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AMINOSTRATIGRAPHY OF EUROPEAN MARINE INTERGLACIAL DEPOSITS

Gifford H. Miller* and Jan Mangerud†
**INSTAAR and Dept. of Geological Sciences, Campus Box 450, University of Colorado, Boulder, CO 80309, U.S.A.*
†Department of Geology, Sec. B, Allégt. 41, University of Bergen, N-5000 Bergen, Norway

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With contributions by:

K.S. Petersen	Danmarks Geologiske Undersögelse 31, Thoravej, 2400 Köbenhavn NV, Denmark
H.P. Sejrup	Geologisk Institutt, Avd. B Universitetet i Bergen, 5000 Bergen, Norway
W. Zagwijn	Rijks Geologische Dienst, Spaarne 17, 2000 AD, Haarlem, Netherlands
B. Menke	Geologisches Landesamt Schleswig-Holstein, Postfach 5049, 2300 Kiel 21, F.R.G.
V. Gudina	Institute of Geology and Geophysics, Siberian Branch Academy of Sciences of the U.S.S.R., Novosibirsk-90, U.S.S.R.
R. Paepe	Quaternary and Marine Geology, Belgische Geologische Dienst, Jennerstraat, 13, 1040 Brussels, Belgium
V. Yevzerov	Institute of Geology, Kola Branch of the Academy of Sciences of the U.S.S.R., Apatity, U.S.S.R.
J.M. Punning	Institute of Geology, Academy of Sciences of the E.S.S.R., Tallinn 200001, Estonia 7, U.S.S.R.
A. Makowska	Instytut Geologiczny, ul Radowiecka 4, 00-975 Warszawa, Poland
T. Påsse	Geological Survey of Sweden, Kungsgaten 4, 411 19 Göteberg, Sweden
K.-L. Knudsen	Laboratoriet for Palaeontologi og Stratigrafi, Geologisk Institut, Aarhus Universitet, 8000 Aarhus C, Denmark
A.-L. Lykke-Andersen	Labyrinten 17, 8220 Brabrand, Denmark
T. Meijer	Rijks Geologische Dienst, Spaarne 17, 2000 AD, Haarlem, Netherlands
J. Sommé	Laboratoire de Géomorphologie et d/Étude du Quaternaire, Université des Sciences et Techniques de Lille, 59655 Villeneuve d'Ascq Cédex, France
G. Linke	Geologisches Landesamt Freie und Hansestadt Hamburg, Oberstrasse 88, 2000 Hamburg 13, F.R.G.
C. Baeteman	Quaternary and Marine Geology, Belgische Geologische Dienst, Jennerstraat, 13, 1040 Brussels, Belgium
W. Hinsch	Geologisches Landesamt Schleswig-Holstein, Postfach 5049, 2300 Kiel 21, F.R.G.
D. Goter	INSTAAR, CB 450, University of Colorado, Boulder, CO 80309, U.S.A.
J. Brigham-Grette	Department of Geology, University of Alberta, Edmonton, Alberta, T6G 2E3, Canada
J. Hollin	INSTAAR, CB 450, University of Colorado, Boulder, CO 80309, U.S.A.

Molluscan fossils collected from shallow water marine sediment across NW Europe and nearby Arctic regions have been analysed for the extent of isoleucine epimerization (D/L ratio) in indigenous protein residues. The D/L ratios confirm that essentially all 'classical' Eemian sites from NW Europe are of the same age, and are correlative with the type locality near Amersfoort in the Netherlands; shells from interglacial marine sediment beneath the type Weichselian till in Poland also correlate with the type Eemian site. D/L ratios in Holsteinian marine shells (0.29) are substantially higher than in their Eemian counterparts (0.17); 'Late Cromerian' shells yield even higher ratios (0.46). D/L ratios in late glacial shells (0.06) and Middle Weichselian shells (0.09) permit differentiation from modern (0.01) and last interglacial material. Based on the position of the Matuyama–Brunhes boundary and the differences in D/L ratios, the Eemian must correlate with isotope substage 5e, whereas the Holsteinian is most likely substage 7c, possibly stage 9 but certainly younger than stage 11. Intra-Saalian warm periods may be terrestrial equivalents of the younger substages of stage 7. Extensive pre-Eemian marine sediments along the SW coast of Denmark previously correlated with the Holsteinian are shown to be of 'Late Cromerian' age. The underlying till there is the first widespread evidence of a pre-Elsterian till in NW Europe.

D/L ratios in molluscs from last interglacial sites along the Arctic coast of the USSR, the Arctic Islands and eastern Greenland are substantially lower than in their European counterparts due to their low thermal histories. The combined mid- and high-latitude data are used to develop a predictive model for the expected D/L ratio in any of several moderate epimerization-rate taxa for last interglacial sites with mean temperatures between −20 and +15°C.

Not all sites could be unambiguously assigned to an established interglacial. The Fjøsanger (Norway) and Margareteberg (Sweden) sites previously thought to be Eemian, yield D/L ratios higher than in secure nearby Eemian material. It is yet unresolved whether these are aberrant sites or if they predate the last interglacial. *In situ* shoreline deposits encountered in borings in SW Belgium and in exposures on the Belgium coastal plain contain molluscs that yield D/L ratios intermediate between secure Eemian and Late Weichselian ratios, raising the possibility that a late stage 5 high-sea-level event attained near-modern levels in the southern North Sea basin. Resolution of these uncertainties is the focus of future work.

INTRODUCTION

Despite nearly a century of investigation, the Quaternary stratigraphy of Northwest Europe has yet to be fully resolved. The classical land-based sequence in Northwest Europe (Table 1) is based on end-moraine systems and correlative till beds, and the palynology and faunal assemblages in associated terrestrial and shallow-water marine sequences. Three main glacial stages are widely recognized: the Elsterian, Saalian and Weichselian separated by the Holsteinian and Eemian interglacials. Over the last decade several pre-Elsterian climatic oscillations have also been described (e.g. Menke, 1970; Zagwijn, 1975; Brunnacker *et al.*, 1982; Urban, 1982; Nilsson, 1983), but their occurrence is relatively rare and regional correlation remains somewhat ambiguous. The Matuyama–Brunhes boundary has been identified in the lower portion of the 'Cromerian complex' (Zagwijn, 1975; Brunnacker and Boenik, 1976; Zagwijn and Doppert, 1978; Brunnacker 1979). The number of glacial–interglacial cycles in Europe between Matuyama–Brunhes and the Elsterian is uncertain, but seldom are more than three proposed, giving altogether six after the Matuyama–Brunhes boundary. In contrast, the deep-sea oxygen-isotype stratigraphy (e.g. Shackleton and Opdyke, 1973) implies that there have been eight glaciations since the

TABLE 1. Classical subdivision of the middle and late Quaternary of NW Europe

	Holocene (Interglacial)
Late Pleistocene	Weichselian (Glacial) Stage Eemian (Interglacial)
Middle Pleistocene	Saalian (Glacial) Stage Holsteininian (Interglacial) Elsterian (Glacial) Stage Probably Four Temperate and Three Cold Stages Collectively Called the 'Cromerian Complex'
Early Pleistocene	Six named stages

Matuyama–Brunhes boundary. The apparent discrepancy between the deep-sea and land-based stratigraphy has stimulated additional investigations into the continental record, and the correlation and dating of Quaternary deposits in northwestern Europe has been vigorously debated in meetings and papers in recent years.

At present a widely held view is that the classical post-Elsterian interglacial sequence is probably correct (e.g. Ehlers *et al.*, 1984), and that knowledge of the pre-Elsterian sequence is so fragmentary that it may accommodate the 'missing' interglacials. In this interpretation, the post-Eemian warm intervals (e.g. St. Germain I and II of Woillard, 1978) are considered to be interstadials within the Weichselian, and the Wacken/Dömnitzian and Holsteinian (*sensu stricto*) are considered to represent a single interglacial complex, the Holsteinian (*sensu lato*). The inescapable conclusion from this perspective is that isotope stage 1 is the Holocene, 2–5d the Weichselian, 5e the Eemian (e.g. Shackleton, 1967; Mangerud *et al.*, 1979), stage 6 the Saalian, stage 7 the Holsteinian and stage 8 the Elsterian.

Opposing this interpretation are several recent proposals that more than three post-Elsterian interglacials occur. Kukla (1977), followed by Bowen (1978, 1979) argued that sites classified as Eemian may represent more than one interglacial that have been grouped as a single event. The type Eemian site in the Netherlands was proposed as the oldest of these interglacials (Kukla, 1977). In their scheme, the Holsteinian (*sensu stricto*) is ascribed to isotope stage 11 or 13 rather than stage 7 as in a classical interpretation. Earlier Frenzel (1973) had argued that the pollen stratigraphy of interglacial sites in Germany could not be accounted for by the classical interglacial sequence and additional interglacials must be present; he proposed two intra-Saalian (*sensu lato*) interglacials. In East Germany, Cepek and Erd (e.g. Cepek and Erd, 1982; Cepek, 1967) have long claimed that at least two and possibly three interglacials occurred between the Holsteinian (*sensu stricto*) and the Eemian: the Dömnitzian, an un-named Saalian I/II event, and the Rügenan. Similarly, Stremme (1982) and Sarntheim and Stremme (1984) proposed correlation of the Eemian with isotope substage 5e, the Holsteinian with isotope stage 11, with two intra-Saalian interglacials as the terrestrial correlatives of isotope stages 7 and 9, a view supported by Bowen (1985). The lack of reliable independent dating methodologies that can be applied to terrestrial sites has hampered resolution of this conflict, although new efforts in U/Th, electron-spin resonance and thermoluminescence dating are in progress.

In 1979, partially in response to the challenge of possible miscorrelation, but also in an attempt to obtain an integrated chronostratigraphy of the European marine interglacial sequence, we initiated a program to determine systematically the extent of isoleucine epimerization in marine molluscs from interglacial sites across Northwest Europe and along the Arctic coast of the Soviet Union. This paper presents the results of nearly 1000 isoleucine epimerization determinations in marine mollusc shells from interglacial and interstadial sites over this region, and also gives a review and appraisal of the geochronological interpretation of these data.

The primary questions we wish to address with these data are:

(1) Are all sites considered Eemian clearly of a single age? If they are not, which represent the last interglacial?

(2) Can we identify marine interglacial beds intermediate in age between Holsteinian and Eemian?

(3) Can the amino acid data be used to test regional correlation of Middle Pleistocene interglacials in NW Europe and can it be used to place constraints on the possible ages of these events?

(4) Are there any indications that the high sea-level events of isotope substages 5a and 5c are preserved around the North Sea.

The analytical results and an appraisal of the questions posed above are presented in two parts. Part 1 contains an overview of the methodology employed and the controlling parameters that govern how the data can be interpreted, and it includes the evaluation of the analytical data from a regional perspective. In Part 2, more detailed site-specific information is presented, including the primary stratigraphic relationships and the basis for the proposed age assignment for the sites investigated. Amino acid ratios for all taxa from each site are tabulated on the accompanying tables. Conclusions of primarily local significance are given with the site descriptions.

