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Correlation of marine events and glaciations on the northeast Atlantic margin

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Stratigraphic units representing high-sea-level events in Britain, northern France, Belgium, The Netherlands, northwest Germany, Denmark, Sweden and Norway, are correlated by aminostratigraphy (*D* (alloisoleucine)/*L* (isoleucine) (ratios from *Littorina littorea*, *Macoma balthica*, *Macoma calcarea* and *Arctica islandica*). The eight sea-level events recognized are modelled with the constraints provided by the oxygen-isotope signal of sea-level variability, and available geochronometric age determinations for calibrating the *D*/*L* data. These data are used to constrain the timing and extent of glaciations in the British Isles and Scandinavia during the Middle and Late Pleistocene.

Introduction

Despite the convincing telecorrelation of continental loess ('glacials') and palaeosol ('interglacials' or 'interstadials') sequences with the oxygen-isotope signal of Brunhes time, notably in Central Europe (Kukla 1977), many uncertainties remain. In particular, the correlation of actual glacial deposits with specific oxygen-isotope stages does not yet rest on a firm stratigraphic basis. As a result much uncertainty occurs and major disagreement obtains on the timing and extent of glaciations, and especially their correlation with the oxygen-isotope signal. One view accepts the number of glaciations recognized by long-standing convention and makes correlation by a 'count from the top' (Kukla 1977) procedure down the even-numbered stages of the oxygen-isotope chronostratigraphic scale. Another has adapted an isoleucine epimerization time scale of marine events and correlated these with the conventionally recognized 'Cromerian', 'Holsteinian' and 'Eemian' Stages of Europe, by implication also dating the glaciations between those events (Miller & Mangerud 1985). Yet another view, widely represented in the IGCP Report on Project-24 'Quaternary glaciations in the Northern Hemisphere' (Sibrava *et al.* 1986) ascribes the European glaciations to the even-numbered stages of the oxygen-isotope signal for all of Middle Pleistocene time, in particular by recognizing two Elsterian Glaciations (I and II) and two (or three) Saalian Glaciations (Sibrava *et al.* 1986). But except for the Late Devensian and Late Weichselian Glaciations, which are constrained by radiocarbon dating, evidence for the age of the earlier ones is still under discussion.

Meanwhile, it is clear that progress is being influenced by pre-existing conventional classifications. The precept of the United States Geological Survey in declaring some of the American historical chronostratigraphic labels (e.g. 'Nebraskan' and 'Kansan') redundant (Richmond & Fullerton 1986) has yet to be followed in Europe despite unmistakable imperatives. For example, in a conventional sequence of three glaciations (from 'Cromerian' to present), the reclassification of a till at Esbjerg, Denmark, as 'pre-Cromerian' (formerly 'Elsterian') and overlying interglacial beds as 'Cromerian' (formerly 'Holsteinian') (Miller & Mangerud 1985) begs searching questions on the validity of correlating deposits by using these and other names elsewhere. Given such circumstances (see numerous examples in Sibrava *et al.* 1986), together with poor subsurface control and a generally inadequate knowledge of the geometry of stratigraphic units over wide areas, it is not unreasonable to suppose that, although correlation should be based on 'all possible means', the correlation and age of glacial stratigraphic units can only be convincingly based on a comprehensive geochronology from multiple dating methods. The promise of relatively new dating methods, such as amino acid epimerization, thermoluminescence dating (TL), electron spin resonance (ESR) dating, and the enhanced means of uranium-series dating (Edwards *et al.* 1986), has not yet been realized, but in combination they offer the prospect of solving many problems of correlation and dating.

The margin of the northeast Atlantic Ocean is an ideal testing ground for some of these methods because of its unique stratigraphic sequences of marine and glacial deposits; and although the 'state of the art' review shows that wider and more intensive dating programmes are desirable, the emerging correlations and age determinations already offer a stratigraphic framework superior to that of long-standing conventional classifications.

To a large and critical extent the global integrity of the oxygen-isotope signal and its unique attributes both as a chronostratigraphic and geochronological framework, and as a surrogate of ice-volume variability and sea-level change (Shackleton & Opdyke 1973), may be used to constrain the timing and patterning of sea-level change, and glaciation based on such application of multiple age determinations. But although the oxygen-isotope signal is a surrogate for global ice-volume variability it does not indicate the changing location nor the relative strength of ice centres, which is a necessary prelude to successful modelling of climatic change in the British Isles and Europe. The location of both these regions on the margin of the northeast Atlantic Ocean makes it likely that they were particularly sensitive to the climatic forcing of ice-sheet growth, especially in the case of western Britain.

The problem of relating the even-numbered stages of the oxygen-isotope signal to regional ice volume and extent is matched by the problem of the regional status of the odd-numbered stages of relatively low global ice volume: while these may rank as 'interglacial' on a global scale, provincial proxy data may be classified as 'interglacial' or 'interstadial' (see in Sibrava *et al.* 1986). Thus there is much potential for regional mis-correlation on the continents and between continents and oceans.

Successful ascription of the timing and relative extent of different ice-centres to the oxygen-isotope timescale will allow modelling of ice accumulation, notably related to patterns of precipitation availability, the circulation of the north Atlantic Ocean and, eventually, to modelling the atmosphere on timescales of 10^5 years.

CORRELATION

On the littoral margin of the northeast Atlantic Ocean in southwest Britain the geochronology of sea-level events and glaciations allows correlation with the oxygen-isotope signal (Bowen *et al.* 1985). It is based on the lithostratigraphy of marine and glacial stratigraphic units, which outcrop along the coastline (Bowen 1973), and its amplification by aminostratigraphy, using D-alloisoleucine: L-isoleucine ratios (D/L) from *Littorina littorea* (together with some other species which epimerize at similar rates), *Macoma balthica*, *Macoma calcarea* and *Arctica islandica*. Such shells occur in marine stratigraphic units as well as in glacial deposits. Shelly glacial deposits occur where Pleistocene glaciers have crossed parts of the continental shelf and former littoral areas, from where they incorporated the marine fauna. Many marine units, still in a geomorphological context of shore-platform and former sea-cliff, have withstood the passage of glacier ice across them (Bowen 1973). But others, notably in northwest Europe, have been brought near to the present surface along thrust planes caused by glacial tectonics: for example, in northwest Germany, 'Holsteinian' marine deposits are 'only exposed where they have been up-thrust by glacial tectonics' (Ehlers 1983). In such circumstances a regional lithostratigraphy is unlikely to be definitive however close the subsurface control may be, a view widely upheld in Sibrava *et al.* (1986), and independent age evaluation by aminostratigraphy and other dating methods is more likely to be definitive than a classification based on the use of facies-floras in 'interglacial' deposits.

