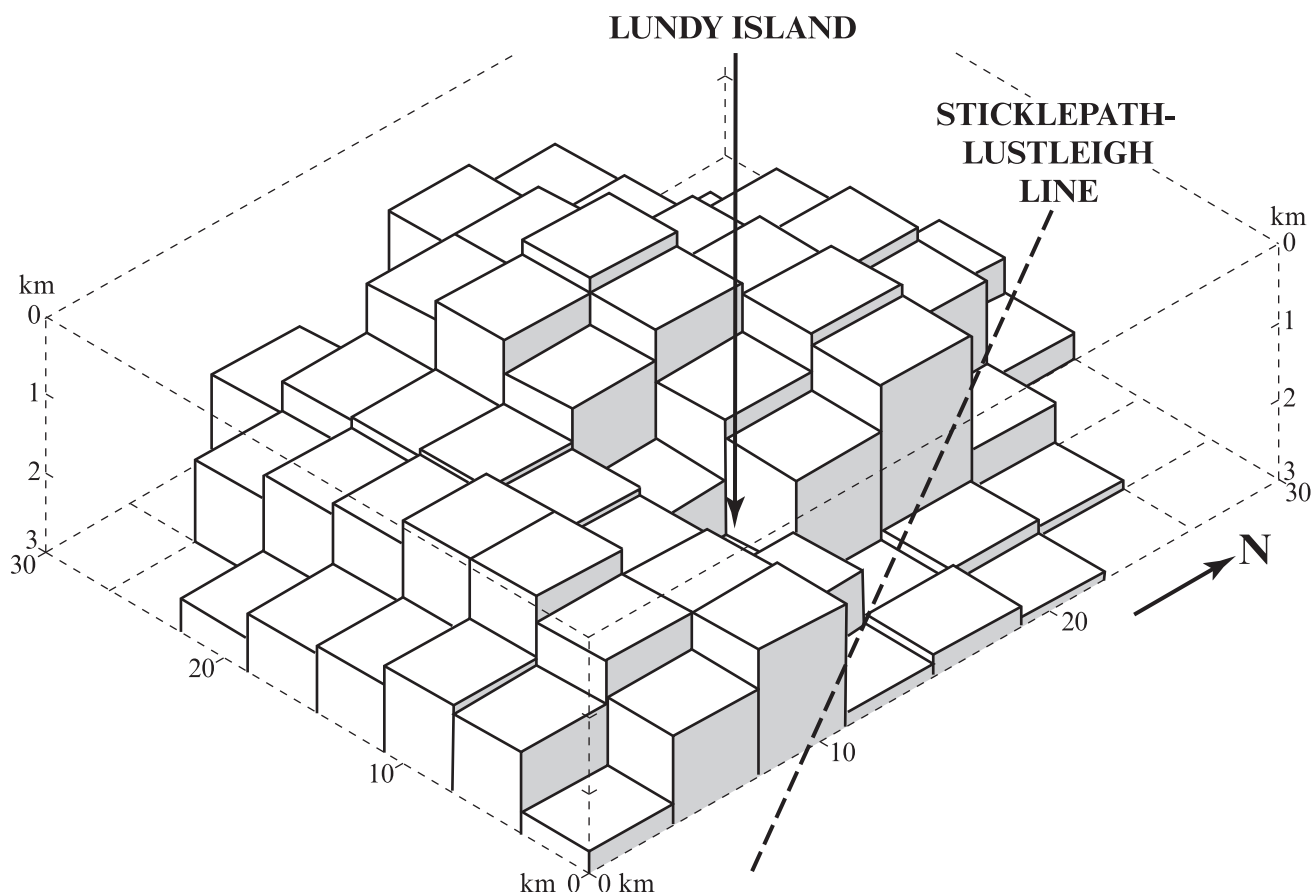


Figure 3. Prismatic model of the basic intrusion around Lundy. Modified after Brooks and Thompson (1973) and reproduced with the permission of the Geological Society of London