Part 1 — Amino Acid Geochronology, Regional Chronostratigraphy and Absolute Age of European Middle- and Late-Pleistocene Marine Interglacials

AMINO ACID GEOCHRONOLOGY

The use of certain reactions involved in the degradation of indigenous proteins and their constituent amino acids preserved in fossils to estimate the age of the enclosing sediment (Amino Acid Geochronology) has gained increasing acceptance since the pioneering studies of Hare, Abelson and colleagues in the late 1960s. In particular, the application to marine carbonate fossils (see Wehmiller, 1983, for review) has been widespread, but work has also been carried out on bone (e.g. Bada, 1985) and wood (Pillans, 1983; Rutter, 1984).

Most studies rely on the fact that protein produced by organisms consists almost exclusively of amino acids in the L-isomer configuration. As the protein is degraded after death of the organism, the L-amino acids invert to their respective D-configurations; the inversion rate is dependent primarily on temperature, and to a lesser degree on taxonomy. Measured D/L ratios can be directly compared ('Aminostratigraphy', Miller and Hare, 1980) only for monospecific samples that have experienced similar (±1°C) thermal histories.

In this study, we have relied on the epimerization of the protein amino acid L-isoleucine to its non-protein diasteriomer, D-alloisoleucine. The ratio of these two isomers is generally abbreviated as alle/Ile or D/L ratio; throughout the remainder of the text we use the D/L abbreviation. The ratio of D- to L-isomers increases from near zero in a modern shell to an equilibrium ratio of 1.30 ± 0.05, at which time the number of L-amino acids inverting to their D-configuration is balanced by the opposite reaction. The time required to reach an equilibrium state is related to the effective diagenetic temperature (EDT) experienced by the fossil; at mid-latitude sites (e.g. 10°C) it takes ca. 2 Ma to attain equilibrium, whereas Arctic sites (<-10°C) will require 20 Ma or more to reach the same state.

ANALYTICAL PROCEDURE

Indigenous proteinaceous residues and associated degradation products are released on decalcification of the shell in acid; peptide remnants are further decomposed into their constituent amino acids by laboratory hydrolysis in 6N HCl for 22 hr at 110°C. All amino acid determinations reported herein follow the standard analytical procedure in effect at the Colorado laboratory since the spring of 1982. From most collections three to five individual shells of a single taxon were prepared for analysis following the procedure outlined in Miller (1985). Separation and detection of individual amino acids was accomplished on an automated high-pressure liquid chromatograph utilizing cation-exchange resin, post-column derivatization with O-Phthaldehyde and fluorescence detection. The ratio of D-alloisoleucine to L-isoleucine (D/L) in the total amino acid population (free plus peptide-bound amino acids) is determined by a recording integrator based on the ratio of peak heights. Each analysis requires less than 2 mg of shell material. For this reason, individual shells can be analyzed separately for nearly all taxa; the only exception being the small gastropod *Bittium reticulatum*, for which up to four individuals were combined in some instances.

To ensure that determinations made throughout the duration of this project were directly comparable three techniques were employed to monitor analytical uncertainties: (1) a calibration standard; (2) an interlaboratory shell standard; and (3) multiple preparations of selected samples.

Two nearly identical amino acid analyzers are in routine use at the Colorado laboratory and a similar instrument is used in the Bergen laboratory. An amino acid control is processed on each analyser every day. Between June 1982 and December 1983, the measured D/L ratio in the control averaged 0.122 ± 0.011 ($n = 123$) on one instrument and 0.123 ± 0.012 ($n = 234$) on the other at the Colorado laboratory. The Bergen laboratory reports similar precision. Additionally, some samples have been processed at both the Colorado and Bergen laboratories with similar results.

In 1982 J. Wehmiller circulated sized shell powders of monospecific mollusc samples from deposits of three very different ages to all laboratories involved with amino acid geochronology (Wehmiller, 1984). The results of four series of analyses at the Colorado laboratory and a single series from the Bergen laboratory (Table 2) indicate that there has been no statistical shift in ratios determined over the duration of the project and that the two facilities produce comparable results.

As a final test of analytical reliability, we analyzed several samples more than once during the program. Similar results for samples prepared near the start of the analytical program and recently confirm that there are no significant analytical problems.

FACTORS AFFECTING THE MEASURED D/L RATIO IN MOLLUSCAN SAMPLES

Time

The degree to which a chemical reaction has proceeded toward equilibrium is related to the time elapsed since the onset of the reaction. In the case of the isoleucine epimerization reaction in a molluscan shell, the reaction effectively starts with death of the organism and proceeds to racemic equilibrium (D/L = 1.30). Measuring the D/L ratio in a mollusc provides an index to the elapsed time since its death.

The general form of the relationship between D/L ratio and time for a specific temperature is distinctly non-linear. As shown in Fig. 1, the conversion of L- to D-amino acids proceeds most rapidly during the early stages of diagenesis, decreasing in the later stages when the forward reaction is counterbalanced by the reverse reaction. Consequently, the resolving power of the D/L ratio in shells from around the North Sea will be greatest for young samples (modern through Holsteinian) and diminish for older shells.

Temperature

The rate of most chemical reactions is strongly dependent on the temperature of the reaction medium. In this study it is the temperature in the sediment enclosing the molluscs (called the effective diagenetic temperature [EDT]) that governs the epimerization rate. Note that the temperature at which the shell lived is inconsequential in this respect. A shell

TABLE 2. Comparison of D/L ratios determined on the interlaboratory calibration standard (Wehmiller, 1984)

Sample ID	Analysis date	Lab ID	D/L (Total fraction)
81 ILC A	July 1982	AAL-2694	0.151 (1)
	October 1983	AAL-3513	0.158 ± 0.005 (3)
	May 1984	AAL-3832	0.158 ± 0.005 (2)
	Sept 1985	AAL-4510	0.165 ± 0.008 (3)
	July 1984	BAL- 334	0.167 ± 0.003 (3)
81 ILC B	July 1982	AAL-2695	0.54 (1)
	October 1983	AAL-3514	0.54 ± 0.05 (3)
	May 1984	AAL-3833	0.49 ± 0.02 (2)
	Sept 1985	AAL-4511	0.50 ± 0.03 (3)
	July 1984	BAL- 335	0.54 ± 0.02 (3)
81 ILC C	July 1982	AAL-2696	1.08 (1)
	October 1983	AAL-3515	1.16 ± 0.04 (3)
	May 1984	AAL-3834	1.06 ± 0.02 (2)
	Sept 1985	AAL-4512	1.08 ± 0.01 (3)
	July 1984	BAL- 336	1.20 ± 0.05 (3)

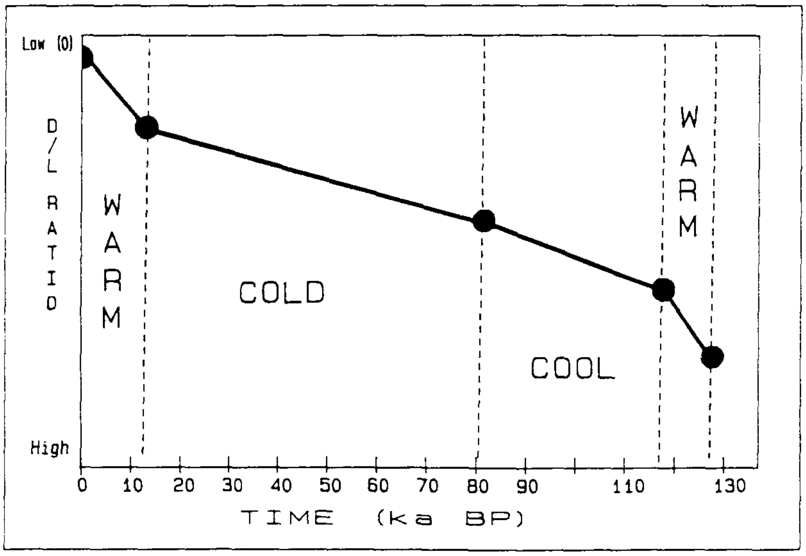

FIG. 1. Simplified diagram showing the increase in D/L ratio in a molluscan fossil from NW Europe over the last 130 ka. The fastest epimerization rate occurs during the warm interglacials, whereas the epimerization rate during the cooler intervening stadials and interstadials was substantially reduced.

that died early during the last interglacial will have experienced rapid epimerization during the rest of the warm interglacial, much reduced rates during the coldest phases of the Weichselian, intermediate rates during the mild interstadials and a rapid rate again during the Holocene (Fig. 2). The temperature dependency of isoleucine epimerization is an exponential relationship, with an approximate doubling of the rate for each 4°C temperature rise.

Clearly, quantification of the thermal history for each site is essential for the interpretation of the measured D/L ratios, yet paleoclimatic data are generally insufficient to assess adequately the thermal factor. As a first approximation of the EDT for each site we have relied on the current mean annual air temperature. At mid-latitudes, mean annual air and ground temperatures are in close agreement (e.g. Gieger, 1965). Implicit with this approach is the assumption that Pleistocene temperature changes occurred uniformly across NW Europe.

This simplified approach to site temperature may obscure important complications in the thermal history of specific sites. Even nearby sites may have experienced significantly different thermal histories. For example, some of the Danish shells were collected from ice-thrusted floes deposited in Late Weichselian time, and may have been below sea-level for most of their history. The integrated thermal history for such collections could be significantly different than for nearby sites that were uplifted shortly after their deposition and have remained above sea level ever since. Other sites that were covered by the continental ice sheet must have been close to 0°C, whereas nearby sites outside the ice margin may have been considerably colder. Periglacial conditions across the Netherlands

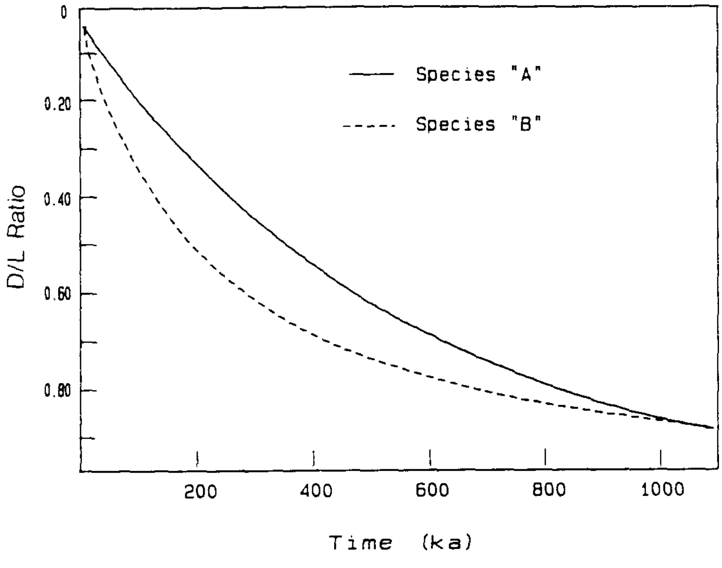

FIG. 2. Theoretical pattern of increase in D/L ratio for two molluscan taxa at a constant temperature of ca. 10°C over a million year interval. The ratio increases nearly linearly over the first few hundred thousand years after which the rate decreases, eventually returning to a linear rate about 1/10th that of the initial period. Hypothetical fast (B) and slow (A) taxa are included to illustrate how the difference in D/L ratio between taxa can vary over long time intervals.

and portions of West Germany at the glacial maximum resulted in lower temperatures than at ice-covered sites in Scandinavia, thus reversing the present-day thermal gradient. Finally, the thermal gradient across NW Europe during interstadials or full glacial conditions may have differed from the current gradient. However, it is important to keep in mind that most of the epimerization occurs in the 'warm' periods; full glacial conditions are not as critical to the average reaction rate as are interstadial and interglacial regimes.