Apart from some possible variability, between southern Britain and southwest Norway, it is assumed that fluctuations in Pleistocene temperatures throughout northwest Europe were uniform, thus eliminating the temperature term in epimerization kinetics. A limited number of geochronometric age determinations supports this. Similarly the species term is eliminated by using molluscs known to epimerize at the same rate. The use of overlapping species which epimerize at different rates from the same lithostratigraphic units extends the range of the method. Two data sets are used: one based on the relatively slow rates of epimerization shown by *Littorina littorea* (and other species (Bowen *et al.* 1985)), and another based on the relatively moderate rates of epimerization shown by *Macoma balthica*, *Macoma calcarea* and *Arctica islandica* (Miller & Mangerud 1985) (figure 1). The overlap between the two data sets is important, not only for use where one may be absent because of different palaeoecological conditions, but also because only *Macoma* and *Arctica* are found in shelly glacial deposits. The approach to correlation and dating, therefore, is unimpeded by conventional models of classification (Kukla 1977), and is based on independent parameters for correlating and dating stratigraphic units.

SEA-LEVEL EVENTS

Reproducible D/L ratios from molluscs in stratigraphic units throughout northwest Europe permit recognition of discrete events of high sea level. The data from *Macoma balthica*, *Macoma calcarea* and *Arctica islandica* show a larger number of sea-level events than the *Littorina* data, but the two data sets may be correlated, and eight high-sea-level events are recognized.

High-sea-level event 1 (*Macoma–Arctica* $D/L = 0.46$). This includes the fossiliferous marine sediments at Esbjerg, Denmark (Hansen 1965; Miller & Mangerud 1985), and the marine beds at Noord Bergum, The Netherlands (Miller & Mangerud 1985).

High-sea-level event 2 (*Macoma–Arctica* $D/L = 0.37$; *Littorina* $D/L = 0.26$). This includes the Vognsbøl Sand and the marine sands at Eartham (Boxgrove) in Sussex, which allows correlation with the *Littorina* D/L data (figure 1). Also included in this event are the marine sands at Hummelsbüttel ('Holsteinian'), Hamburg (Miller & Mangerud 1985).

High-sea-level event 3 (*Macoma–Arctica* $D/L = 0.29$; *Littorina* $D/L = 0.2$). This includes the upthrusted marine clays at Wacken ('Holsteinian'), which contain both *Macoma–Arctica* and *Littorina*, thus allowing correlation with the *Littorina* data (figure 1), including a reworked

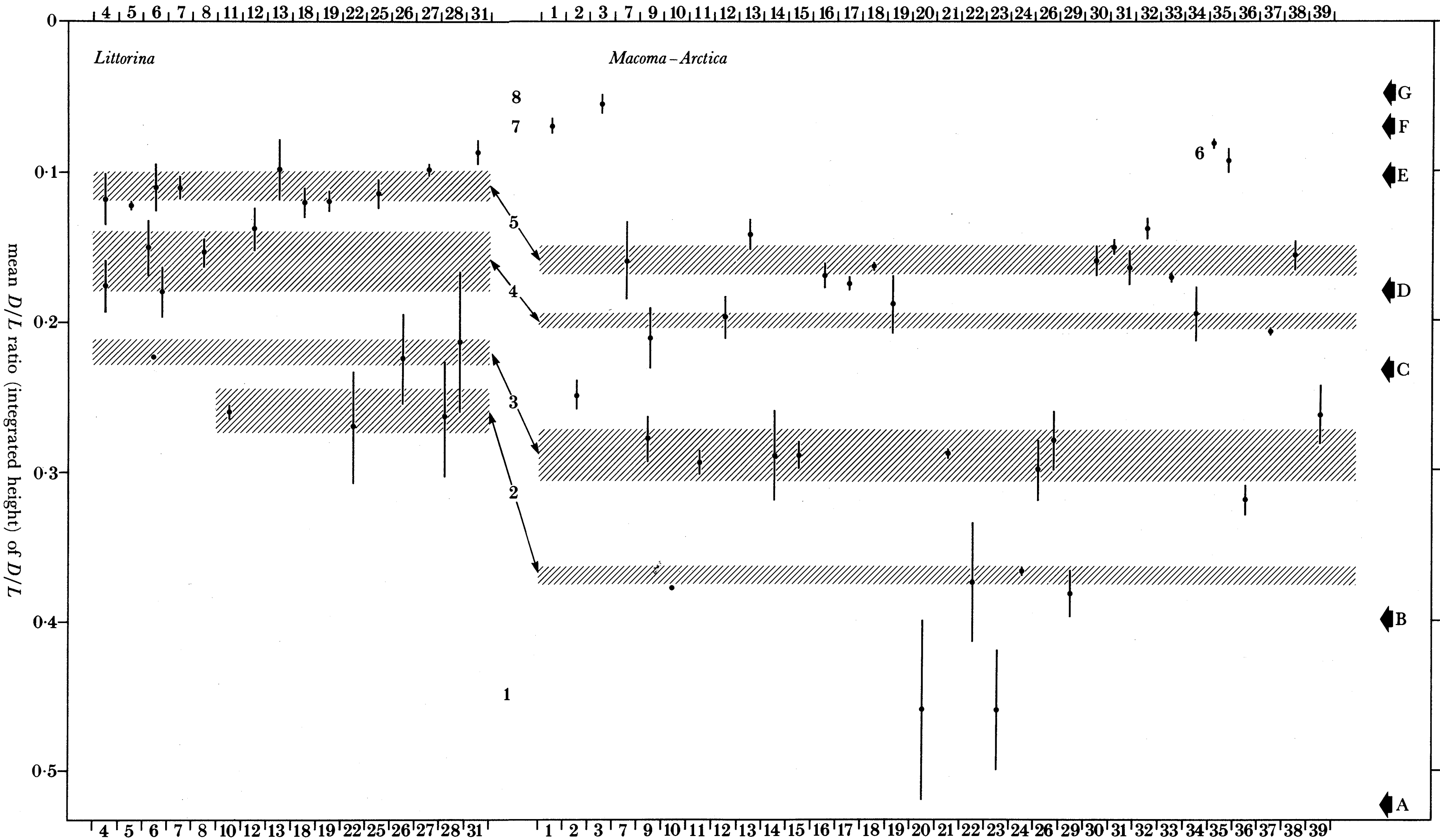

FIGURE 1. Aminostratigraphic correlation of *D/L* sea-level events in north-west Europe and the British Isles (based on Miller & Mangerud 1985; Bowen *et al.* 1985, unpublished data). One standard deviation for each sea-level event recognized is shown by the shading. The sea-level events are numbered 1 to 8, and glaciations lettered A to G. Two separate data points (*Arctica* and *Macoma*) are given for Wacken. The Sussex coastal plain data are from separate localities and are not stratigraphically superposed. Numbers at top and bottom indicate localities:

1, Belderg, Co. Mayo, Ireland; 2, Cleongart, Kintyre, Scotland; 3, Ardyne, Firth of Clyde; 4, Minchin Hole Cave, Gower; 5, Bacon Hole Cave, Gower; 6, southwest Britain (Pembrokeshire to Dorset); 7, Burtle Beds, Somerset; 8, Easington, Co. Durham; 9, Sussex; 10, Norton Farm, Sussex; 11, Eartham (Boxgrove), Sussex; 12, Fjøsanger, Norway; 13, Bø, Norway; 14, Herzeele, France; 15, Zeebrugge, Belgium; 16, Koolkerke, Belgium; 17, Bergen, The Netherlands; 18, Castricum, The Netherlands; 19, Zunderdorp, The Netherlands; 20, Noord Bergum, The Netherlands; 21, Scharnhorn, northwest (NW) Germany; 22, Vognsbøl, Denmark; 23, Esbjerg, Denmark; 24, Kaas Hoved, Denmark; 25, Tønder, Denmark; 26, Wacken, NW Germany; 27, Rodemis, NW Germany; 28, Halstenbek, NW Germany; 29, Hummelsbüttel, NW Germany; 30, Holnis, NW Germany; 31, Stensigmose, Denmark; 32, Mommark, Denmark; 33, Trappeskov, Denmark; 34, Ristinge, Denmark; 35, Skaerumhede, Denmark; 36, Slettenshage, Denmark; 37, Strandegaard, Denmark; 38, Stubberup, Denmark; 39, Margareteburg, Sweden.

fauna in Gower (Bowen *et al.* 1985). Included in this event are marine beds at Herzeele, some of the Norton Farm boring beach sands of the Sussex coastal plain (Lovell & Nancarrow 1983), and the marine beds at Margareteburg in Sweden. *Macoma balthica* shells from Margareteburg give slightly lower D/L ratios (Miller & Mangerud 1965), which could be explained by a small difference in the integrated temperature history of that locality.

High-sea-level event 4 (*Macoma–Arctica* $D/L = 0.2$; *Littorina* $D/L = 0.16$). This includes the Fjøsanger marine beds, as well as those at Strandegaard and Ristinge Klint in Denmark (Miller & Mangerud 1985). These European sites are correlated with stratigraphic units identified throughout southwest Britain and, in particular, with the stratotype at Minchin Hole Cave, Gower (Bowen *et al.* 1985). The slightly lower *Littorina* D/L ratios of 0.14 at Fjøsanger are explained by a small difference in the integrated temperature history of that site, which lies some 10° north of Gower.

High-sea-level event 5 (*Macoma–Arctica* $D/L = 0.16$; *Littorina* $D/L = 0.11$). The Eemian parastratotype of Castricum is included in this event, together with numerous other localities in northwest Europe. This high-sea-level event is recognized throughout southwest Britain and is represented by the Outer Gravel Beach at Minchin Hole Cave, Gower, and the marine beds at Bacon Hole Cave, Gower (Bowen *et al.* 1985). Overlapping *Macoma* and *Littorina* species in the Burtle Beds of Somerset and at Castricum and Zunderdorp in The Netherlands (Eemian parastratotypes), demonstrate the strength of this correlation. The marine beds of Bø, Norway, yield *Littorina* with somewhat lower D/L ratios (0.097) (Miller & Mangerud 1985), but are correlated with Rodemis in northwest Germany (0.098) and Stensigmose in Denmark (0.086); but it is possible that the marine beds at the two latter localities may be slightly younger.

High-sea-level event 6 (*Macoma* $D/L = 0.093$; *Arctica* $D/L = 0.082$). This is based on measurements of D/L ratios from shells in the marine sediments encountered in the Skaerumhede Borings (Miller & Mangerud 1985). These D/L ratios correlate with those measured in *Macoma* and *Arctica* shells from shelly glacial deposits in the British Isles, which show a marine transgression of that age across the British seas.

High-sea-level event 7 (*Macoma* $D/L = 0.07$). This glaciomarine high-sea-level event is shown by D/L ratios of 0.07 from *Macoma calcarea* shells collected from a glaciomarine delta at Belderg, County Mayo, Ireland (McCabe 1986). These ratios correlate with similar ones on the east coast of Ireland at Tullyallen, Drogheda.

High-sea-level event 8 (*Arctica* D/L 0.055). This event is based on D/L ratios from *Arctica* shells from the marine Clyde Beds of Scotland at Ardyne (Miller *et al.* 1987).

GEOCHRONOLOGY

The geochronology of the eight high-sea-level events is modelled in terms of oxygen-isotope stages (figure 2) according to different assumptions, available independent geochronometric age determinations and other geological information. The age of the younger D/L sea-level events is secure and is based on a combination of radiocarbon, uranium-series and thermoluminescence (TL) dating. Electron spin resonance (ESR) ages for some of the intermediate-aged sea-level events are few or, at one locality, in conflict. All the models are limited by the paucity of independent age determinations to calibrate the D/L timescale, and modifications may be necessary as new geochronometric ages are forthcoming.

High-sea-level event 8 is ascribed to Stage 2 (of the oxygen-isotope scale) by radiocarbon

