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LATE CENOZOIC WALES AND SOUTH-WEST ENGLAND

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Aspects of the late Cenozoic history of Wales and south-west England are reviewed in the light of new evidence both internal and external to the region. It is concluded that aminostratigraphy, standardised to *Littorina littorea*, shows evidence for three raised beaches, which are correlated with oxygen isotope stratigraphy: OI Stage 7 (AAR 0.18) and sub-stage 5e (0.15 and 0.11). An earlier sea-level, identified from reworked faunas (0.22), is ascribed to OI Stage 9. Uplift rates show that erosion surfaces of the region could have been uplifted since the late Miocene. Evidence for glaciation is enhanced by ^{36}C1 dates. Glacial deposits in the Bristol area are correlated with oxygen isotope stage 16. The hypothesis of an Anglian glaciation carrying bluestone erratics to Stonehenge is contradicted by a ^{36}Cl age on igneous rock fragments from Stonehenge. Periglacial denudation, through 50 ice-age cycles since 2.4 Ma, was probably the main agent of geomorphological development. It is proposed (1) that the interstadials recorded in Greenland ice-cores are recorded by speleothems; and (2) that the giant erratics of Devon and Cornwall were emplaced by ice-floes during pre-Devensian Heinrich events.

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INTRODUCTION

The pace of late Cenozoic research has quickened in recent years with new discoveries and the application of new tools, particularly for geochronology. This has increasingly shown the global importance of the North Atlantic Ocean (e.g. Broecker and Denton, 1989; Broecker, 1991) around which large mid-latitude ice-sheets grew, and where variability in thermohaline circulation played a fundamental role in the climate system. Time series of δ^{18}O variability in ocean water, (Shackleton and Opdyke, 1973), δ^{13}C variability (Charles and Fairbanks, 1992), and sea surface temperature data have shown the essential links between atmosphere, oceans and the terrestrial environments, both for the Pleistocene (Ruddiman, 1987) and later Cenozoic (Cronin and Dowsett, 1991). During the assembly of time-series data of different kinds, the terrestrial domain has lagged behind that of the ocean, and future efforts are likely to be enhanced. Thus, the location of south-west England and Wales on the north-east margin of the Atlantic Ocean, between the extremes of continental Eurasia and the North Atlantic, could be one containing important data for elucidating rhythms and changes internal to natural systems as opposed to external orbital forcing. This review considers some new and existing information on the geology and geomorphology of south-west England and Wales. It attempts to focus on regional issues in a wider context, and it proposes some hypotheses for testing.

PLEISTOCENE SEA-LEVELS

Modern work on Pleistocene sea-levels has been concerned with the number and age of the raised beaches. Zeuner (1959) recognised two levels, one at 60 feet (18.3 m), the other at 25 feet (7.6 m), both of which he ascribed to the 'Last Interglacial'. Mitchell (1960) and Stephens (1966) ascribed the raised beaches to the Hoxnian (Gortian). But subsequently, Mitchell and Orme (1967) ascribed two beaches to the Hoxnian and Ipswichian in the Isles of Scilly. Mitchell (1972) further recognised older, Hoxnian (erratic free), and younger, Ipswichian (with erratics) raised beaches in Gower. Bowen (1969a, 1973a) suggested that because the raised beaches are overlain by beds that can be interpreted as the product of only one ice-age, then the underlying raised beaches are probably last interglacial in age. A similar view was taken by Kidson (1971) and Kidson and Wood (1974). The evidence from Minchin Hole Cave in Gower, however, is critical because two high stands of sea-level are demonstrated by lithostratigraphy (Sutcliffe and Bowen, 1973). Their possible correlations with oxygen isotope stratigraphy were addressed by Bowen (1973b). Subsequently, and currently, the application of geochronological methods (amino acid geochronology and uranium series) have resolved some problems, although others remain.