Taxonomic Effects

As has been noted previously, the epimerization rate can vary between taxa. The reason for the different rates has not yet been demonstrated, but is probably in part related to the position of isoleucine in the peptide chains. The difference in epimerization rate between taxa may also change over time. The theoretical relationships are illustrated in Fig. 1, showing an initial difference in D/L ratio of a factor of 2 for two hypothetical taxa, decreasing over time until the epimerization rates are the same in the later stages of diagenesis. Such changes in relative epimerization rates are unlikely to alter the interpretation of samples of Holsteinian and younger ages, but may become important in evaluating ratios from older deposits.

Because of the wide range in paleoenvironmental conditions that characterize the various localities, there is not a single taxon that is common to all sites. In our search for appropriate taxa, amino acid determinations were undertaken on nearly 30 species of marine molluscs. Some of these taxa were not useful for geochronological studies, in some cases due to the restricted occurrence of the taxon either temporally or spatially, whereas for other taxa the measured D/L ratios were not reproducible.

The main criteria for evaluating the reliability of a taxon are empirical. In most instances, at least three individuals have been analysed from each locality. If the measured D/L ratios scatter widely (coefficient of variation greater than 15 to 20% of the mean), that species is potentially of questionable reliability. If a taxon yields similarly scattered results at several localities it is considered to be of low reliability. Another factor is the concentration of protein within the shell matrix, which can vary by a factor of 10 between genera. Those taxa containing the lowest levels of protein contain so little alloisoleucine and isoleucine that the instrumental detection limit is approached and the precision of the measurement decreases.

Proteins in different structural layers of a shell frequently differ in their amino acid composition and rate of epimerization. Taxa with multiple structural layers must be sampled from the same layer to ensure reproducible results. In thick-shelled species such as *Arctica*, this can usually be accomplished easily, but thin-shelled taxa cannot always be confidentially separated. This may be a contributing factor to the scatter in data obtained from the often diminutive shells of *Cardium*, an ecologically diverse taxon that is often a major constituent of Eemian marine deposits. The failure of *Cardium* to yield reproducible D/L ratios was a major disappointment of this study. Shells of relatively homogenous structure such as *Mya* or *Hiatella*, require less rigorous sampling (cf. Brigham, 1983), although we routinely sample from the center of the shell near its apex to minimize intra-shell variation. Shells with multiple structural layers are sampled from the inner layer, which is generally denser and less susceptible to leaching than the outer layer.

Our evaluation of taxa analysed in this study is given in Table 3. There is a group of several pelecypod taxa for which isoleucine epimerization proceeds at a similar, moderate rate. Many members of this group are widely distributed and have moderate to high reliability. The core of the interpretations of this project are based on results from five representatives of this group: *Arctica islandica, Macoma balthica* and *Macoma calcarea, Venerupis senescens* and *Mya truncata*. Important taxa that yield reliable ratios but have a significantly different epimerization rate include *Littorina* (several species but principally *littorea*) which yields D/L ratios nearly half those in the moderate-rate group and *Divaricella divaricata* which has an epimerization rate about 1.5 × faster than in moderate-rate taxa. Additional species in the moderate-rate group that provide important control for some sites include *Hiatella arctica, Corbula gibba* and *Spisula subtruncata*.

Other factors

Although the only established variables that control the measured D/L ratio in a shell are time, temperature and taxonomy, there may be other less obvious environmental parameters that can alter the apparent epimerization rate. The carbonate matrix effectively buffers the system from local pH changes, and moisture content is not a limiting factor even under high-arctic conditions. Pressure (e.g. beneath a thick ice sheet) does not seem to be significant as there is no change in volume associated with the epimerization reaction, although hydrolysis, involving a volumetric increase, may be impeded. A possible explanation for accelerated epimerization could the incorporation of impurities, such as radioactive elements, within the shell matrix that catalyze the epimerization reaction, although none have been identified yet in sufficient concentrations. The leaching of low molecular weight free amino acids, most severe in the outer portion of a shell, can lower the D/L ratio in the total amino acid population. The sampling methods employed in our laboratories minimize this effect.

EPIMERIZATION DURING THE EEMIAN

Because of the sensitivity of the reaction rate to temperature, it is important to evaluate the extent of epimerization that occurs during an interglacial, the warmest and, hence most rapid epimerization rate in the post-depositional history of a sample. The D/L ratios in 11 to 13 ka old shells of the moderate-rate taxa range from 0.05 (Norway) to 0.07 (Scotland). *Macoma balthica* collected from marine sediments in the Netherlands dated 4500 BP have a D/L ratio of 0.035 ± 0.002 (3). When extrapolated to 10 ka BP this gives a D/L ratio of 0.07. Subtracting the D/L ratio in a modern shell gives a net epimerization of between 0.035 and 0.055 during the Holocene. The Eemian was of similar duration to the Holocene (Müller, 1974a), and at its thermal maximum was at least two degrees warmer. Thus at least the same amount of epimerization is to be expected for Eemian time as occurred during the Holocene.

Sites that span an interglacial should demonstrate whether shells from late in the interglacial yield ratios significantly lower than from early in the interglacial. Two such sites are the Schnittlohe boring (W. Germany) and the Fjøsanger excavation (Norway).

TABLE 3. Mollusc taxa used in this study and an evaluation of their reliability and relative isoleucine epimerization rate

Species	Synonyms	Epimerization[1] rate	Reliability	Amino acid abundance*	D/L†
		Pelecypods			
Arctica islandica (L)	*Cyprina*	Moderate −	High	High	0.17
Mya truncata (L)		Moderate	High	High	0.18
Hiatella arctica (L)	*Saxicava*	Moderate	High	High	0.18
Venerupis senescens (Döderlein)	*Tapes aurea* var. eemensis (Nordman)	Moderate +	Moderate	Moderate	0.20
Venerupis rhomboides (Pennant)	*Tapes*	‡	‡	Moderate	
Corbula gibba (Olivi)	*Vericorbula, Aloides*	Moderate +	Moderate	Moderate	0.22
Macoma calcarea (Gmelin)	*Tellina*	Moderate	High	Moderate	
Macoma balthica (L)	*Tellina*	Moderate +	High	Moderate	0.20
Divaricella divaricata (L)		Fast	Moderate	High	0.27
Lucinoma borealis (L)		Fast	Low	Moderate	
Cardium edule (L)	*Cerastoderma*	Moderate	Low	Low	ca. 0.18
Cardium lamarcki (Reeve)	*Cerastoderma*	Moderate	‡	Moderate	
Donax spp		Moderate	‡	Low	
Corbicula fluminalis		Moderate	‡	Moderate	
Glycymeris spp		Moderate	High	Moderate	0.20
Portlandia arctica		Moderate(?)	‡	High	
Spisula subtruncata (da Costa)		Moderate	Moderate	Moderate	0.17
Zirfaea crispata (L)		‡	‡	Moderate	
		Gastropods			
Littorina littorea (L)		Slow	High	High	0.11
Bittium reticulatum (da Costa)		Slow(?)	Low(?)	Low	0.12–0.17
Turritella communis (Risso)	*terebra*	Moderate	Moderate	Low	0.2
Turritella erosa		Moderate	‡	Low	
Nassarius pygmaeous (Lam.)		Slow	‡	Moderate	0.14
Nassarius reticulatus (L)		Slow	‡	Moderate	0.14
Hydrobia ulva (Pennant)		Slow	‡	Moderate	0.10

*Qualitative evaluation of the concentration of the amino acid isoleucine relative to the mass of inorganic matrix in the shells of each species.

†Average ratio of D-alloisoleucine to L-isoleucine in the total acid hydrolysate for shells from Eemian sites in NW Germany, Netherlands, Belgium.

‡Insufficient samples analysed to assess the reliability and/or epimerization-rate of this taxon.

[1] + or − suffix indicates slighter more rapid (+) or slower (−) rate than other members of a specific group.

The Fjøsanger site essentially contains a complete sequence of marine deposits from the onset through to the termination of an interglacial episode. We have analysed three taxa from Fjøsanger that span the interglacial (*Mya*, *Hiatella* and *Littorina*, Table 4). D/L ratios from samples collected respectively at the base and top of the interglacial beds give conflicting information on the epimerization that occurred during the interglacial period. *Mya* and *Littorina* show a clear decrease in D/L ratios up-section, whereas ratios in *Hiatella* are similar throughout.

The Schnittlohe I boring penetrated more than 5 m of Eemian marine sediments. Samples of *V. senescens* and *Corbula gibba* were obtained from levels within the upper part of the *Picea*/lower part of the *Abies* pollen zone (13 m), the base of the *Tilia* zone (15 m), while the 16 m sample predates the *Corylus* zone. Mean D/L ratios (Table 4) do not show the expected down-core increase, and the deepest sample gives the lowest ratio for both taxa. However, at the 1σ confidence level the ratios are almost undifferentiable.

The lack of a consistent increase in ratios through both sites is surprising. Although the precision of the data is less than expected, the results do indicate that D/L ratios in molluscs from a single interglacial probably will include a range of ratios. The typical range of values may be between 0.03 and 0.06, and is caused both by the differences in the duration of 'warm' interglacial conditions experienced by different samples, and possibly other unidentified factors.

TABLE 4. Mean D/L ratios in selected taxa from two sites that span most of an interglacial. See text for discussion of results

Fjøsanger (Norway)				Schnittlohe (West Germany)		
Bed	*Mya*	*Hiatella*	*Littorina*	Depth in core	*Venerupis*	*Corbula*
F	0.19					
G	0.22	0.22				
H			0.11	13 m	0.16	0.18
I	0.22		0.14	15 m	0.18	0.20
J			0.12			
K			0.14	16 m	0.16	0.16
L			0.14			
M	0.28	0.22				

RESOLVING POWER OF THE AMINO ACID DATA

Of fundamental interest to users of amino acid data is the level to which deposits can be separated. Because of the non-linearity of the reaction rate, the isoleucine epimerization reaction has greater resolving power for young samples than for older samples. For Holocene sites at temperatures around 10°C, the limits of separation are probably about 3 ka. This capability decreases rapidly for Weichselian samples, largely because the lower temperatures during the Weichselian substantially diminished epimerization rates. In Danish samples, for instance, the measured D/L ratio increases from 0.013 (modern) to ca. 0.055 by 12 ka in the moderate-rate group, but increases only to ca. 0.085 in shells dated >40 ka. More epimerization occurred during the last 12 ka than in the preceding 30 ka or more. Consequently, resolution within the Weichselian is probably no better than 20 to 30 ka.

For older sites, a useful rule of thumb is that two sites of similar thermal history are of significantly different age if their mean D/L ratios do not overlap at two standard deviations. In most instances there should be no ambiquity between Eemian and Holsteinian sites, but if there is an intra-Saalian interglacial, it might be difficult to separate it clearly from either the Eemian or Holsteinian. Pre-Holsteinian interglacials probably require at least a 100 ka separation, and by early Pleistocene time, the resolving power of the data is undoubtedly even further reduced. One of the primary contributing factors in improving the resolving power of the data is the number of individuals measured. Based on this study we suggest a minimum of five different individuals are required to characterize adequately a specific stratigraphic level. The resolving power essentially increases with the square root of the number of samples analysed (*cf.* Miller *et al.*, 1979). An increase to 20 in the number of individuals processed would double the resolving power. Such an effort may be justified in certain instances.