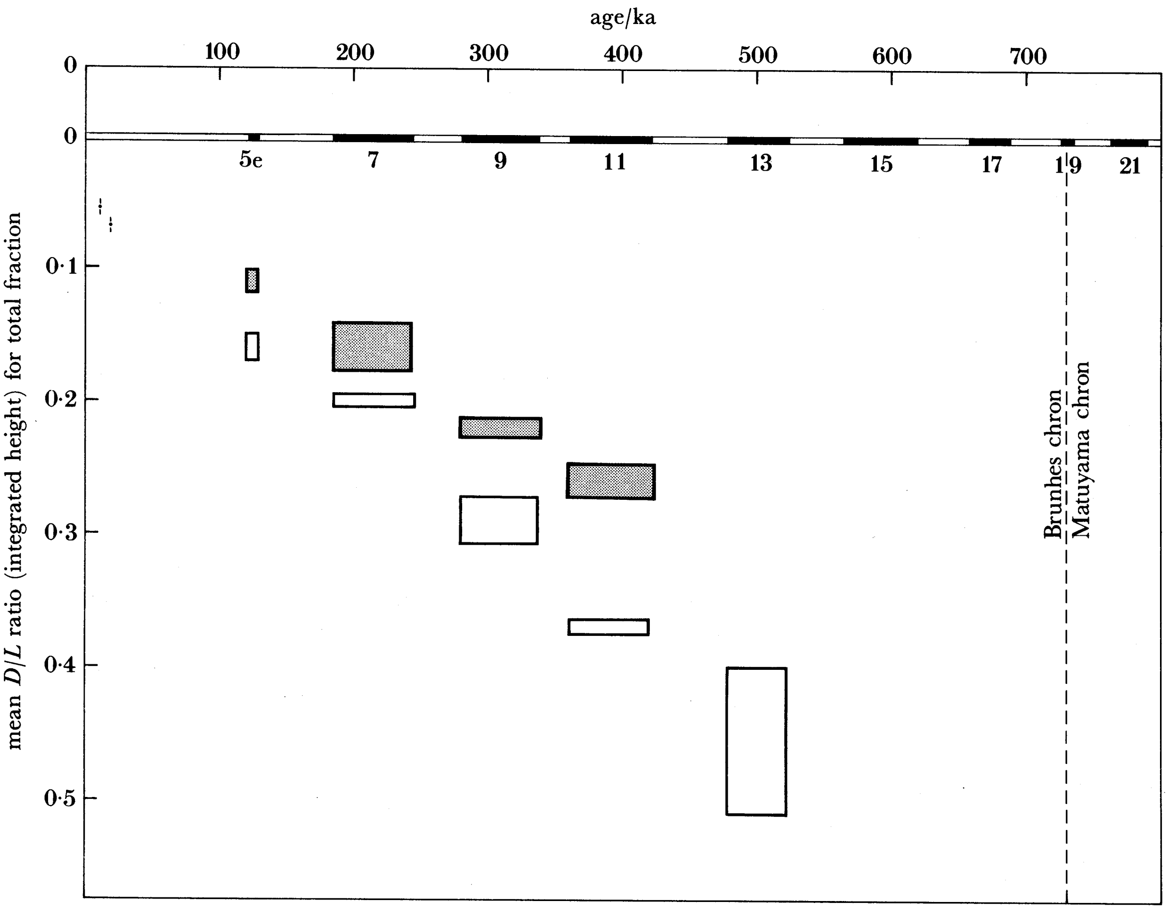

FIGURE 2. Correlation of D (alloisoleucine)/L (isoleucine) high-sea-level events with odd-numbered oxygen-isotope stages on the SPECMAP timescale of Imbrie *et al.* (1984). The rectangles show one D/L standard deviation correlated with odd-numbered oxygen-isotope stages. Shaded boxes show the *Littorina* D/L data; unshaded boxes, *Macoma–Arctica* D/L data. (Model 1 assumptions.)

dates of 11.2 and 11.6 ka BP on *Arctica* shells from Ardyne, Scotland (Miller *et al.* 1987). Sea-level event 7 is dated by radiocarbon ages of 16.9 and 17.3 ka BP on an *in situ Macoma calcarea* fauna from a glaciomarine delta, at 40 m above sea-level, at Belderg, County Mayo. Correlation by aminostratigraphy shows that the glaciomarine deposits at a similar elevation on the east coast of Ireland at Tullylallen, Drogheda, are the same age. Sea-level event 6 is not directly dated by a geochronometric age determination but is ascribed to Stage 3 because it lies between sea-level event 8 (*ca.* 17 ka BP) and sea-level event 5 (122 ka BP; see below).

Sea-level events 5 and 4 are calibrated by uranium-series and thermoluminescence dates from Gower. At Bacon Hole Cave, D/L ratios on *Littorina* of 0.122 are overlain by speleothem fragments with a mean age of 122 ka BP (Stringer *et al.* 1986). The Bacon Hole marine beds are correlated with the Outer Gravel Beach and associated beds at the adjacent cave of Minchin Hole both by aminostratigraphy and by further uranium-series dates of 116 ka BP, from a speleothem block in a similar relation to the beach deposits as at Bacon Hole Cave (Sutcliffe & Currant 1984). The outer gravel beach overlies and is separated from an inner sand beach by a thermoclastic deposit with a cold-stage fauna (Sutcliffe & Currant 1984). The inner sand beach at Minchin Hole Cave, Gower, contains *Littorina littorea* shells with a D/L

ratio of 0.176. It also has a mean TL age of 191 ka BP (Southgate 1986). Thus the beds with a D/L ratio of 0.1 are correlated with Substage 5e and those with a D/L ratio of 0.176, with Stage 7. The stratotype for both sea-level events is Minchin Hole Cave, where the lithostratigraphic sequence shows the Stage 7 beach overlain by a cold-climate head deposit, in turn overlain by the Substage 5e marine beds (Sutcliffe & Bowen 1973; Bowen 1977). The Bacon Hole succession shows no further marine event in a sequence of fossiliferous terrestrial deposits between the 5e marine beds and a stalagmite floor dated by uranium series to 81 ka BP (Stringer *et al.* 1986) at the base of Devensian head deposits. Thus along the northern side of the Bristol Channel there is no evidence for 5c or 5a sea levels. These age ascriptions have an important bearing on similarly aged events on the continent and in Scandinavia. Much rests, therefore, on the lithostratigraphy, D/L data, and geochronology of Minchin Hole Cave. The only uncertainty arises because the speleothem age determinations are on broken samples, not *in situ*.

In southwest Britain an overlap between *Littorina* (and *Patella*) and *Macoma balthica* occurs in the Burtle Beds of Somerset, where *Littorina* D/L ratios of 0.11 ± 0.007 ($n = 11$) overlap with *Macoma balthica* D/L ratios of 0.163 ± 0.025 ($n = 17$) (0.15 if possible re-worked samples are excluded from the calculation). This compares with the overlap relations shown by Miller & Mangerud (1965) for *Littorina* (0.098) and *Arctica* (cf. *Macoma*) (0.016) in Schleswig-Holstein. The D/L data from Minchin Hole Cave and Gower show a sea-level event (the Minchin Hole (D/L) Stage (Bowen *et al.* 1985)) with a mean ratio of 0.175, ascribed to Stage 7, which is apparently unrecorded in Schleswig-Holstein (table 1). After allowing for a 10° latitudinal distance between Gower and southwest Norway, with a consequent difference in integrated temperature history, it may be possible to recognize that sea-level at Fjøsanger (*Littorina* $D/L = 0.15$); the beds at nearby Bø (*Littorina* $D/L = 0.097$), although correlated by Miller & Mangerud (1985) with those at Fjøsanger, may correlate with the Pennard (D/L) Stage 0.11, which is ascribed to Substage 5e (Bowen *et al.* 1985). Thus Fjøsanger is ascribed to Stage 7 (as in one of the two models of Miller & Mangerud 1985)), and Bø to Substage 5e. Clarifying the *Arctica–Macoma* data is less straightforward. But the *Arctica* D/L ratios at Bø of 0.14 compare

TABLE 1. CORRELATION OF D/L RATIOS IN *LITTORINA LITTOREA*

(B, Bø; F, Fjøsanger; asterisks indicate the stratigraphic position of the thermoclastic scree (with cold-stage fauna) at Minchin Hole Cave, Gower (Bowen *et al.* 1985).)

Minchin Hole Cave	Bacon Hole Cave	southwest Britain	Norway	Schleswig-Holstein
0.12 ± 0.018	0.12 ± 0.002	0.11 ± 0.016	0.09 ± 0.017(B)	0.098 ± 0.004
**********				
		0.153 ± 0.018[a]		
0.18 ± 0.017		0.18 ± 0.015	0.15 ± 0.03(F)[c]	
		0.21 ± 0.008[b]		0.22 ± 0.03

[a] Separate D/L sea-level event identified by Bowen *et al.* (1985) throughout SW Britain (equivalent *Patella* D/L ratio is 0.135); it is suggested that this is close in time to the 0.18 D/L sea-level event.