The removal of the Cretaceous cover and erosion of underlying rock would have diminished in intensity once the initial doming around Lundy had been eroded. However, it is likely that removal of the load of rock from the up-domed area would have induced isostatic readjustment, causing further uplift and erosion. By mid-Eocene times, however, it is clear that the dominant south-easterly transport of sediment across the more northerly regions of Cornubia was terminated by significant strike-slip movement, producing pull-apart basins along the line of the Lustleigh-Sticklepath Fault and other similar faults. Along the line of the former, the Bovey and Petrockstow (Freshney *et al.*, 1979) basins are all floored by probable mid-Eocene sediments; the drainage in the Petrockstow Basin was from the south-east, whilst that of the Bovey Basin was from the north-west (Edwards and Freshney, 1982). A watershed between the two basins suggests that tropically weathered Carboniferous shales produced the ball clays that are worked in these basins, although local kaolinization of the Dartmoor Granite may have played a minor role too. In the Bovey Basin sedimentation continued through until late in the Oligocene, or even into early Miocene times. The nearby Dutson Basin developed along a similar strike-slip fault, but the oldest sediments there appear to be of late Eocene age (Freshney *et al.*, 1982).

NEOGENE

In the absence of an extensive Cretaceous cover in south-west England it is difficult to determine the extent of movements of Oligocene-Miocene age. However, folding in the Chalk in the areas surrounding the Cornubian peninsula makes it clear that there was significant deformation at this time. Thus in the western Bristol Channel Chalk is folded into a syncline, which does not exactly coincide with the similarly E-W

orientation of the Late Cimmerian syncline with Wealden Beds in its core. This folding can be traced eastwards along the line of the Bristol Channel, through the Glastonbury syncline and into the Chalk to the north of the Vale of Wardour. The complementary anticline to the south of this runs westwards from the Vale of Wardour, whose northern margin is in part the Mere Fault that has a demonstrable post-Cretaceous northerly downthrow (the reverse of its Late Cimmerian throw). It continues westwards as the Somerton anticline, through the Quantocks and presumably westwards into Exmoor, where its trace is lost in the Devonian outcrop. To the south of this anticline another synclinal tongue of Chalk extends westwards from the Broadwindsor area of Dorset, through the Chard region of Somerset and into Devon; the fold trace continues into central Devon around Tiverton, where Permian rocks are the youngest cropping out. In general it appears that earlier structures, in particular, those of the Late Cimmerian period, have been tightened by posthumous movements of this age, although, as mentioned above, the Miocene movements are not always exactly coincident with the Late Cimmerian folds.

There are various patches of essentially undeformed younger deposits found in west Cornwall; it is not known to what extent these small preserved outliers of Neogene sediments are remnants of formerly far more extensive cover. The outcrops are found at several places on the peneplaned surface of western Cornwall; this surface varies in elevation between 50 and 120 m above OD. The most reported sediments on the peneplane are those of St Erth which have yielded a marine fauna of Late Pliocene age; thus the surface has often been ascribed to marine erosion of Pliocene age (e.g. Edmonds *et al.*, 1975). Some 20 km north-east of St Erth is St Agnes, a locality that has sediments of generally similar appearance to those of St Erth, but lacking macrofossils; these rocks, though lacking macrofossils, have often been correlated with the St Erth deposits.

However, pollen samples from the lower part of this sequence at Beacon Cottage Farm have indicated a mid to late Oligocene age (Atkinson *et al.*, 1975) and the middle levels of the sequence yielded a Miocene microflora (Walsh *et al.*, 1987); the latter authors also concluded that the St Agnes sediments were terrestrial. Reviewing these deposits, Walsh *et al.* (1999) concluded that in part, at least, the planation of west Cornwall occurred around the Palaeogene-Neogene boundary.