PRESENTATION OF THE DATA

In the following discussions, amino acid data are restricted to widely distributed taxa of the moderate-rate group, and the relatively fast-epimerizing bivalve *Divaricella* and the slow-epimerizing gastropod, *Littorina*. The D/L ratios are measured to three significant figures and are so presented in the site tables and figures. However, inter-site variation is such that for regional correlations the ratios are cited to two significant figures only. D/L ratios are presented in the format 0.19 ± 0.02 (5), where the first number is the mean ratio of all individual shell preparations of a given taxon from the site(s) being discussed, the second number is the standard deviation of the measurements and the number in parentheses represents the number of individual preparations analysed. In most cases each analysis is of a different individual, but in collections for which the sample size is limited, this may include more than one analysis of some individuals. For a very few sites only one individual was available from which up to four separate preparations may have been analysed. Such data may be less representative than ratios based on a similar number of analyses of different individuals, although frequently as much intra-shell variation can be expected in the measured D/L ratio as inter-shell variation (e.g. Brigham, 1980).

REGIONAL CORRELATION OF INTERGLACIAL AND INTERSTADIAL DEPOSITS ACROSS THE CORE AREA: THE NETHERLANDS, WEST GERMANY, DENMARK, SWEDEN AND POLAND

The Eemian marine deposits were selected as the major focus of our study because they have been well studied for nearly a century and are geographically widespread. We accept the borings along the Eem River near Amersfoort, Netherlands (Zagwijn, 1961) as the type locality of the Eemian and all other Eemian sites are to be compared to the ratios obtained from the type locality.

To test the controversy whether more than one interglacial is represented by deposits considered Eemian, we began with the hypothesis that all Eemian sites are of a single age. Within the restricted area of the Netherlands, NW Germany and Denmark, the density of sites is sufficiently high that site-by-site correlation is possible despite the decreasing thermal gradient across this region. All sites proposed to be Eemian should yield similar ratios with a modest trend of decreasing values in Germany and Denmark. Sites with anomalously high (or low) ratios are potentially mis-correlated. Outside of this limited geographic region, possible differences in the integrated thermal history of the sites complicates the amino-acid based correlations. However, we do expect to find a coherent pattern of changing D/L ratios that can be clearly correlated with a realistic thermal gradient.

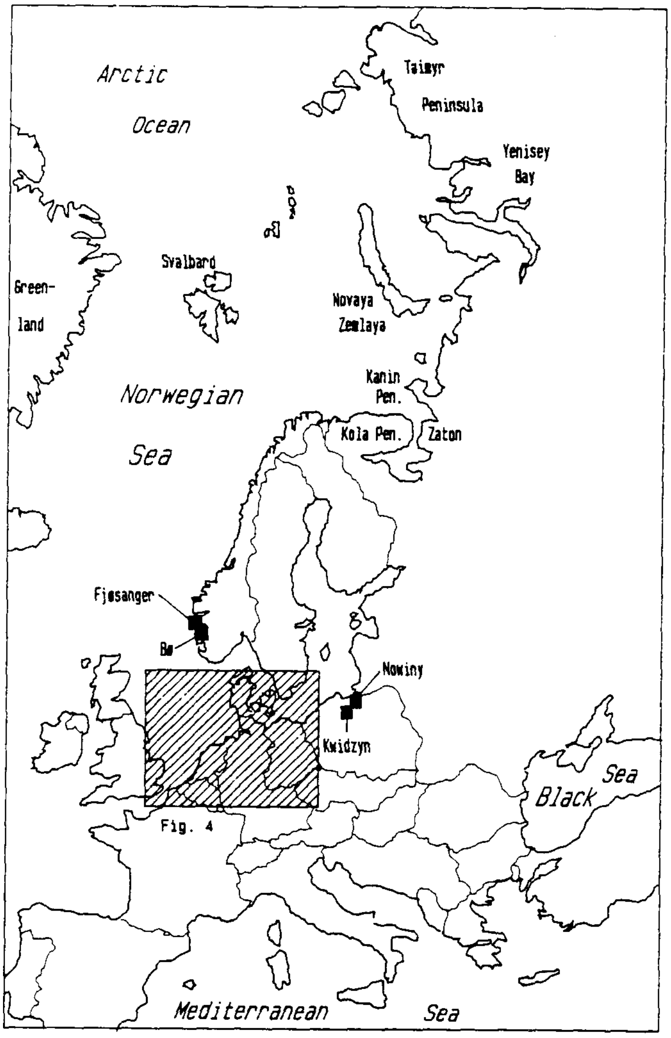

FIG. 3. Regional location map indicating sites studied in this survey outside the core area of Belgium, Netherlands, NW Germany and Denmark.

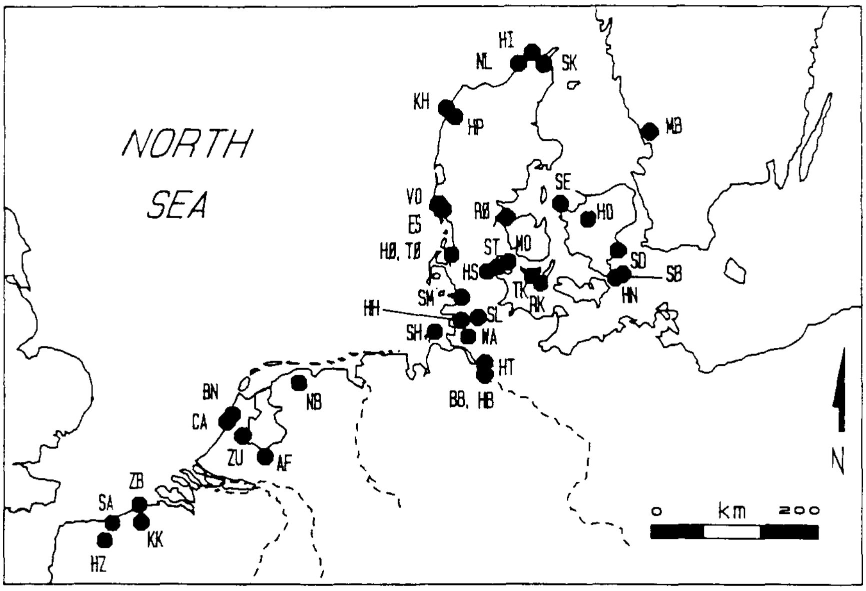

FIG. 4. Detailed locality map of Northwest Europe showing sites from which samples have been analysed. Sample abbreviations are as follows. Sweden: Margareteberg (MB). Denmark: Skærumhede (SK), Hirtshals (HI), Nørre Lyngby (NL), Kås Hoved (KH), Hostrup (HP), Vognsbøl (VO), Esbjerg (ES), Røgle (RØ), Slettenshage (SE), Holmstrup (HO), Strandegaard (SD), Stubberuphave (SB), Hjelm Nakke (HN), Ristinge Klint (RK), Trappeskov Klint (TK), Mommark (MO), Stensigmose (ST), Højer (HØ), Tønder (TØ). West Germany: Holnis (HS), Südermarsch (SM), Heide (HH), Rödemis, Offenbüttel and Schnittlohe (SL), Scharhörn (SH), Wacken (WA), Hummelsbüttel (HB), Billbrook (BB), Halstenbek (HT). Netherlands: Noord Bergum (NB), Bergen (BN), Castricum (CA), Zunderdoorp (ZU), Amerfoort (AF). Belgium: Zeebrugge (ZB), Koolkerke (KK), St Antoine (SA). France: Herzeele (HZ).

Eemian Type Site and Adjacent Correlatives in The Netherlands

The type Eemian sediments were deposited at the head of an estuary near the maximum inland penetration of the Eem Sea into the Netherlands (Fig. 4) and the euryhaline fauna is relatively impoverished in the open-ocean normal salinity taxa that are found at many other sites. The only representatives of the moderate-rate group are *V. senescens* for which ten preparations gave a mean D/L ratio of 0.20 ± 0.03 (Fig. 5) and a few diminutive shells of *H. arctica* that average 0.19 ± 0.02 (4). The nearby Bergen boring, correlated by its similar pollen stratigraphy, penetrates more open-marine sediments that contain additional moderate-rate taxa. The D/L ratio in four *Venerupis* samples substantiates the correlation to the type Eemian locality. D/L ratios in moderate-rate taxa from nearby borings at Castricum and Zunderdorp are similar to the same genera at the Bergen Boring (Fig. 5). The amino acid data thus confirm the previously established correlation of these borings with the type locality at Amersfoort. Collectively, the results from these four sites form the basis for correlation to more distant localities.

Eemian Sites in NW Germany, Denmark and Poland

Correlation of sites in NW Germany and Denmark with the type Eemian locality and adjacent correlatives in the Netherlands is given by mean D/L ratios in four taxa (Fig. 6).

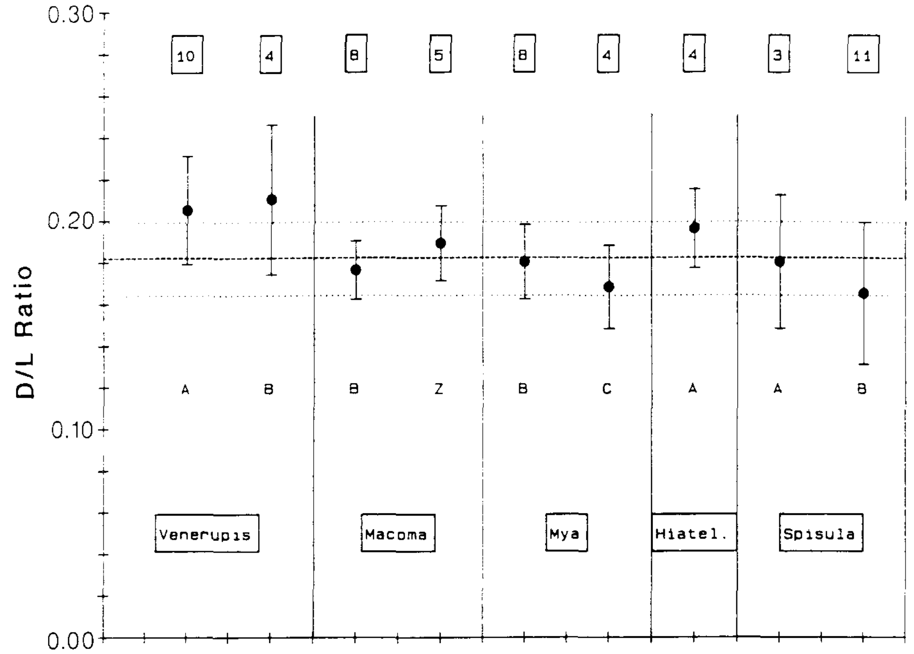

FIG. 5. Mean and standard deviations of D/L ratios measured in representatives of 5 taxa of the moderate-rate group found in 4 borings in The Netherlands. Boring abbreviations are Amersfoort (A), Bergen (B), Castricum (C) and Zunderdorp (Z). The number of individual analyses from which the mean is derived are shown in square boxes at the top of the figure. The mean D/L ratio in all moderate-rate taxa from the four borings is 0.182 (dashed line); the standard deviation is ±0.017 (dotted line).