[b] D/L ratios from *Littorina littoralis*, *Nucella lapillus* and *Patella vulgata* standardized to *Littorina littorea* (see Bowen *et al.* 1985).

[c] It is probable that two distinct populations are represented by this mean ratio; on this assumption two populations could be represented by D/L ratios of 0.193 ± 0.01 ($n = 4$) and 0.137 ± 0.011 ($n = 8$), thus demonstrating possible reworking of older fauna and sediments.

with those of 0.16 from the Burtle Beds in Britain and Schleswig-Holstein; and the *Arctica D/L* ratios of 0.197 from Fjøsanger could compare with ratios of *ca.* 0.21 as typical Stage 7 values elsewhere. Such an expectation is fulfilled, and other Stage 7 sea-level events may be recognized, at Ristinge (Denmark) (*Arctica* $D/L = 0.2$), Strandegaard, Denmark (*Arctica* $D/L = 0.21$), and Ham Cottages, Sussex (*Macoma* $D/L = 0.21$). All of these localities were previously considered to be Eemian or 'last interglacial'. Some stratigraphic units ascribed to Substage 5e, e.g. at Castricum and Koolkerke, include some re-worked fauna of Stage 7 age.

ESR age determinations from Hummelsbüttel ('Holsteinian'), in northwest Germany, which give Stage 7 ages (Linke *et al.* 1985), are incompatible both with the *D/L* data (*Macoma* $D/L = 0.382$) from that site (Miller & Mangerud 1985), and with a further ESR determination of 371 ka BP (Sarnthein *et al.* 1986). The *D/L* data and the ESR age determination of Sarnthein *et al.* (1986), are, however, not incompatible.

For high-sea-level events previous to those correlated with Stage 7, the *D/L* data can be modelled in at least three ways.

Model 1

The ESR determinations of Sarnthein *et al.* (1986) may be used to ascribe *D/L* high-sea-level event 3 (represented by the marine deposits at Wacken ('Holsteinian'), dated to 300 ka BP, and those at Herzeele, dated to 348 ka BP) to Stage 9. Similarly the ESR age of 371 ka BP at Hummelsbüttel ('Holsteinian') (Sarnthein *et al.* 1986) is used to ascribe *D/L* sea-level event 2 to Stage 11. Assuming that no major breaks in the stratigraphic record occur, *D/L* high-sea-level event 1 can therefore be ascribed to Stage 13. Zagwijn ascribed the Esbjerg marine beds (*D/L* sea-level event 1) to 'Cromerian IV' (in Mangerud & Miller 1985).

Model 2

It is possible, however, that the difference of 0.09 between the 0.46 and 0.37 *Macoma–Arctica D/L* groups represents more than the 55 ka between Stages 13 and 11. The oldest available *D/L* ratios (*Macoma* $D/L = 0.46$) are from Noord Bergum in The Netherlands (formerly classified as 'Holsteinian' but revised to 'Cromerian' by Ter Wee (1983)), and Esbjerg in Denmark (also formerly classified as 'Holsteinian' but revised to 'Cromerian' (Miller & Mangerud 1985). The Esbjerg marine deposits grade upwards from late-glacial beds which overlie a till, formerly classified as 'Elsterian' (Sjørring 1983). On the basis of model 1, the glaciation which deposited the till is ascribed to Stage 14. It is, however, possible that the basal till at Esbjerg is older. One possibility for correlation is with the till at the top of the North Sea Aberdeen Ground Beds Formation, which lies just above the Matuyama–Brunhes boundary (Cameron *et al.* 1987). If this correlation is correct, the basal till at Esbjerg could be time-equivalent to, for example, Stage 18, and sea-level event 1 occurred in Stage 17. Consequently slower epimerization kinetics must be assumed and sea-level event 2 could be ascribed, for example, to Stage 13 (figure 2), and sea-level event 3 to Stages 11 or 9. Equally the glacial beds could be ascribed to Stage 16; this ascription is advantageous because, in global terms, this was a time of exceptional ice-volume on the continents. On this basis the *Macoma* $D/L = 0.46$ sea-level event could be Stage 15 in age.

Model 3

A further consideration arises from contextual changes in sea-levels throughout the global ocean. It has been shown, for example, that a major 'lacuna' (Blackwelder 1981) occurs with no dated marine deposit between Stage 11 and 1.1 Ma BP. This may correspond with the lower temperatures and lower sea-levels inferred from the isotope signal for Stages 13 to 21 (see, for example, Shackleton *et al.* 1984). Sea-level data showing this are widespread and include those from the coasts of the Mediterranean basin (Hearty *et al.* 1986), California (Karrow & Bada 1980; Muhs & Szabo 1982), Atauro (Chappell & Veeh 1978), and the eastern U.S.A. (Blackwelder 1981). Yet models 1 and 2 (above) recognize pre-Stage 11 sea-levels in northwest Europe. This result may have been brought about by neotectonic movements, or it may be that the sequence is incorrectly ascribed to the isotope signal. Alternatively, if the data are modelled from Stage 11 onwards, then two of the D/L high-sea-level events need to be subsumed within the same stage. Similar problems of ascription of the sea-level events arise if the epimerization kinetic pathway is more rapid than that assumed in model 1.

The reproducibility of D/L ratios from marine molluscs is clear (figure 1) (Miller & Mangerud 1985; Bowen *et al.* 1985), although more information could modify the pattern of high-sea-level events adduced here. Similarly, the timing of these events may be modified by further geochronometric age determinations. But, with the available information, model 1 is preferred and to some extent can be used to place constraints on the extent and timing of glacial advances (table 2).

TABLE 2. CORRELATION OF D/L RATIOS IN *MACOMA* AND *ARCTICA*

(B, Bø; F, Fjøsanger; *, Arctica.)

southern Britain			
Burtle Beds	Sussex	Norway	northwest Europe
0.157 ± 0.018		0.14 ± 0.01*(B)	0.16 ± 0.01*
0.21 ± 0.004[a]	0.206 ± 0.015[b]	0.197 ± 0.01*(F)	
	0.30 ± 0.02		0.28 ± 0.01*
			0.30 ± 0.02

[a] A reworked faunal element is assumed in the Burtle Beds and is represented by D/L ratios of 0.21.

[b] The same stratigraphic unit contains *Littorina littoralis* ($D/L = 0.144 \pm 0.006$) and *Littorina saxatilis* ($D/L = 0.132 \pm 0.006$); standardized to *Littorina littorea*, these data give a D/L ratio of 0.144 ± 0.006 ($n = 10$) (cf. table 1).