The Neogene evolution of Cornubia is one of the least well understood periods in its history. That there has been rapid and significant sea-level change cannot be doubted, much of which occurred during the Pleistocene as waxing and waning of ice-sheets caused great sea-level fluctuations. It is also clear that there has been significant tectonic movement within the Neogene. Such factors as the present elevation of Exmoor appear to be very recent phenomena and without this realisation, it becomes difficult to separate relatively recent topographical changes from those of more ancient origin.

Studies by Clayton and Shamooin (1999) suggest that many parts of southern Britain have witnessed very considerable Neogene changes in relief. They point out that after uplift has been induced (by whatever means) in an area, its effects are subsequently magnified by further uplift that occurs in response to isostatic rebound. Thus, as an area is uplifted, it is eroded and isostatic response to that erosion causes further uplift, occasioning another erosional episode, and so on; thus, much of the uplift occurs subsequently to the initial movement.

One of the conclusions drawn by Clayton and Shamooin (1999) is highly relevant to the Neogene evolution of the south-west England peninsula. That is that local differences in average altitude of as much as 400 m can be explained entirely by the effects of contrasts in the resistance of rocks to erosion. Thus they contrasted the hardness of the Devonian and Old Red Sandstone of North Devon with the much softer Culm ground to the south. The area of the granite intrusions they also showed to be more resistant than the Culm area. Thus, after the Palaeogene removal of the Mesozoic cover of Cornubia and the early Neogene warping of the area, it seems likely that differential weathering of the Upper Palaeozoic rocks has led to the much higher topography of Exmoor in the north and Dartmoor and Bodmin Moor in the south.

SUMMARY

It thus appears that the post-Variscan history of south-west England was a complex process, involving many factors. The accumulation of a significant red-bed Permian and Triassic sequence over much of the peninsula is supported not only by the pattern of distribution of the Permian sediments at the present day, but by reddening of the older Palaeozoic rocks beyond these margins. Cross-cutting veins within the latter also demand a formerly more extensive red-bed cover and cementation temperatures in existing Permian breccias also demand deep burial. Because all this evidence suggests a considerable Triassic cover to the region, in the light of regional basin development, it appears likely that there was a good Jurassic cover too for much of the area; much of this may have been stripped off during the Late Cimmerian movements, which were succeeded by the Mid-Albian transgression over the area. Inundation of the whole peninsula under the rising sea-levels of the Late Cretaceous seems very probable and the doming induced by the large scale intrusion of basaltic magma at high crustal levels, during the Eocene, produced rapid and pronounced erosion centred on the Lundy Island area, removing the Chalk cover. Strike-slip faulting during the later part of the Eocene and Oligocene produced a series of pull-apart basins. These were succeeded by late Oligocene to early Miocene folding of the area and planation of the western part of Cornwall; on this surface relics exist of the youngest sediments of the region.

ACKNOWLEDGEMENTS

Dr R.C. Scrivener is thanked for invaluable discussion and for providing useful information on literature. Thanks are also due to Mrs L.C. Norton for cartographic work.