The first amino acid analysis of protein fossilised in gastropods and bivalves from the raised beaches suggested that at least two high stands of sea-level, possibly three, had occurred in southwest England and South Wales (Andrews *et a1*.,1978). A wider aminostratigraphic survey throughout south-west Britain, upheld the hypothesis of two separate interglacial beaches (Davies, 1983; Davies and Keen, 1985; Mottershead *et al*., 1987) These earlier amino acid data were superseded by a new data set based on a different method of sample preparation, used in all analyses since 1983 (Bowen *et al*., 1985).The differences between the two methods are not inconsiderable, and preclude precise comparison for the following reasons: (i) the current method gives lower amino acid ratios, (ii) the earlier ratios were measured manually from a strip-chart (to two decimal places; cf Fig.2 in Davies, 1983), unlike instrumental calculations since 1983, (iii) the large data set available since 1983 has allowed statistical standardisation of ratios from species with different epimerization rates; initially this used *Patella vulgata* (Bowen et al., 1985), but since 1988, *Littorina littorea* has been used as the standard (Bowen and Sykes, 1988), (iv) the earlier data set failed to detect two further high stands of sea-level and was unable to explore the significance of re-worked faunas (below). Thus reliance on the earlier data set (e.g. Proctor and Smart, 1991) is misleading.

Based on amino acid data from 30 localities between Sussex and Milford Haven, five separate Pleistocene sea-levels have been identified (Bowen *et al*., 1985; Bowen and Sykes, 1988; Bowen *et al*., in preparation). If the 30-40 m marine beds of west Sussex are excluded, the remaining four sea-levels are recorded in the 'low' raised beaches of Sussex, Dorset, Cornwall, Devon, Avon, Gwent, Gower and South Dyfed. Their characteristic amino acid ratios, standardised to *Littorina littorea* (and correlation with oxygen isotope stages) are: 0.22 (OI 9), 0.18 (OI7), 0.11(OI sub-stage 5e). The age of a separate sea-level, with characteristic ratios of 0.15, has been the subject of debate (below). Three possible models were presented by Bowen *et al*., (1985):

These models have been discussed by Proctor and Smart (1991) and Hollin *et al*., (1994). Proctor and Smart (1991) correlated uranium-dated speleothems in the Berry Head cave systems with the raised beaches of the Torbay area, notably at Shoalstone. They suggested that the 0.15 sea-level event occurred early during sub-stage

Amino acid ratios	Model 1	Model 2	Model 3
(L.littorea)	Oxygen isotope stages		
0.11	5e	5a 5c	5e
0.15		5e	7
0.18	7	7	7

5e, and that the 0.11 event represented marine regression. Careful scrutiny of the applicable data set, however, revealed that a considerable amount of re-working occurs in the Torbay marine faunas. What the combined data from the Torbay raised beaches show is evidence for three sea-levels. These have characteristic AARs of: 0.18 ± 0.13 (13), of which the basal conglomerate at Hope's Nose is an example of a discrete deposit; 0.15 ± 0.009 (17) represented at Hope's Nose, Thatcher Rock and Shoalstone; and, 0.12 ± 0.008 (18). Thus data for three sea-levels and not two (Proctor and Smart, 1991) occurs in Torbay. Over 60% of the Shoalstone raised beach fauna is related to the 0.12 AAR event and nearly 40% to the 0.15 AAR event. The youngest AARs date the sea-level event: that is OI substage 5e.