THE SEQUENCE OF GLACIATIONS

The earliest northwest European glaciations of the past 3 million years are older than the available D/L data. The oldest one inferred is based on the evidence of ice-rafting in DSDP hole 552a (Rockall), dated to 2.4 Ma BP (Shackleton *et al.* 1984), which in the broadest terms could correlate with the Scandinavian erratics found in Pliocene deposits in northwest Germany (Ehlers 1983). Subsequent glaciation may be inferred from the heavy mineral assemblage derived from a northerly source in the Baventian deposits of East Anglia (Solomon, in Funnell & West 1962) and the Yorkshire Wolds (Catt 1982), and the Menapian deposits of The Netherlands (Zagwijn 1986). But the first major glaciations, around about the

Matuyama–Brunhes boundary, are to be inferred from erratics of north Wales provenance found in the Kesgrave Formation of Essex (Rose & Allen 1977; Hey 1965). Rose (in Bowen *et al.* 1986) has inferred four glaciations of upland Britain from such evidence in the sediments of the Kesgrave Formation and its correlatives in the Middle Thames (Green *et al.* 1980). These are correlated with the Yarmouth Roads Formation of the North Sea (Balson & Cameron 1985) and the Sterksel Formation of The Netherlands (Zagwijn 1986).

Glaciation A (*Stage* 14) (‘*Elster* I’?)

The oldest glacial deposit directly related to the *D*/*L* sea-level sequence is the till beneath the marine sediments of sea-level event 1 at Esbjerg, Denmark. On model 1 considerations it is ascribed to Stage 14 because its deposits grade upwards into the (Stage 13) Esbjerg marine beds. This till is probably the same age as the one beneath the interglacial beds at Harreskov (‘Cromerian’), Denmark (Sjorring 1983), and thus could be equivalent to the pre-Voigstedt (‘Cromerian’) Elster I Glaciation proposed in East Germany (Cepek 1986). On model 2 assumptions, the till, correlated with the one on top of the Aberdeen Ground Beds Formation, just above the Matuyama–Brunhes boundary (‘Glacial A’ of Cameron *et al.* (1987)), could represent a glaciation (?Stage 18) broadly coeval with one of the early upland glaciations of western Britain. But, as previously discussed, this glaciation could be time-equivalent to Stage 16.

Glaciation B (*Stage* 12) (‘*Elster* II’?, *Anglian*, ‘*older drift*’ *Irish Sea*)

This is younger than *D*/*L* sea-level event 1 (Stage 13), but older than sea-level event 2 (Stage 11). On this basis the upper till at Esbjerg and the glaciolacustrine beds at Noord Bergum are ascribed to the Stage 12 (B) Glaciation. If *D*/*L* sea-level event 2 (Stage 11) is taken as a minimum age for the Stage 12 (B) Glaciation, the basal tills at Kaas Hoved and Hummelsbüttel are ascribed to this event. Because a Stage 10 glaciation has not been widely recognized in the northern hemisphere, including Europe, it is assumed that this relatively brief cold stage did not witness extensive glaciers; this assumption is supported by the available geological evidence (Sibrava *et al.* 1986). It follows, therefore, that the marine deposits ascribed to the *D*/*L* sea-level event 3 (Stage 9) may also be used as minimum ages for the Stage 12 (B) Glaciation. Thus the ‘Holsteinian’ deposits at Wacken may also be used in this way, although they are not the same age as the ‘Holsteinian’ deposits at Hummelsbüttel (as shown by both *D*/*L* ratios (Miller & Mangerud 1986) and ESR age determinations (Sarnthein *et al.* 1986)). In Gower the mixed faunas (sea-level event 3) of Hunts Bay can be used to fix a minimum age for a Stage 12 (B) ‘Irish Sea’ Glaciation of the Bristol Channel, which includes the Fremington Till of north Devon (Bowen *et al.* 1985). *D*/*L* measurements on non-marine shells from ‘interglacial’ deposits overlying the Anglian tills (Hughes 1987) are ascribed to Stages 11 and 9, thus dating the underlying tills as Stage 12 (Glaciation B). This dating is consistent with the views of Perrin *et al.* (1979) that the chalky tills of the Anglian Glaciation in midland England and in East Anglia represent the maximum extension of ice in lowland Britain, which is correlated with the post-Esbjerg interglacial (sea-level event 1) glaciation of The Netherlands, that is, with the glaciolacustrine deposits of the Elster Glaciation (Elster II?). This view accords with those of Sarnthein *et al.* (1986), who also ascribed the Elster Glaciation to Stage 12, and Bowen (1985), who ascribed this event to Elster II. (On model 2 considerations this glaciation would be ascribed to Stage 14, the Elster I advance of Cepek (1986) and others; see Sibrava (1986).)

Table 3. Correlation of oxygen-isotope stages, D/L sea-level events and glaciations, based on model 1 assumptions

age[a]	stage	D/L sea-level event *Macoma–Arctica* (*Littorina*)		geochronology ka BP	glaciation	
		8	0.05	11	G	Loch Lomond
	2					
		7	0.07	17	F	late Devensian late Weichselian
24						
	3	6	0.085			
59						
	4				E	in Scotland, Ulster and Ireland
71						
	5					
122						
	5e	5	0.16 (0.11)	122		
128						
	6				D	‘Warthe’
186						
	7	4	0.2 (0.16)	191		
245						
	8				C	‘Drenthe’ ? Paviland
303						
	9	3	0.29 (0.22)	300 348		
339						
	10					
362						
	11	2	0.37 (0.26)	371		
423						
	12				B	‘Elster’ (Anglian, ‘Irish Sea’)
478						
	13	1	0.46			
524						
	14				A	‘Elster’ (‘Elster I’ ?)
565						

[a] SPECMAP age (Imbrie *et al.* 1984).

Glaciation C (*Stage* 8) (*Paviland*, ‘*Drenthe*’)

This glaciation is fixed between D/L sea-level events 3 (Stage 9) and 4 (Stage 7). Ice-thrusted marine sediments of D/L sea-level event 3 age occur at Halstenbek, near Hamburg. At this locality the D/L ratios (Miller & Mangerud 1985) are in conflict with a U-series age which places the sediments in the Eemian (5e) interglacial (Sarnthein *et al.* 1986). At Slettenshage, Denmark, marine clay with D/L ratios of sea-level event 3 (Stage 9) occurs in till, which is thus ascribed to Stage 8 (Glaciation C). That same glaciation (C) is comparatively restricted in the British Isles. In Gower, the Paviland Moraine and its deposits are older than marine deposits of the D/L sea-level event 4 (Stage 7) and have been ascribed to Stage 8 (Glaciation C) (Bowen *et al.* 1985). Possible correlatives of this have been identified in the west Midlands of England at Quinton, Birmingham, which is the basis for the extent shown in figure 3. At Welton, in Lincolnshire, a till sequence has also been ascribed to the Stage 8 (Glaciation C) advance (Bowen *et al.* 1986). Because the March Gravels of the Fenland (ascribed to *D/L* sea-level event 9) are not overridden by glacial deposits they may also be used to constrain the extent of Stage 8 glaciation. In all three cases in the British Isles the limit of the Stage 8 (Glaciation C) advance lies immediately outside the limit of late Devensian glaciation. On this evidence it is most unlikely that the British and European ice-sheets were in contact at this time.