REFERENCES

- ARTER, G. and FAGIN, S.W. 1993. The Fleetwood Dyke and the Tynwald fault zone, Block 113/27, East Irish Sea Basin. In: PARKER, J.R. (Ed.), *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 835-843.
- ATKINSON, K., BOULTER, M.C., FRESHNEY, E.C., WALSH, P.T. and WILSON, A.C. 1975. A revision of the geology of the St Agnes Outlier, Cornwall. *Proceedings of the Ussher Society*, **3**, 286-287.
- AWAD, N.T., MEREFIELD, J.R., SCRIVENER, R.C. and STONE, M. 1996. Geochemistry and petrogenesis of volcanic clasts in the Permian breccias around Exeter. *Journal of the Geological Society, London*, **153**, 669-672.
- BRITISH GEOLOGICAL SURVEY. 1991. 1:1 000 000 map of the geology of the United Kingdom, Ireland and the adjacent continental shelf (South Sheet).
- BROOKS, M. and THOMPSON, M.S. 1973. The geological interpretation of a gravity survey in the Bristol Channel. *Journal of the Geological Society, London*, **129**, 245-274.
- BROOKS, M. and AL SAADI, R.H. 1977. Seismic refractive studies of geological structure in the inner part of the Bristol Channel. *Journal of the Geological Society, London*, **133**, 433-445.
- BROOKS, M., THAYNER, P.M. and TRIMBLET, J. 1988. Mesozoic reactivation of Variscan thrusting in the Bristol Channel area, UK. *Journal of the Geological Society, London*, **145**, 439-444.
- BURLEY, S.D. and CORNFORD, C. 1998. Carbonate cements constrain the burial history of the Portledge-Peppercombe Permian outlier, north Devon. *Geoscience in south-west England*, **9**, 188-202.
- CASEY, R. 1973. The ammonite succession at the Jurassic-Cretaceous boundary in eastern England. In: CASEY, R. and RAWSON, P.F. (eds), *The Boreal Lower Cretaceous*, Geological Journal Special Issue **5**, 193-266, pls. 1-10. Seel House Press, Liverpool.
- CHEN, Y., ZENTILLI, M.A., CLARK, A.H., FARRAR, E., GRIST, A.M. and WILLIS-RICHARDS, J. 1996. Geochronological evidence for post-Variscan cooling and uplift of the Cammenellis granite, SW England. *Journal of the Geological Society, London*, **153**, 191-195.
- CLAYTON, K. and SHAMOON, N. 1999. A new approach to the relief of Great Britain. III Derivation of the contribution of neotectonic movements and exceptional regional denudation to the present relief. *Geomorphology*, **27**, 173-189.
- COPE, J.C.W. 1978. The ammonite faunas and stratigraphy of the upper part of the Upper Kimmeridge Clay of Dorset. *Palaeontology*, **22**, 469-534, pls. 45-56.
- COPE, J.C.W. (ed.) 1980. A correlation of Jurassic rocks in the British Isles. Part 2. Middle and Upper Jurassic. *Geological Society of London, Special Reports*, **15**, 109 pp.
- COPE, J.C.W. 1988. The Pre-Devonian history of South-west England. *Proceedings of the Ussher Society*, **7**, 468-473.
- COPE, J.C.W. 1994. A latest Cretaceous hotspot and the south-easterly tilt of Britain. *Journal of the Geological Society, London*, **151**, 905-908.
- COPE, J.C.W. 1995. Reply to discussion of A latest Cretaceous hotspot and the south-easterly tilt of Britain. *Journal of the Geological Society, London*, **152**, 729-731.
- COPE, J.C.W. 1998. The Mesozoic and Tertiary history of the Irish Sea. In: MEADOWS, N.S., TRUEBLOOD, S., HARDMAN M. and COWAN, G. (eds), *The Petroleum Geology of the Irish Sea and adjacent areas*. Geological Society Special Publication, **124**, 47-59. [Dated 1997]
- COPE, J.C.W. and BASSETT, M.G. 1987. Sediment sources and Palaeozoic history of the Bristol Channel area. *Proceedings of the Geologists' Association, London*, **98**, 315-330.
- COPE, J.C.W., INGHAM, J.K. and RAWSON, P.F. 1999 (eds). *Atlas of palaeogeography and lithofacies*. Geological Society, London, Memoir 13.