The mean ratios for *Mya*, *Venerupis* and *Macoma* from Denmark and NW Germany are generally slightly lower than in the same taxa from the Netherlands, in keeping with the thermal gradient. The mean ratios in specific taxa at four sites in Denmark fall outside the one standard deviation confidence interval. These sites (Strandegaard, *Arctica*, *Corbula*; Mommark, *Arctica*; and Ristinge, *Mya*) are discussed in Part 2.

The marine embayment of the Eem Sea in the Vistula Valley of Poland (Fig. 3) supported an impoverished and diminutive fauna; from the available borings the only material of the moderate-rate group obtained common to other sites were a few small individuals of *Venerupis senescens*, *Corbula gibba* and *Spisula subtruncata*; *Divaricella divaricata* (fast epimerizer) also occurs at both the Amersfoort (Netherlands) and Nowiny (Poland) borings as well as in one of the Danish collections. The mean D/L ratios in three of the four taxa decrease in the direction of the current thermal gradient, with the highest ratios in the Netherlands, lower ratios in the sites from NW Germany and Denmark, and the lowest ratios from Poland (Fig. 7). The only taxon that counters this trend is *Venerupis*, for which the large standard deviation on the Polish collection allows the possibility that a more precise determination would support the trend of the other three taxa. The parallelism of thermal gradient and trend in measured D/L ratios confirms the correlation of the Tychnowy Sea deposits in the Vistula Valley of Poland with the type Eemian in the Netherlands.

Additional support for the correlation of Eemian sites across the region comes from the amino acid ratios in the slow-epimerizing species *Littorina littorea* (Table 5). This taxon is present at two of the Dutch sites (Castricum and Zunderdorp), both of which have representatives of the moderate-rate taxa that substantiate the correlation to other Eemian sites in the region. *L. littorea* from Rödemis in NW Germany and from Stensigmose and

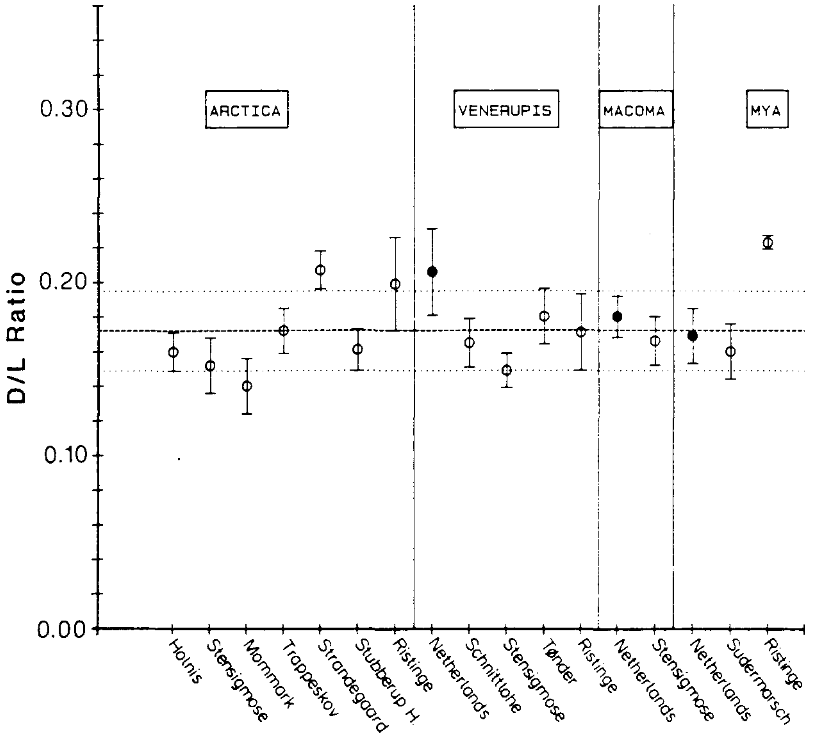

FIG. 6. Mean D/L ratios in four moderate-rate taxa from Eemian sites in NW Germany and Denmark (open circles); for comparison, mean ratios from The Netherlands are indicated by filled circles. Sites are located on Fig. 4. The mean D/L ratio for the four taxa from core area is 0.172 (dashed line) with a standard deviation of ±0.023 (dotted line).

TABLE 5. Comparison of D/L ratios measured in *Littorina* from sites in Norway, Denmark, West Germany and The Netherlands

MAT*	Country	Locality	Age	Mean	σ	*n*
7.5	Norway	Fjøsanger (Beds L–I)	Fjøsangerian	0.14	0.02	26
7.5	Norway	Bø (Bed D)	Avaldsnes	0.097	0.017	3
8.0	Denmark	Stensigmose (Tapes sand)	Eemian	0.086	0.008	3
8.0	Denmark	Tønder (Boring 4, 14.3m)	Eemian	0.11	0.01	5
8.5	W. Germany	Rødemis	Eemian	0.098	0.004	3
8.5	W. Germany	Wacken	Holsteinian	0.22	0.03	6
10.5	Netherlands	Castricum (19C/648)	Eemian	0.12	0.01	5
10.5	Netherlands	Zunderdorp (25E/344)	Eemian	0.12	0.01	5

*Current mean annual temperature in the vicinity of the collection site.

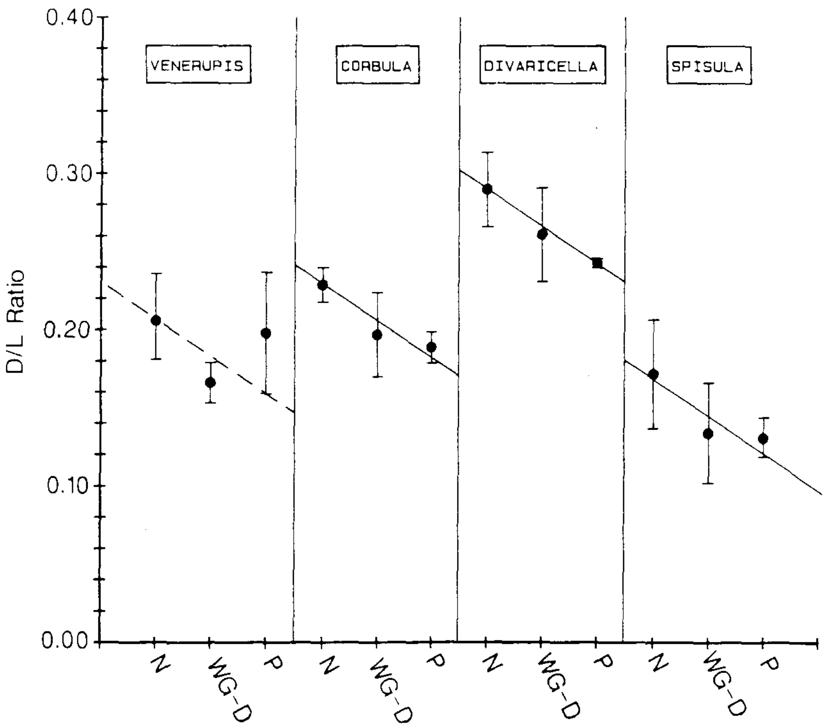

FIG. 7. Mean D/L ratios in three moderate- and one high-rate taxa from last-interglacial localities summarized by region for sites in the Netherlands (N) (Amersfoort and adjacent correlatives), NW Germany (W) and Denmark (O) and from the Vistula Valley borings (Poland) (P). The general trend of decreasing ratios across this region conforms to the current thermal gradient and implies a broadly similar gradient must have dominated the epimerization-rate over the area over last 100 ka or so.

Tönder in Denmark gave slightly lower ratios than in the Netherlands. These data support the conclusions derived from the moderate-rate group that the associate deposits are of a single age, with a trend toward decreasing D/L ratios along the present thermal gradient.

Within the resolving power of the amino acid method, there is no significant difference in age between the type Eemian site in the Netherlands and the classical Eemian correlatives analysed from other localities in the Netherlands, or the sites so identified in NW Germany, Denmark and Poland. The decrease in D/L ratios to the north and east of the Netherlands corresponds well with the present thermal gradient, and presumably reflects an integrated paleo-thermal gradient that at least in general form, mirrored that of the present.

Pre-Eemian Sites

Molluscs have been obtained from classical Holsteinian marine deposits in NW Germany (Wacken, Scharhörn borings 55 and 57, Hummelsbüttel, Billbrook and Heide). The mean D/L ratios in taxa that are common with the Eemian sites clearly separate the interglacials (Table 6). Using the group means for both moderate- and slow-rate taxa, the two interglacials are separated at the 95% confidence level.

TABLE 6. D/L ratios in Eemian and Holsteinian molluscs from the Schleswig-Holstein region of West Germany

Taxon	Eemian sites	Holsteinian sites
Arctica islandica	0.16 ± 0.01 (12)	0.30 ± 0.02 (9)
Macoma balthica		0.28 ± 0.01 (13)†
Mya truncata	0.16 ± 0.01 (8)	0.25 ± 0.02 (9)
Corbula gibba	0.18 ± 0.02 (9)	0.26 ± 0.03 (5)
Spisula subtruncata	0.11 ± 0.02 (2)	0.30 ± 0.02 (7)
Mean moderate-rate taxa	0.17 ± 0.01 (29)*	0.28 ± 0.02 (43)
Littorina littorea	0.098 ± 0.004 (3)	0.22 ± 0.03 (6)

* *Spisula* excluded from the averaging; ratios considered aberrantly low relative to ratios in the same taxa from other Eemian sites in the core area.

† *Macoma* from Hummelsbüttel excluded from averaging.

Although the mean Holsteinian ratio is easily differentiated from the mean Eemian ratio, an important additional consideration is with what reliability a specific site can be placed in its appropriate interglacial period. There are no potential miscorrelations within the suites of samples analysed from West Germany. Similarly, most of the Danish sites can be unambiguously assigned to their appropriate interglacial using the mean ratios in Table 6, although a few sites yield specific taxa with ratios intermediate between the group means. The lowest Holsteinian ratios are in *Mya* and *Corbula* from the Holsteinian (*sensu stricto*) beds at Wacken (*Mya* 0.25; *Corbula* 0.26). Within the Eemian sites in Denmark the highest ratios for *Mya* are 0.22 in a single individual from Ristinge, and for *Corbula*, 0.23 in two individuals from Strandegaard. Both examples overlap their Holsteinian counterparts at the 1σ level. In contrast, eight preparations of *Mya* from the Südermarsch boring in Germany average 0.16 ± 0.01, and 9 preparations of *Corbula* from the Schnittlohe boring average 0.19 ± 0.02, well below the ratios in the same taxa from Wacken.

Shells have also been analysed from a number of sites in Denmark that had been previously correlated with the Holsteinian sites of NW Germany. Three *Mya truncata* from Kaas Hoved gave a mean D/L ratio of 0.31 ± 0.05, suggesting a possible Holsteininan age but with considerable scatter in the data. In contrast, three *Arctica islandica* from the same collection yielded a mean ratio of 0.37 ± 0.01, well above the typical Holsteinian values in Germany. Without additional analyses, the conclusion can only be made that the site is certainly at least of Holsteinian age, but may be from an older interglacial.