Glaciation D (*Stage* 6) (‘*Warthe*’)

This occurred between *D/L* sea-level events 4 (Stage 7) and 5 (Substage 5e). In Europe, possible representatives of this glaciation (D) are tills above marine deposits of *D/L* sea-level 4 at Ristinge Klint and Strandegaard in Denmark. At both localities three till units overlie marine deposits of Stage 7 age. Till units beneath Substage 5e marine beds occur at Tønder and Stubberup in Denmark (Miller & Mangerud 1985). There is no unequivocal evidence in the British Isles for glaciation during Stage 6. Certainly any ice did not extend as far south as County Durham, on the east coast of England, where the Easington raised beach (sea-level event 4, Stage 7) is overlain by Late Devensian till. Equivocal *D/L* data from shelly tills in Ireland and Scotland (Caithness and Orkney) may show Stage 6 glaciation of these areas. But an alternative interpretation is that these are Stage 4 (Early Devensian) in age (below). More data, and geochronometric calibration, may resolve this problem. In any event, it is difficult to envisage no ice cover in the British Isles at this time, which corresponds generally to the ‘Warthe’ Glaciation of Europe (figure 3); upland Britain, at least, would have been ice-covered at this time.

Three separate glaciations are recognized in the Devensian Stage of Britain. These are: an early Devensian Glaciation (E), the Late Devensian Glaciation (F) (Dimlington Stadial of Rose (1985)), and the Loch Lomond Glaciation (G). *D/L* data for recognizing these comes principally from the western seaways and continental shelf areas of Britain.

Glaciation E

An Early Devensian Glaciation (E) is recognized in Ireland and Scotland. In both areas, tills occur containing only molluscs ascribed to the Substage 5e sea-level event (5) or older (D. Q. Bowen, G. A. Sykes, D. G. Sutherland, J. Gordon & A. M. McCabe, unpublished data). None of these contains molluscs with a Middle Devensian (Weichselian) *D/L* signature (Bowen, Sykes, Sutherland, Gordon & McCabe, unpublished data). It follows, therefore, that glaciation occurred after Substage 5e (sea-level event 5) but before sea-level event 6 (Middle Devensian, Stage 3). In contrast, glacial deposits of the Late Devensian Glaciation contain molluscs from both the Substage 5e (sea-level event 5) and Stage 3 (sea-level event 6) marine transgressions, and sometimes, from a glacio-marine sea-level event (7) contemporaneous with Late Devensian ice. Because the sea would have occupied some areas of the continental shelf more or less continuously, especially as the result of isostatic depression during and after the glaciations, it may be difficult to discriminate precise high-sea-level events on the basis of *D/L* signature, as is evident from the spread of *D/L* ratios from molluscs in glacial deposits. But, as one interpretation of the available data shows, a post-Substage 5e and pre-Stage 3 glaciation affected parts of Caithness and Orkney in Scotland, and Ulster and the eastern coast of Ireland (figure 3). In the absence of independent geochronological control, however, it is impossible

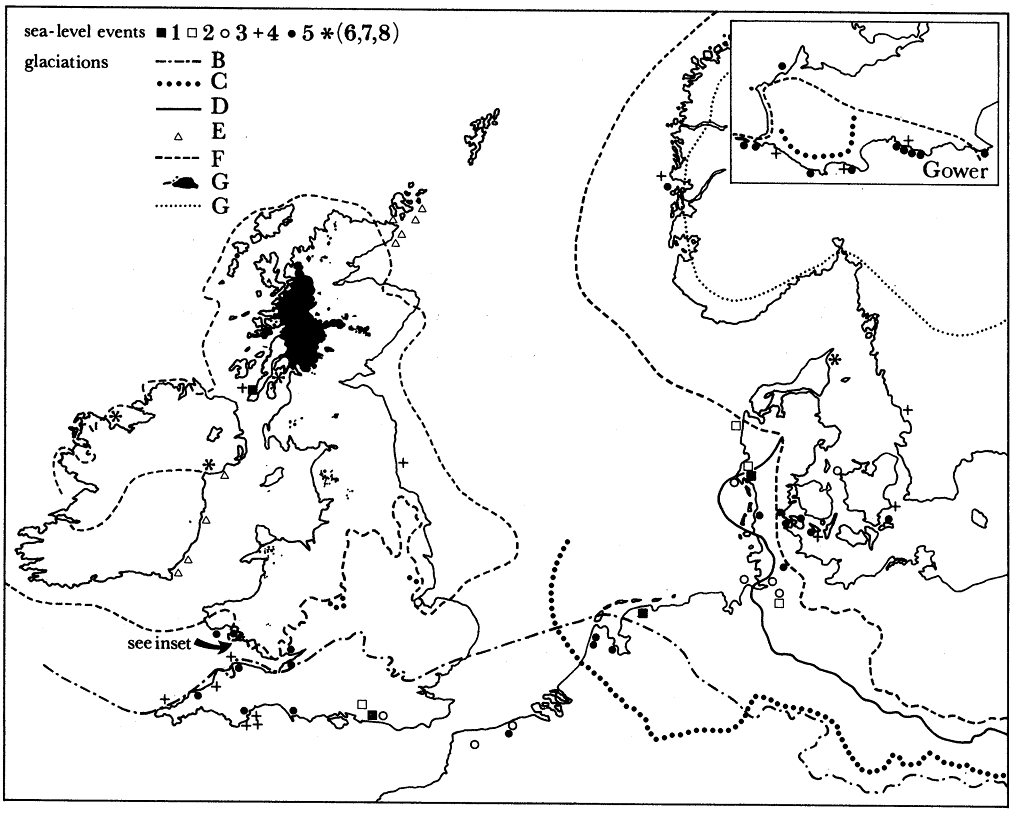

FIGURE 3. Extent of glaciations in the British Isles and northwest Europe. Sea-level events (*Macoma*/*Arctica* data): 1, $D/L = 0.46$ (Stage 13); 2, $D/L = 0.37$ (Stage 11); 3, $D/L = 0.29$ (Stage 9); 4, $D/L = 0.2$ (Stage 7); 5, $D/L = 0.16$ (Substage 5e); 6, $D/L = 0.83, 0.92$ (Stage 3); 7, $D/L = 0.07$ (Stage 2); 8, $D/L = 0.055$ (Stage 2). Glaciations: B, Stage 12 ('older drift' Irish Sea, Anglian, Elster' (II ?); C, Stage 8 (Paviland, 'Warthe'); D, Stage 6 ('Warthe'); E, ?Stage 6, or Substage 5d or Stage 4 (shelly glacial deposit localities); F, Stage 2 (Late Devensian, Late Weichselian); G, Stage 2 (Loch Lomond; asterisk indicates Ra and central Sweden moraines).

to ascribe this event to either Stage 4 or 5d. Independent calibration, however, may demonstrate an important temperature term in the data, and it is not impossible that some of the D/L ratios currently interpreted as 5e in age could be older, perhaps of Stage 7 age. In that eventuality, the glacial deposits of Caithness and Orkney could be older and possibly ascribed to Stage 6. As such they would find a ready parallel with the 'Warthe' advance of Denmark and northwest Germany, which also extended beyond the margin of Late-Devensian–Weichselian glaciation.