Based on temperature measurements from inside and outside Minchin Hole Cave, which showed that the cave interiors were about 1°C cooler, Hollin *et al*., (1994) suggested that characteristic ratios of 0.11 from both Minchin and Bacon Hole Caves were equivalent to the 0.15 ratios from raised beaches on the outer coast. They also suggested that ratios of 0.11 from outside sites may be correlated with OI sub-stages 5c and or 5a. Their reasoning is flawed because, at both sites, the raised beaches occur either at (Minchin Hole) or outside (Bacon Hole) the cave entrances. The correlation they propose with substages 5c and 5a is implausible. 'Slow' epimerising species (Miller and Mangerud, 1985) from Pleistocene marine (*Littorina littorea* standard) and non-marine deposits may be directly compared (Bowen, 1992). Thus, an implication of the views of Hollin *et al*., (1994) is that the stratotype of the Ipswichian (5e), with ratios of 0.1, is time-equivalent to substages 5c and 5a! This is highly unlikely, and is contrary to the evidence from well-established palaeo-vegetational and palaeo-temperature gradients across western Europe (Behre, 1989). It is also totally contradicted by palaeontological evidence (fossil mammals), and uranium-series ages of 80 ka from speleothem, both discovered in the deposits overlying the raised beach (0.11 ratios) at Bacon Hole Cave (Stringer *et al*., 1986).

Stratigraphical evidence may be available to establish the age of the AAR 0.15 sea-level from Horton, Gower. Two separate raised beaches occur: one at 10 m (upper), overlain by a sequence of beds typical of the Devensian (Bowen 1971); the other, not so covered, in a gully some 1-2 m below. The fauna of the lower beach gave ratios of 0.11 ± 0.007 (2). Two populations occur in the upper beach: 0.185 ± 0.01(4) and 0.144 ± 0.01 (9). The typical Devensian sequence overlying the upper beach could suggest that it is Ipswichian (5e). If so, the younger population represented by AAR of 0.144 ± 0.01 (9) (the 0.15 L. littorea group) could be Ipswichian; and the older popoulation (0.185 ± 0.0114]) could be re-worked material from the OI Stage 7 sea-level. It follows from these aminostratigraphical, but essentially lithostratigraphical considerations, that both the 0.15 and 0.11 groups can be ascribed to the Ipswichian (5e). A similar situation in North Devon, at Baggy Point and at Saunton, may also be resolved by assuming faunal re-working, and where the raised beaches are also Ipswichian.

Recognition of two sea-levels in the Ipswichian (5e) is consistent with growing evidence from elsewhere (e.g. Sherman *et a1*.,1993; Jones, 1994). The two events could correspond to the orbitally tuned oxygen isotope events 5.53 (125ka) and 5.51 (122ka) (Martinson *et al*.,1987). Indeed many records show climatic variability during during sub-stage 5e (Imbrie *et a1*.,1992). The 0.04 difference in the extent of epimerization between the 0.15 and 0.11 sea-level events is not excessive when compared with the 0.04 of epimerization experienced since the mid-Holocene (Andrews *et al*., 1978).

UPLIFT HISTORY

Knowledge of the height of sea-level at a precise time in the past is valuable for calculating rates of coastal uplift. There is a measure of agreement that sea-level during the last interglacial was about 6 m higher than present. Sherman *et a1*.,(1993) have calculated that sea-level in Hawaii reached 5.5 m on two occasions during sub-stage 5e. Many raised beaches ascribed to sub-stage 5e in south-west England and Wales lie at higher elevations: e.g. Portland East up to 10.76 m, Thatcher Rock 10 m, Hope's Nose 7.3 m, Langland Bay 10 m, Horton 10 m,and Bacon Hole 12 m. This suggests that uplift has occurred since that time. The similar elevation of the raised beaches, ascribed to OI stage 7, when the contemporary sea-level was below present (Shackleton, 1987) is further evidence of uplift.

Research on the raised beaches of west Sussex has shown that an uplift rate of 0.07m/ka is consistent with the field and aminostratigraphical evidence (Bowen *et al*., in preparation). Such a rate is relatively slow compared with those at plate margins, such as in New Guinea (>4m/ka), California (0.35m/ka), Japan (3.9m/ka), New Zealand (4m/ka) (Lajoie, 1986), or the fastest known rates of 5-6m/ka in the New Hebrides (Gray, AGU Fall Meeting paper,1993), and much slower than regional uplift rates of (+100m/ka) in rebound regions after the last ice age (Lajoie, 1986). But it is slower than in Hawaii 0.02m/ka (Jones, 1994).