The other Danish sites expected to be Holsteinian (Rögle Klint and the numerous sites in the Esbjerg area) gave ratios (Table 11) that are substantially higher than in the West German Holsteinian sites. From the Esbjerg region *Mya* averaged 0.45 ± 0.04 (19), *Macoma calcarea* 0.46 ± 0.04 (5), and *Hiatella* 0.47 ± 0.03 (8). Only *Hiatella* has been analysed from Rögle, but the ratios [0.54 ± 0.08 (3)], although limited in number and rather scattered, are nonetheless well above a possible Holsteinian level. We conclude that all of these sites are from a pre-Holsteinian interglacial.

The age of the pre-Holsteinian interglacial in Denmark is best constrained by the results from Noord Bergum, a pre-Elsterian site in the Netherlands. D/L ratios in four valves of

Macoma balthica from this site averaged 0.46 ± 0.06, similar to the Esbjerg ratios and suggesting that the sites may be from the same interglacial. Based on this correlation, the ratios obtained from the Esbjerg region and from Rögle Klint are interpreted to indicate that the associated interglacial beds are of pre-Elsterian rather than Holsteinian age as had been previously proposed. The till that underlies the marine bed at both sites is, by implication, from a pre-Elsterian glaciation. Tills of this age have not been previously identified from NW Europe except at Harreskov, Denmark where glacial-fluvial sediments and till underlie limnic sediments of Harreskovian ('Cromerian') age (Sjörring, 1983). Glacial-fluvial sediment of pre-Cromerian age are reported from the Netherlands (de Jong and Maarleveld, 1983), but the oldest till there is Elsterian.

The Slettenshage (Denmark) site had been previously correlated with the Eemian based on the broadly similar mollusc-faunas, although the classical indicator species *Bittium reticulatum* and *Venerupis senescens* were absent. *Arctica* from the site gave ratios of 0.32 ± 0.01 (3), well above the Eemian ratio for this species. The amino acid data suggest a correlation to the Holsteinian of NW Germany where the same species averages 0.30 ± 0.01 (9).

We have analysed two taxa from the recently discovered marine interglacial beds at Margareteberg, SW Sweden (Fig. 4). Ten preparations of *Hiatella* gave a mean ratio of 0.25 and 6 preparations of *Macoma* averaged 0.26 (Table 10), well above the mean values in moderate-rate taxa from Eemian sites in nearby Denmark (ca. 0.16 to 0.17), but not as high as in classical Holsteinian sites in adjacent NW Germany (ca. 0.29). The pollen stratigraphy is similar to that at Fjösanger (Norway) and dissimilar to the Holsteinian. Primarily on the basis of the pollen stratigraphy an Eemian age has been proposed for the site (T. Påsse, *written comm.*, 1985). The amino acid data suggest that the marine beds pre-date the Eemian, but are certainly no older than Holsteinian. We favor a correlation of Margareteberg with the Fjøsangerian of western Norway, for which we offer two age interpretations (see following section); the two sites may be Eemian or they may be from an interglacial between the Eemian and Holsteinian (*sensu stricto*).

Weichselian Sites

Shells of the moderate-rate group analysed from deposits known to be of Middle Weichselian age in Denmark (Hirtshals, Nörre Lyngby, Holmstrup and the upper 100 m of the Skaerumhede borings) consistently yield D/L ratios between 0.08 and 0.10, intermediate between those in the same taxa from Eemian and Late Weichselian deposits.

Lateglacial Sites

Shells from radiocarbon-dated Lateglacial and Holocene sites have been analysed from localities in Svalbard, Norway, Denmark, Scotland and the Netherlands (*cf.* Miller, 1985). D/L ratios are consistent with present site temperatures.

INTERGLACIAL SITES IN BELGIUM AND NORTHERN FRANCE

To the south of the Netherlands at least some of the deposits in Belgium considered to be Eemian correlate on D/L ratios with the Eemian sites in the Netherlands. *Venerupis* from the Oostende Formation in the Flemish Valley of Belgium has a mean D/L ratio of 0.17, and from the Netherlands 0.21; mean ratios in *Macoma* from Belgium are 0.19, the same as in the Dutch sites.

We have analysed *Macoma balthica* and *Cardium lamarcki* from the brickyard at the type locality of the Herzeele Formation in northern France. *M. balthica* yielded mean ratios of 0.31 consistent with a correlation to the Holsteinian marine deposits of NW Germany, and *C. lamarcki*, although not one of the primary taxa, did yield ratios appropriate for a Holsteinian age (0.28).

Borings in the Belgian coastal plain close to the French border and outcrops near Zeebruge have yielded moderate-rate taxa with D/L ratios that are lower than expected for Eemian deposits (ca. 0.11 to 0.13 in *Mya* and *Hiatella*). Because they are associated with high sea-level events well beyond the zone of isostatic depression from the Fennoscandinavian Ice Sheet, the deposits are tentatively associated with an Early Weichselian (late isotope stage 5) transgression, although this interpretation must await a larger data set before its validity can be tested.

INTERGLACIAL SITES IN WESTERN NORWAY

Two *in situ* marine interglacial sites are known from western Norway; the Fjøsanger site near Bergen and the Bö site on the island of Karmöy, 100 km to the south (Fig. 3).

Details of the stratigraphy within the interglacial beds at Bö remain incompletely understood (Andersen *et al.*, 1981). D/L ratios in presumably interglacial molluscs (Table 10) are slightly lower than ratios in the same taxa from Eemian sites in NW Germany and Denmark, supporting an Eemian age for the interglacial at Bö as proposed by Andersen *et al.* (1981).

The Fjøsanger site is one of the most thoroughly studied interglacial sites in NW Europe, containing a complete depositional sequence through an interglacial cycle and into the succeeding glaciation. Mangerud *et al.* (1979, 1981a) have suggested from the floral and faunal data that the interglacial beds correlate with the Eemian of the continent. D/L ratios in molluscs and foraminifera from the Fjøsanger site have been assembled from analyses at both the Bergen and Colorado laboratories (Mangerud *et al.*, 1981a; Miller *et al.*, 1983; H.P. Sejrup, *unpublished data*). Note, however, that the ratios presented in previous publications were prepared under a different system than used in this project, and are consistently higher than reported herein. Re-analysis of the earlier-prepared samples confirms the same apparent relationships as proposed previously, but the absolute values are ca. 70% of those reported earlier.

The D/L ratio in 40 preparations of 4 species of the moderate-rate group at Fjøsanger (Table 10) is 0.21 ± 0.04, whereas 11 specimens of two species of the same group at Bö average 0.14 ± 0.01. The two sites are separated at 1σ, but not at the 2σ confidence level. As with the bivalve mollusc ratios, D/L ratios in *Littorina* from the Bö sites are the same or slightly lower than in Eemian sites in NW Germany and Denmark, whereas the *Littorina* ratios from Fjøsanger are slightly higher, although still well below ratios in *Littorina* from the Holsteinian beds at Wacken. Countering the argument that Fjøsanger predates Bö are

TABLE 7. Mean D/L ratios used to construct figures 8 and 9 listed by site

		Species					
Site	Relative Age*	*Hiatella arctica*	*Mya truncata*	*Venerupis senescens/ rhomboides*	*Macoma balthica/ calcarea*	*Arctica islandica*	*Curbula gibba*
NORWAY							
Bø (bed d2)	MW					0.14 ± 01 (12)	0.14 ± 0.01 (4)
Fjøsanger		0.22 ± 0.02 (4)	0.26 ± 0.03 (11)	0.16 ± 0.03 (12)	0.22 ± 0.03 (2)	0.21 ± 0.01 (16)	
Rogne	MW		0.090 ± 0.007 (3)			0.086 ± 0.005 (3)	
Bø (b)	E		0.090 ± 0.010 (4)				
Vigra	MW		0.11 ± 0.01 (3)				
SWEDEN							
Margareteberg		0.25 ± 0.01 (10)			0.26 ± 0.02 (6)		
DENMARK							
Hirtshals	MW	0.093 ± 0.010 (7)			0.098 ± 0.009 (3)		
Nørre Lyngby	MW	0.086 ± 0.011 (7)					
Skaerumhede	MW				0.093 ± 0.007 (5)	0.082 ± 0.001 (4)	
Stensigmose	E			0.15 ± 0.01 (4)	0.17 ± 0.01 (8)	0.15 ± 0.01 (6)	
Mommark	E					0.14 ± 0.02 (8)	
Trappeskov Klint	E					0.17 ± 0.01 (8)	
Ristinge Klint	E		0.22 ± 0.01 (3)	0.17 ± 0.02 (11)		0.20 ± 0.03 (9)	
Strandegaard	E					0.21 ± 0.01 (6)	0.23 ± 0.01 (2)
Stubberup Have	E					0.16 ± 0.01 (8)	
Tønder	E			0.18 ± 0.02 (5)			
Slettenshage	H					0.32 ± 0.01 (3)	
Esbjerg	C	0.47 ± 0.04 (8)	0.45 ± 0.04 (14)		0.46 ± 0.04 (5)		
Røgle	C	0.54 ± 0.08 (3)					
Vognsbøl	C		0.44 ± 0.02 (5)			0.38 ± 0.04 (4)	

POLAND							
Nowiny	E			0.20 ± 0.03 (6)			0.19 ± 0.01 (5)
NW GERMANY							
Schnittlone	E			0.17 ± 0.01 (9)			0.18 ± 0.02 (9)
Holnis	E					0.16 ± 0.01 (12)	
Südemarsch	E		0.16 ± 0.01 (8)				
Scharhörn 57	H				0.29 ± 0.01 (3)		
Scharhörn 55	H				0.29 ± 0.01 (3)		
Wacken	H		0.25 ± 0.02 (3)		0.28 ± 0.02 (7)	0.30 ± 0.02 (9)	0.26 ± 0.03 (5)
NETHERLANDS							
Amersfoort	E	0.20 ± 0.02 (4)		0.20 ± 0.02 (10)			
Bergen	E		0.18 ± 0.02 (4)	0.21 ± 0.03 ($)	0.18 ± 0.01 (8)		0.23 ± 0.01 (4)
Bergen	E		0.20 ± 0.01 (3)				
Castricum	E		0.17 ± 0.02 (8)		0.18 ± 0.03 (12)		
Zunderdorp	E				0.19 ± 0.02 (5)		
Noord Bergum	C				0.46 ± 0.06 (4)		
BELGIUM							
Koolkerke	E			0.16 ± 0.03 (12)	0.18 ± 0.02 (14)		
Zeebrugge	EW	0.13 ± 0.01 (2)					
FRANCE							
Herzeele	H				0.29 ± 0.03 (10)		

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*MW = Middle Weichselian, EW = Early Weichselian, E = Eemian, H = Holsteinian, C = 'Cromerian'.

the amino acid ratios in foraminifera from the two sites. These data, while not as extensive as the mollusc data, suggest that the interglacial beds are the same age (Miller *et al.*, 1983). D/L ratios in *Lucinoma borealis* from Bö averaged 0.23, whereas the same taxon from Fjøsanger averaged only slightly higher (0.26). Although D/L ratios in *Arctica*, *Littorina*, *Mya* and *Macoma* are higher than in their Eemian counterparts in Denmark and NW Germany, *Venerupis* ratios are similar.