Glaciation F (*Stage* 2) (*Late Devensian–Late Weichselian*)

The establishment of the margins of the Late Devensian Glaciation (F) has been controversial (Bowen 1973) (figure 3). But Late Devensian glacial units containing marine molluscs of Stages 3 and 2 have been identified throughout the British Isles. Molluscs from glaciomarine beds at Belderg, County Mayo, Ireland, have been dated to *ca.* 17 ka BP. In elevation (*ca.* 40 m above sea-level) they compare with similar deposits on the east coast of Ireland at Tullyallen in County Meath. The beds at both localities are contemporaneous with the

'Drumlin Readvance' and show considerable isostatic recovery since that time. At the time of maximum advance it is reasonable to assume that a large ice sheet occupied the Irish Sea basin and St George's Channel. During deglaciation, deposition in glaciomarine environments was widespread (McCabe 1976, 1987*a*, *b*).

Analysis of the total amino-acid ratios of molluscs collected from glacial units in the Isle of Man show that all the exposed deposits are Late Devensian in age, as was previously suggested on lithostratigraphic grounds (Thomas 1976). In southwest Wales and in the Cheshire–Shropshire–Staffordshire lowland, similar D/L data demonstrate Late Devensian glacial deposits. In Scotland, shelly drift near Irvine in Ayrshire, which contains Late Devensian molluscs, overlies interstadial deposits dated to 29 ka BP (W. G. Jardine, personal communication). The shelly tills of northwest Lewis, Outer Hebrides, are Late Devensian in age, as are those at Latheron Wheel on the northwest side of the Moray Firth.

Glaciation G (*Stage* 2) (*Loch Lomond*)

During Younger Dryas time, between 11 and 10 ka BP, ice of the Loch Lomond Advance (Glaciation G) covered much of southwest Scotland, while glacier ice and large snow patches occupied cirques farther south in Britain (Sissons 1979). This event corresponds to the position of the late Weichselian ice margin in Scandinavia at the Ra moraines in Norway. Till of the Loch Lomond ice-cap on the island of Mull contains *Arctica islandica* shells with D/L ratios of 0.4. The marine Clyde Beds at Ardyne contain *A. islandica* shells with D/L ratios of 0.5 and have been ^{14}C dated to 11160 and 11575 years BP (Miller *et al.* 1987).

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Discussion

C. Turner (*Department of Earth Sciences, The Open University, Milton Keynes, U.K.*). The reported amino-acid measurements suggest that the Holsteinian marine deposits at Hummelsbüttel in the type area at Hamburg are (*a*) of equivalent age to the deposits at Boxgrove in southern England and (*b*) distinctly older than the Holsteinian marine deposits at Wacken, Schleswig-Holstein. This proposal causes considerable stratigraphic problems. The Quaternary deposits of the Hamburg area have been investigated both at depth and more intensively than perhaps anywhere else in northern Europe. It is clear that the Holsteinian deposits in Hamburg and at Wacken post-date the youngest of the Elsterian tills and can be correlated with each other from many section and borehole records in considerable detail based on marine macro- and micro-fauna and palynology. This was well demonstrated at a recent meeting of the INQUA Sub-commission on European Quaternary Stratigraphy in Hamburg. Both Hummelsbüttel and Wacken unequivocally belong to the same interglacial stage. On palaeontological grounds, the Boxgrove site is now agreed to relate to a temperate stage older than the Anglian glacial stage (and, of course, older than the Hoxnian interglacial). The correlations proposed in this paper would, therefore, imply that the Anglian glacial period of Britain is younger than, and not to be correlated with, *any* part of the Elsterian complex in Europe, and that the Holsteinian typesite is not only older than other Holsteinian sites nearby but likewise older than the Hoxnian, with which the Holsteinian is now firmly correlated.

These deductions from amino-acid measurements fly in the face of some of the most carefully and firmly established correlations in North European stratigraphy. Such problematical and apparently aberrant results have to be looked into more carefully, even if initially repeatable (which is, in itself, not an explanation) to maintain confidence in the use of amino-acid racemization measurements as a precise and useful chronostratigraphic tool.

D. Q. Bowen. One of the principal thrusts of this paper has been to show that existing classifications of the continental Quaternary are inadequate and mostly oversimplified. The isoleucine epimerization data (amino acid geochronology) show this for 'interglacial' marine stratigraphic units, as has already been shown for non-marine 'interglacial' units (Hughes 1987). Dr Turner's comments are based on the view that classification based on assemblage floras of 'interglacial aspect' may be used as a suitable means of identifying fixed points in time. Such an approach, however, is inappropriate because it is not based on first appearances, nor extinctions of fossil taxa, but on facies–floras controlled by climate. His comments also seem to be a defence of the view that Middle Pleistocene deposits in Europe and Britain represent a 'short chronology', as opposed to a longer one inferred from signals of climatic change based on oxygen isotope variability.

Dr Turner is incorrect to suggest that an implication of the paper is that the 'Anglian' of England is younger than the 'Elsterian' of Europe. The data presented cannot be interpreted in that way. What the isoleucine epimerization on shells of *Macoma* from Hummelsbüttel (0.382) and Wacken (0.283) show, is that the latter is clearly younger than the former, a view held by many German workers on other grounds (see, for example, Sarnthein *et al.* 1986; Cepek 1986). Regardless of how these data are modelled, they show that not all 'interglacial' deposits labelled 'Holsteinian' are the same age (see also Kukla 1977).

Dr Turner comments that the Quaternary deposits of the Hamburg area have been investigated 'more intensively that perhaps anywhere else in northern Europe'; yet regional lithostratigraphy is hardly secure when 'Holsteinian' deposits are only exposed where they have been brought to the surface along thrust planes (Ehlers 1983). I agree with him that the Eartham (Boxgrove) site is older than the Hoxnian of Suffolk: what the data show is that the Boxgrove site is the same age as Hummelsbüttel.

Finally, it is misleading of Dr Turner to say that his correlations are based on 'stratigraphy': they are based on a facies–flora biostratigraphy, entirely lacking in geochronometric control, which shows a comparatively simple model of climatic history. The isoleucine epimerization data, on the other hand, show that the Middle Pleistocene history of Europe was as complex as suggested by the models of Kukla (1977), Sibrava (1986) and Cepek (1986).