Even at the rate of uplift calculated in west Sussex, however, the 130 m (430 ft) platforms of south-west England and Wales could have been uplifted from the Early Pleistocene onwards, Davidstow Moor (305 m) since the Pliocene, and the High Plateau of Wales (610 m) since the late Miocene. Such estimates are, of course, not intended to be more than broadly indicative.

GLACIATION

Glacial deposits of the British Isles have been subdivided using aminostratigraphy and correlated with oxygen isotope stratigraphy using amino acid geochronology (Bowen and Sykes, 1988; Bowen, 1991, 1994). The timing of the maximum of Late Devensian glaciation in South Wales is enhanced by a ^{36}C1 (chlorine-36) age of 22.8 ka (sidereal years BP) on Arthur's Stone, Gower, a large erratic boulder (Phillips *et al*., 1994a, 1994b, and in preparation).

Deglaciation of the Irish Sea Basin during the Late Devensian has been reinterpreted as the collapse of a marine-based ice-sheet (Eyles and McCabe, 1989). Rapid retreat of the ice-margin, through ice-calving into a glacio-marine embayment, allowed marine transgression across an isostatically depressed crust. The extent of isostatic subsidence around and beyond the margins of an ice-sheet is not clear. Walcott (1970) and Officer *et al*., (1988), however, have shown that such downwarping can extend for a distance of up to twice the radius of the ice-sheet. On this basis, Eyles and McCabe (1989) predicted that the 'peripheral trough' around the ice-sheet would have included north Devon, where they identified the Fremington clays as distal glacio-marine deposits. Further work is required to test that hypothesis, but similar clays in Ballycotton Bay (outside the limit of Late Devensian ice) in Ireland contain shell fragments with Late Devensian amino acid ratios (Bowen and Vernon, unpublished), and are thus interpreted as distal glacio-marine muds. Similarly, laminated clays of the lower Teifi Valley and the Ewenny Valley, have been so interpreted (Campbell and Bowen, 1989). Late Devensian amino acid ratios from *Macoma balthica* collected in 'bedded till' (Campbell *et a1*.,1982) in North Gower may also indicate a glacio-marine origin. Widespread evidence of such a glacio-marine trespass on the present coastline is unlikely, because it was still partly buried by the Devensian deposits which were not driven landwards to their present position until the Holocene.

Amino acid analysis of shell fragments from Fremington (collected by H R L James and D Q Bowen), and from offshore samples (submitted by J Scourse), show a mixture of ages from which no definitive conclusions emerge. From Fremington, *Arctica islandica* fragments, recognisable because of distinctive hinge lines, give ratios of: between 0.24 (OI Stage 8) and 0.75 (Early Pleistocene). Individual ratios are: 0.24, 0.33, 0.39, 0.41, 0.53, 0.56, 0.65 and 0.75. Other ratios are: *Astarte* (0.35) and an entire *Nucula* sp gave an anomalously low ratio of 0.03 (Late Devensian?). Offshore ratios are: 0.29 *(Arctica),* 0.44 *(Arctica),* 0.22 *(Astarte),* and 0.077 *(Spisula).* Characteristic European ratios for *Spisula* are: Hosteinian 0.29, and Eemian 0.16 (Miller and Mangerud, 1985). On this basis, the ratio of 0.077 must be Late Devensian.

Glacial deposits of the Ridgeacre Formation, West Midlands, have been correlated with Oxygen Isotope Stage 6. This used the amino acid geochronology of the Kidderminster Station Member (formerly the Kidderminster Terrace) of the Severn Valley Formation which consists partly of outwash gravels (Maddy *et al., in* press); and ^{36}C1 ages on erratic boulders, south of Birmingham (Phillips *et al.,* 1994a, 1994b and in preparation). The Kidderminster Station Member lies just above O.D. before it passes below Holocene alluvium at the Severn Tunnel.