- CURRY, D. 1992. Tertiary. In: DUFF, P. McL.D. and SMITH, A.J. (eds), *Geology of England and Wales*. Geological Society, London, 389-411.
- De la BECHE, H.T. 1839. *Report on the geology of Cornwall, Devon and west Somerset*. Memoir of the Geological Survey of Great Britain, London.
- DONOVAN, D.T., HORTON, A. and IVIMEY-COOK, H.C. 1979. The transgression of the Lower Lias over the northern flank of the London Platform. *Journal of the Geological Society, London*, **136**, 165-73.
- EDMONDS, E.A., MCKEOWN, M.C. and WILLIAMS, M. 1975. *South-west England*. British Regional Geology, 4th edition, HMSO, London.
- EDMONDS, E.A. WILLIAMS, B.J. and TAYLOR, R.T. 1979. *Geology of Bideford and Lundy Island*. Memoir of the Geological Survey of Great Britain.
- EDWARDS, R.A. and FRESHNEY, E.C. 1982. The Tertiary sedimentary rocks. In: DURRANCE, E.M. and LAMING, D.J. (eds) *The geology of Devon*. University of Exeter, Exeter, 204-237.
- EVANS, C.D.R. 1990. *United Kingdom offshore regional report: the geology of the western English Channel and its western approaches*. HMSO for the British Geological Survey.
- EVANS, D.J. and THOMPSON, M.S. 1979. The geology of the central Bristol Channel and the Lundy area, South Western Approaches, British Isles. *Proceedings of the Geologists' Association, London*, **90**, 1-14.
- FRESHNEY, E.C., BEER, K.E. and WRIGHT, J.E. 1979. *Geology of the country around Chumleigh*. Memoir of the Geological Survey of Great Britain.
- FRESHNEY, E.C., EDWARDS, R.A., ISAAC, K.P., WITTE, G., WILKINSON, G.C., BOULTER, M.C. and BAIN, J.A. 1982. A Tertiary Basin at Dutson, near Launceston, Cornwall, England. *Proceedings of the Geologists' Association*, **93**, 395-402.
- HAMBLIN, R.J.O. 1973. The Haldon Gravels of south Devon. *Proceedings of the Geologists' Association*, **84**, 459-476.
- HANCOCK, J.M. 1969. Transgression of the Cretaceous sea in south-west England. *Proceedings of the Ussher Society*, **2**, 61-83.
- HANCOCK, J.M. and KAUFMANN, E.G. 1979. The great transgressions of the Late Cretaceous. *Journal of the Geological Society, London*, **136**, 175-186.
- HILLIS, R.R. 1995. Regional Tertiary exhumation in and around the United Kingdom. In: BUCHANAN, J.G. and BUCHANAN, P.G. (eds), *Basin Inversion*. Geological Society, London, Special Publications, **88**, 167-190.
- HILLIS, R.R. and CHAPMAN, T.J. 1992. Variscan structure and its influence on post-Carboniferous basin development, Western Approaches Basin, SW UK Continental Shelf. *Journal of the Geological Society, London*, **149**, 413-416.
- McMAHON, N.A. and TURNER, J. 1998. The documentation of a latest Jurassic—earliest Cretaceous uplift throughout southern England and adjacent offshore areas. In: UNDERHILL, J.R. (ed.), *Development, Evolution and Petroleum Geology of the Wessex Basin*. Geological Society, London, Special Publication, **133**, 215-240.
- MILIORIZOS, M., RUFFELL, A. and BROOKS, M. 2004. Variscan structure of the inner Bristol Channel, UK. *Journal of the Geological Society, London*, **161**, 31-44.
- MILLSON, J.A. 1987. *The sedimentology of the Celtic Sea Jurassic*. PhD thesis, University of Wales.
- MURRAY, J.W. 1999. Palaeogene and Neogene. In: COPE, J.C.W., INGHAM, J.K. and RAWSON, P.F. (eds), *Atlas of palaeogeography and lithofacies*. Geological Society, London, Memoir 13, 2nd edition, 141-147.