The available amino acid data (Table 7) support a correlation of the Bö site with the classical Eemian sites in Denmark and NW Germany. The data also indicate that the extent of epimerization is generally greater in molluscs from Fjøsanger than from Bö. Whether that difference is sufficient to conclude that they are from different interglacials or simply represents scatter in the data from sites of the same age remains unresolved. We propose two alternatives: Alternative 1 (Fig. 8) assumes that the Fjøsangerian was deposited in an interglacial preceding the Eemian but post-dating the Holsteinian. Alternative 2 (Fig. 9) assumes that the Fjøsangerian is of Eemian age, and that the site experienced either a relatively high EDT or as yet unknown environmental effects that catalyzed the epimerization reaction. This interpretation is supported by the occurrence of the indicator species *Bittium reticulatum*, the palynology and recent TL dates (Hütt *et al.*, 1983).

THE EEMIAN IN THE ARCTIC

A number of samples have been analysed from marine deposits along the Arctic coast of the Soviet Union and some of the Arctic Islands. Due to the large difference in temperature between these sites and the secure Eemian sites in Europe, and lack of an independent absolute date on any of the Arctic samples, the interpretation of the measured amino acid ratios must necessarily be tentative. As a first approximation, we have assumed that the ages provided by the collectors are correct, and that the first deposit below the Holocene with a fauna beyond its present range is the most likely candidate for the last interglacial.

Arctica islandica, which has a current northern limit in the White Sea, occurs in deposits along the Arctic coast of the U.S.S.R. from Kola Peninsula to Taimyr Peninsula. Following Kellogg *et al.* (1982), the most likely time that North Atlantic Drift water entered the Norwegian Sea and extended farther along the arctic coast of the Soviet Union than during the Holocene would have been during isotope sub-stage 5e, the last interglaciation. Certainly the deposits could not be younger.

The measured D/L ratio in *Arctica* (Fig. 10) decreases between Kola Peninsula and the Yenisey Bay region. *Mya truncata* from Yenisey Bay have a mean D/L ratio about the same as in *Arctica*, but the spread in measured values is somewhat higher. Probable last interglacial deposits on Taimyr Peninsula (MAT −13 to −15°C) contain *Arctica*, but only *Mya truncata* and *Hiatella arctica* were available for analysis. The mean ratios (Fig. 10, J.K. Brigham-Grette, *unpublished data*), are lower than from Yenisey Bay, as are the ratios in *M. truncata* from a purported last interglacial deposit on Novaya Zemlya.

The overall trend of these data are as would be expected for last interglacial deposits under low thermal conditions, although it must be remembered that at such low temperatures the epimerization rate is so reduced that the potential resolving power of the

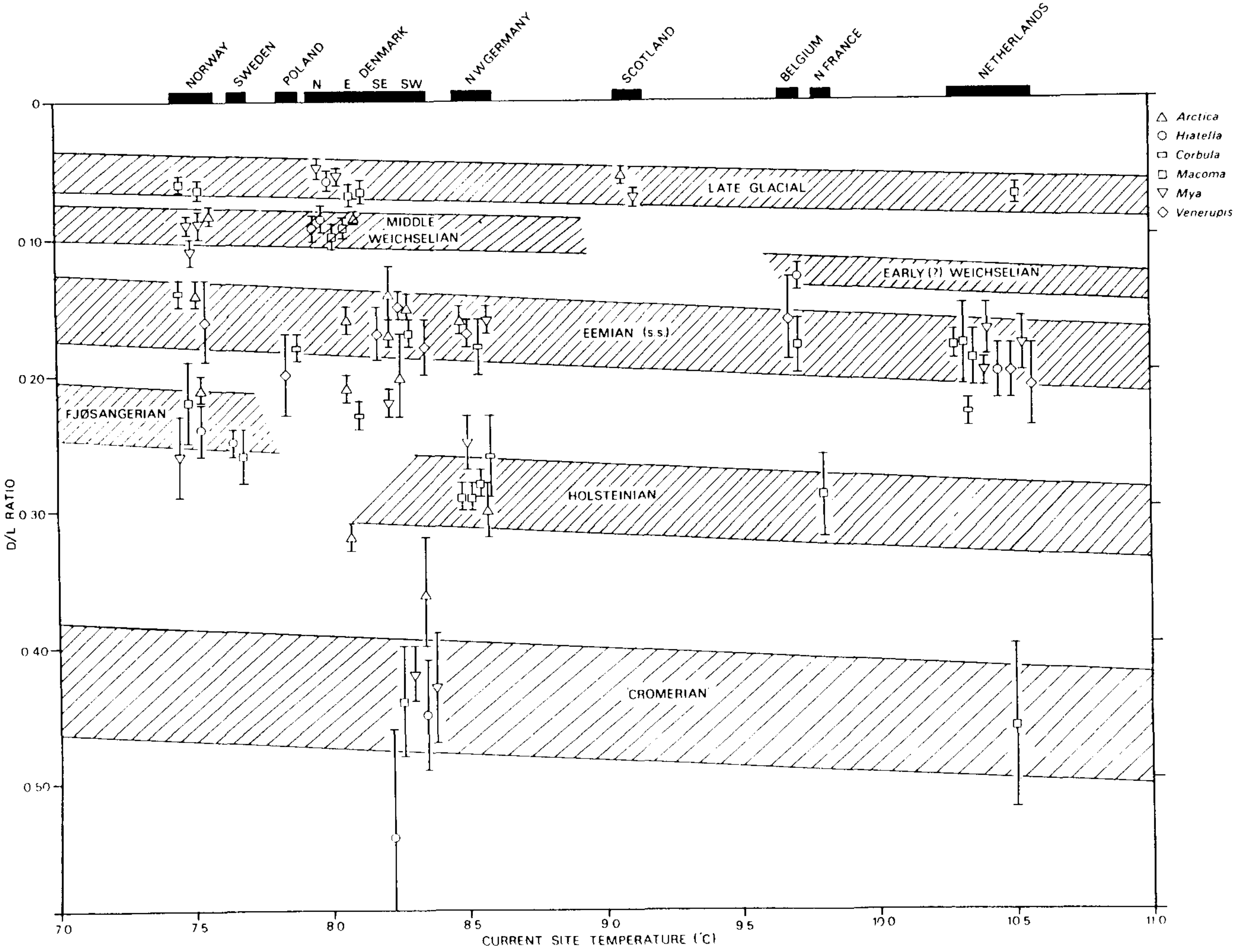

FIG. 8. Mean D/L ratios and one standard deviation for six of the dominant taxa in the moderate-rate group plotted against site temperatures for all sites with current mean annual temperatures between 7 and 11°C. (Data are from Table 7 except late glacial ratios which are from Miller, 1985.) Hatured envelopes define aminozones separating high-sea-level events across this region. The slope of the aminozones is due to the thermal gradient. More rapid epimerization in the warmer sites has produced higher D/L ratios in equivalent time periods than in cooler sites. In this alternative the Fjøsangerian is considered to be from a pre-Eemian (intra-Saalian or Holsteinian) interglacial and the Eemian (*sensu stricto*) group is correlated with the interglacial beds at Bø. Two *Corbula* from Strandegaard and a single individual of *Mya* from Ristinge are the only known Eemian measurements to fall outside the boundaries; they are considered aberrant data.

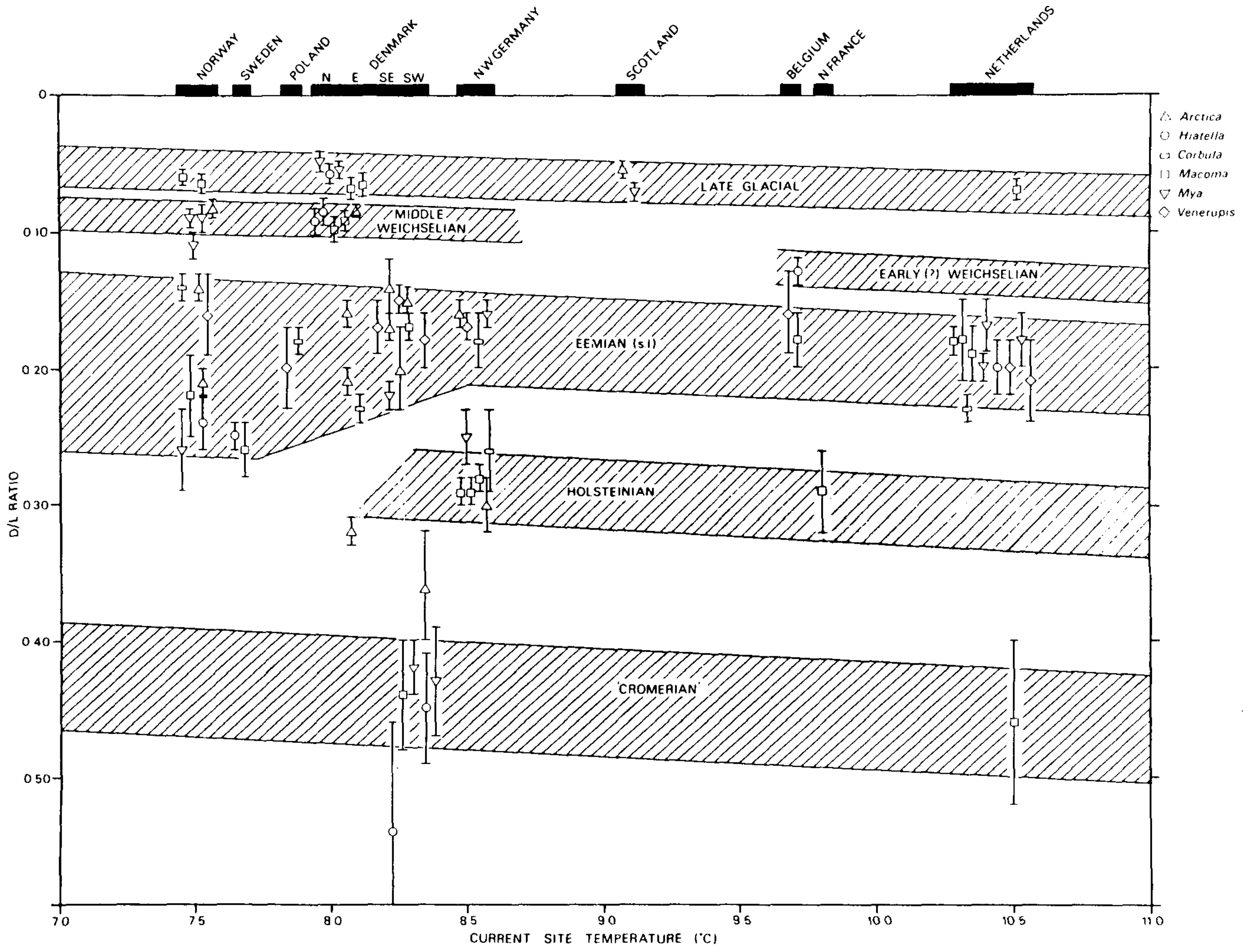

FIG. 9. Mean D/L ratios and one standard deviation for six of the dominant taxa in the moderate-rate group plotted against site temperatures for all sites with current mean annual temperatures between 7 and 11°C. (Data are from Table 7 except late glacial ratios which are from Miller, 1985.) In this alternative (option 2), the Fjøsangerian and Bø interglacials are considered to be from the same interglacial and both are correlated with the Eemian (*sensu lato*). If this interpretation is correct, then the range of D/L ratios that might be encountered from a specific interglacial has considerable scatter and the resolving power of the amino acid data is diminished relative to alternative 1 (Fig. 8).