New evidence confirms the suggestion that the Llanddewi Formation of Gower (Bowen, 1969b) and its Paviland Moraine should be correlated with the Anglian (Bowen *et al.,* in preparation). This, however, represents glaciation from due north, and does not support the hypothesis of an Anglian ice-sheet (~450 ka) that transported 'bluestones' from Preseli to Stonehenge (Kellaway, 1971; Thorpe *et al.,* 1991).Cogent arguments have been assembled against this hypothesis (Kidson and Bowen, 1976; Green, 1973;(in press); Darrah, 1993), and are supported by a ^{36}C1 age determination on an igneous rock from the Stonehenge collection in the Salisbury Museum. This shows that it was still buried at its source outcrop during the Anglian (400 ka), and did not become exposed by denudation to the atmosphere until the Late Devensian (Bowen *et al*., in preparation), after which it was presumably quarried by prehistoric people and taken to Stonehenge.

The earlier 'Irish Sea Glaciation' of the Bristol Channel region, as shown by the south-easterly carriage of erratics across south Pembrokeshire, may, or may not be the same age as the outcrops of glacial deposits identified in the Bristol district (Andrews *et al.,* 1984). These antedate the freshwater 'interglacial' deposits at Kenn Pier that have amino acid ratios of 0.39 (Andrews *et al.,* 1984). The aminostratigraphic model of Bowen *et al.,* (1989) would correlate the Kenn Pier beds with those at Waverley Wood in Warwickshire (Shotton *et al.,* 1993), and with oxygen isotope stage 15 (600ka). The underlying glacial deposits may, therefore, be time-equivalent to oxygen isotope stage 16 (Bowen, 1994), which the OI signal shows was one of the largest ice-volume episodes of the Middle Pleistocene. This glaciation may also have been responsible for the glacial gravels on Lundy Island (Mitchell, 1968) and the glacial deposits of the Isles of Scilly (Barrow, 1904; Mitchell and Orme, 1967), which have been redistributed by solifluction on numerous occasions (Bowen, 1973a). But there is no evidence to support any longer the ice-margin reconstructed by Mitchell (1960), Stephens (1970) and Bowen (1973a) along the northern coast of south-west England. The hypothesis of Late Devensian glaciation of the Scillies, is based on radiocarbon ages of 'organic silts', which range in age between 21,500 and 34,500 BP (Scourse 1991). Even if these dates are correct, they do not invalidate the view that the overlying diamicts consist of head (Bowen 1973a). A programme for obtaining ^{36}C1 ages, on exposed bedrock north and south of the reconstructed ice-limit in the Isles of Scilly, may have a bearing on this problem.

Deposits of this extensive OI Stage 16 glaciation suggest that the general relief of the upper Bristol Channel was similar to the present. It occurred close in time to the Matuyama-Brunhes (780 ka) magnetic reversal when the catchment of the Upper Thames was reduced in size (Whiteman and Rose, 1992). Previously the fluvial Sudbury Formation was derived from outside the present catchment, whereas subsequently, the Colchester Formation originated within it. Such a glaciation at that time, therefore, may have overdeepened the Vale of Gloucester and reduced the extent of the upper Thames catchment.

Understanding the operation of the climate system during the last ice-age (Devensian/Wisconsinan) has been revolutionised by data from Greenland ice-cores. Rapid rises in temperature (interstadials), and atmospheric carbon dioxide levels, after longer periods of progressive cooling, occur immediately following major discharges of ice-floes into the North Atlantic from a collapsed Laurentide ice-sheet (LIS). These are recognised from ice-rafted debris (IRD) in North Atlantic cores, and they also coincide with major faunal (foraminifera) depletions called *Heinrich events* (Bond *et al.,* 1992). To explain the paradox of ocean chilling followed by rapid warming, MacAyeal (1993) suggested that the LIS collapsed on reaching a critical thickness (~3km) when it surged on a bed lubricated by saturated till. Previously, the elevation of the ice-sheet had split the jet stream into components north and south of the ice-sheet. After LIS collapse the jet stream was rejoined, warmer air was directed northwards, and thermohaline circulation in the North Atlantic (Broecker, 1991) was resumed. This raised air temperatures (interstadials), but was switched off again once ice-melting produced a lid of cold fresh water over the North Atlantic. But how does this relate to south-west England and Wales, which must have experienced such climatic changes?