- PSYRILLOS, A., BURLEY, S.D., MANNING, D.A.C. and FALLICK, A.E. 2003. Coupled mineral-fluid evolution of a basin and high: kaolinization in the SW England granites in relation to the development of the Plymouth Basin. In: PETFORD, N. and McCAFFREY, K.J.W. (eds), *Hydrocarbons in crystalline rocks*. Geological Society, London, Special Publications, **214**, 175-195.
- RAWSON, P.F. 1999. Cretaceous. In: COPE, J.C.W., INGHAM, J.K. and RAWSON, P.F. (eds), *Atlas of palaeogeography and lithofacies*. Geological Society, London, Memoir 13, 2nd edition, 131-139.
- ROBERTS, D.G. 1989. Basin inversion in and around the British Isles. In: COOPE, M.A. and WILLIAMS, G.D. (eds), *Inversion tectonics*. Geological Society, London, Special Publications, **44**, 131-150.
- ROGERS, I. and SIMPSON, B. 1937. The flint deposits of Orleigh Court, Buckland Brewer, north Devon. *Geological Magazine*, **74**, 309-316.
- SCRIVENER, R.C., LEAKE, R.C., LEVERIDGE, B.E. and SHEPHERD, T.J. 1989. Volcanic-exhalative mineralization in the Variscan province of SW England. *Terra Abstracts*, **1**, 125.
- SCRIVENER, R.C. DARBYSHIRE, D.P.F. and SHEPHERD, T.J. 1994. Timing and significance of crosscourse mineralization in SW England. *Journal of the Geological Society, London*, **151**, 587-590.
- SELWOOD, E.B., EDWARDS, R.A., SIMPSON, S., CHESHER, J.A., HAMBLIN, R.J.O., RIDDOLLS, B.W. and WATERS, R.A. 1985. *Geology of the country around Newton Abbot*. Memoir of the British Geological Survey.
- SHAIL, R.K. and ALEXANDER, A.C. 1997. Late Carboniferous to Triassic reactivation of Variscan basement in the western English Channel: evidence from onshore exposures in south Cornwall. *Journal of the Geological Society, London*, **154**, 163-168.
- SHEPHERD, T.J. and SCRIVENER, R.C. 1987. Role of basinal brines in the genesis of polymetallic vein deposits, Kit Hill-Gunnislake area, SW England. *Proceedings of the Ussher Society*, **6**, 491-497.
- SMITH, D.B. and TAYLOR, J.C.M. 1999. Permian. In: COPE, J.C.W., INGHAM, J.K. and RAWSON, P.F. (eds), *Atlas of palaeogeography and lithofacies*. Geological Society, London, Memoir 13, 2nd edition, 87-96.
- SUMBLER, M.G. 1996. *London and the Thames Valley*. British Regional Geology, 4th Edition. H.M.S.O., London.
- TAPPIN, D.R., CHADWICK, R.A., JACKSON, A.A., WINGFIELD, R.T.R. and MITH, N.J.P. 1994. *The geology of Cardigan Bay and the Bristol Channel*. British Geological Survey offshore Regional Report.
- THORPE, R.S., TINDLE, A.G. and GLEDHILL, A. 1990. The petrology and origin of the Tertiary Lundy granite (Bristol Channel, UK). *Journal of Petrology*, **31**, 1379-1406.
- TRUEMAN, A.E. 1922. The Liassic rocks of Glamorgan. *Proceedings of the Geologists' Association, London*, **33**, 245-284.
- WALSH, P.T., ATKINSON, K., BOULTER, M.C. and SHAKESBY, R.A. 1987. The Oligocene and Miocene outliers of West Cornwall and their bearing on the geomorphological evolution of Oldland Britain. *Philosophical Transaction of the Royal Society of London*, **A323**, 211-245.
- WALSH, P.T., BOULTER, M. and MORAWIECKA, I. 1999. Chattian and Miocene elements in the modern landscape of western Britain and Ireland. In: SMITH, B.J., WHALLEY, W.B. and WARKE, P.A. (eds) *Uplift, erosion and stability: perspectives on long-term landscape development*. Geological Society, London, Special Publications, **162**, 45-63.
- WARRINGTON, G. and IVIMEY-COOK, H.C. 1999. Triassic. In: COPE, J.C.W., INGHAM, J.K. and RAWSON, P.F. (eds), *Atlas of palaeogeography and lithofacies*. Geological Society, London, Memoir 13, 2nd edition, 97-106.
- WHITTAKER, A. (ed.) 1985. *Atlas of onshore sedimentary basins in England and Wales*. Blackie, Glasgow (for the British Geological Survey).