The arboreal pollen record from Grande Pile in south-east France shows such brief interstadials. Limestone localities in Wales and south-west England, should also have evidence of such interstadials in the form of speleothem deposits. It is not insignificant that a speleothem at Bacon Hole Cave, Gower, has uranium-series ages of 13,000 ± 3,000 and 12,800 ± 1,700 (Stringer *et al.,* 1986). This corresponds to the interstadial warming immediately after Heinrich event H1 (Bond *et al.,* 1993). It is suggested that other speleothem horizons will be found to correspond in age to the interstadials that followed earlier Heinrich events in the Devensian.

Heinrich events also occurred during pre-Devensian ice-ages. During the Devensian the ocean transport gyre was anticlockwise and IRD events are recorded in the north-east Atlantic sector. Is it possible, therefore, that pre-Devensian such events may have delivered the 'giant erratics' on to the isostatically depressed coastal fringe of south-west England (Bowen, 1974)? What is the exact provenance and timing of delivery of the Saunton pink granite and the Giant Rock's garnetiferous microline gneiss? Is it possible that their provenance lies outside the British Isles, perhaps in Greenland if not from the LIS?

SOME WIDER CONSIDERATIONS

Considerable volumes of rock debris throughout the region can be attributed to the Devensian: for example, at Mattiscombe Sands the head is 27-33 m thick, and at Langerstone Point it extends outwards from the old cliff line for 270 m (Mottershead, 1971). Periglacial denudation during the 50 earlier ice-ages since 2.4 Ma, therefore, must have been the major landforming process. In Wales, such processes would have been preparatory to, concomitant with, and subsequent to glaciation. Between 2.4 and 0.9 Ma the relatively high frequency (41ka [tilt] frequency) but relatively low (global) ice-volume could imply that only upland areas in Wales carried ice-sheets. The evidence of acid igneous rocks from North Wales in the fluvial Sudbury Formation of the Thames Valley suggests as much. But it is possible that contemporary Welsh ice-sheets extended at least as far as the Cotswolds. This means that the geomorphology of Wales, like that of south-west England, consisted of undissected plateaux, not yet deeply incised. During the Middle and Late Pleistocene, when the 100ka cycle drew large ice-sheets into the lowlands of northern Europe and North America (Bowen, 1994), the Welsh ice-sheet was never as extensive as on earlier occasions. Might this have been the consequence of a now deeply dissected Wales, with a correspondingly greater capacity for ice 'storage'? This is also suggested by the comparative strength of successive Welsh and Irish Sea ice-sheets in contact along the Welsh Borderland and the Cheshire-Shropshire-Staffordshire lowland.

Extensive and repetitive periglacial and glacial erosion would appear to mitigate against the survival of earlier erosion surfaces. Yet, the distribution of outlying Tertiary deposits in both the -west England and Wales suggests that overall geomorphic profiles may approximate to an uplifted and deformed Oligocene landsurfaces (e.g. Brown, 1960; George, 1974; Straw, 1985). Given that the 'oldland' terrains of both Wales and South West were subject to pulsed late Cenozoic uplift (above), it is not impossible for erosion surface fragments to have survived. It is not difficult to conclude that the existing landforms of south-west England and Wales were fashioned primarily by periglacial and glacial processes, but neither erased completely earlier Cenozoic landforms, the palimpsests of which persist.

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