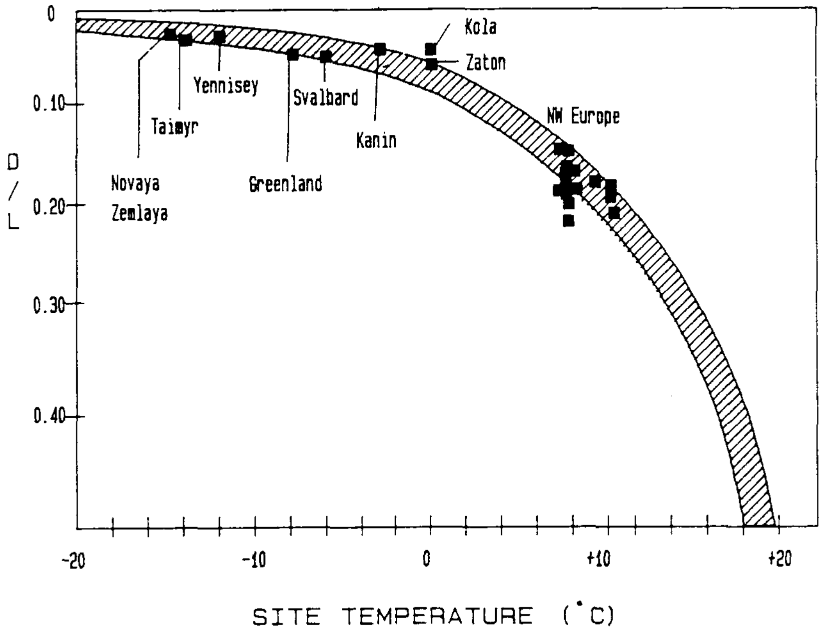

FIG. 10. Mean D/L ratios in moderate-rate taxa all last-interglacial sites included in this study. The hatured envelope defines an exponential relationship between D/L ratio and site temperature. This relationship can be used as a predictive model to provide an estimate of the D/L ratio for sites with temperatures different from ones already studied.

method is less than at mid latitudes. The measured D/L ratios generally decrease in an easterly direction, with the lowest ratios found on Taimyr Peninsula and the Arctic Islands.

On Svalbard (Fig. 3), the last interglacial is currently considered to be represented by deposits of aminozone C (Miller, 1982) based on unpublished U-series and TL dates and the associated microfauna (G.H. Miller, H.P. Sejrup, S.J. Lehman and S.L. Forman, *unpublished data*). D/L ratios in *Mya* and *Hiatella* from deposits of aminozone C average 0.044 ± 0.005.

Interglacial deposits thought to be correlative with the Eemian have recently been reported from Greenland (Petersen, 1982; Funder, 1984). *Mya truncata* from three levels within the interglacial beds produced mean D/L ratios of 0.047 ± 0.002, in keeping with a last interglacial age.

PREDICTIVE MODEL FOR D/L RATIOS IN LAST INTERGLACIAL SITES

The wide thermal range of last interglacial localities analysed (−15 to +11°C) allows the construction of an empirical model describing the relationship of D/L ratio to site temperature. The mean D/L ratios in all moderate-rate taxa from all last interglacial localities analysed are plotted against current site temperatures on Fig. 10. The curve fitted to these data describes an exponential relationship in keeping with the general form defined by epimerization kinetics. This relationship also provides a predictive model that allows the estimation of the D/L ratio for last interglacial representatives of the moderate-rate taxa from any site within the temperature range of the current data set. Such a model will be particularly helpful for future studies in sites that are slightly colder or warmer than NW Europe.

ABSOLUTE AGE ESTIMATES FOR HIGH SEA-LEVEL EVENTS AROUND THE NORTH SEA

Although the conversion of D/L ratios to absolute age is hampered by uncertainties in the thermal histories of the sites, the ratios can be used to place constraints on the possible ages. This appraisal is dependent on the correct interpretation that the Eemian Interglacial occurred about 120 ka ago. Based on that assumption and the relative differences in D/L ratios for the other high sea-level events, limiting absolute ages can be assigned.

We assume that all European interglacials are correlated with odd-numbered stages in the deep-sea isotope record, but that not all such stages are necessarily represented in the terrestrial record. Furthermore, with our present understanding of the isotopic signal, it is not possible to say which of the isotopic peaks represent terrestrial interglacials and which are interstadials. In the introduction we argued that if the land-based interglacial sequence is complete, then the Eemian must represent isotope substage 5e, the Holsteinian stage 7 and the youngest of the pre-Elsterian ('Cromerian') warm stages, isotope stage 9. Alternatively, the Holsteinian interglacial might represent isotope stage 9, 11 or 13.

Prior to using the measured D/L ratios to constrain the absolute ages of European interglacials, it is essential to note whether the samples are from early or late in the interglacial. For example, most Holsteinian molluscs that we have analysed come from the late Elsterian–early Holsteinian transition or from early in the Holsteinian and have consequently experienced nearly the full duration (ca. 15 ka) of interglacial warmth (rapid epimerization) as well as that of the subsequent Wacken Interglacial. Our Eemian samples, on the other hand, cover a wider range of the interglacial. We estimate that they average from the middle Eemian and so experienced only 5 ka of interglacial warmth. Because the Holsteinian was longer than, and about as warm as the Eemian (e.g. Meyer, 1974; H. Müller, 1974b), we expect the Holsteinian shells to have experienced a higher proportion of interglacial warmth than did the Eemian samples. Consequently, the D/L ratios in Holsteinian shells may be disproportionately higher than expected for their age relative to the Eemian ratios. With these guidelines and the assumption that the midpoint of the Eemian dates from about 120 ka ago, the D/L ratios can be used to evaluate whether the Holsteinian is isotope stage 7, 9, 11 or 13.

The most concentrated data set from a similar temperature is from the sites in Denmark, NW Germany and the Netherlands. The mean D/L ratios (Table 8) have been plotted against their known or possible ages (based on the recent SPECMAP timescale; Imbrie *et al.*, 1984) in Fig. 11. The three scenarios depicted are for the Holsteinian to be correlated with stages 7, 9 or 11. The slope of the straight-line segments connecting each point is directly proportional to the integrated temperature during that time interval. Assuming that

TABLE 8. Mean D/L ratios in shells from high sea-level events in NW Europe (Denmark, NW Germany, Netherlands) with postulated correlations to the deep-sea oxygen-isotope stratigraphy and limiting absolute age estimates. These data are used to construct Fig. 11

Relative age	Mean D/L ratio Moderate-rate	 Slow-rate	Suggested correlation	Limiting absolute age
Modern	0.013 ± 0.002	0.013 ± 0.002	Modern	0
Late Weichselian	0.060 ± 0.010	about 0.04	1/2 boundary	10 to 12 ka
Middle Weichselian	0.090 ± 0.010	—	3	> 40 ka
Early Weichselian	0.12 ± 0.01	—	5a/c	70 to 100 ka
Eemian	0.18 ± 0.02	0.11 ± 0.01	5e	125 ka
Holsteinian	0.29 ± 0.02	0.22 ± 0.03	7 (or 9)	240 (or 330 ka)
Pre-Elsterian	0.46 ± 0.04	—	> 11 < 19	400 to 700 ka

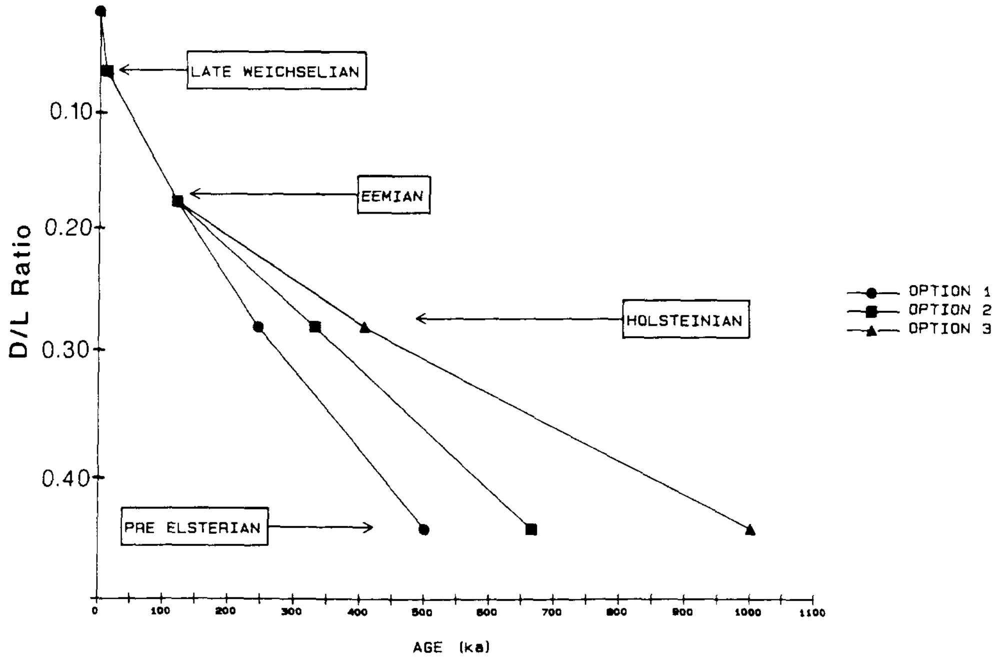

FIG. 11. Possible absolute age relationships for interglacial deposits in NW Europe. See text for discussion of the most probable option.

the temperatures characterizing each of the glacial–interglacial cycles should be about the same requires that the slopes of the various line segments be similar. However, the situation is complicated by the general decrease in apparent epimerization rate over time as the proportion of isoleucine in the slower-epimerizing free form increases. Consequently a decrease in slope during successively older glacial cycles may be expected, but not an increase in slope.

If we assume that the Holsteinian is early stage 7 (option 1, Fig. 11) then the projection to the 'late Cromerian' ratios in shells from the Netherlands predicts a minimum age of ca. 500 ka (stage 13) in keeping with their stratigraphic position above the Matuyama–Brunhes (M–B) boundary. Assuming that the Holsteinian shells are from early in stage 9 (330 ka; option 2), then the extrapolation to the 'late Cromerian' beds yields an age of 670 ka. This date is already close to the M–B boundary and leaves little time for additional climatic oscillations in the normally magnetized 'late Cromerian' sequence. Although we favor a stage 7 age for the Holsteinian, we cannot exclude a stage 9 correlation. Option 3, in which the Holsteinian is correlated with stage 11 can be excluded because the extrapolated age for the 'late Cromerian' shells lies within the Matuyama reversed polarity zone.

These considerations suggest that the Holsteinian (*sensu lato*) is most likely correlative with isotope stage 7. The stage 7 isotope peak is complex, and has been subdivided into two 'light' substages (7a and 7c) separated by substage 7b (Ninkovitch and Shackleton, 1975). Substage 7a, in turn, consists of two distinct peaks (e.g. Imbrie *et al.*, 1984, p. 68). These complexities are mirrored in the deep-sea faunal record; in the North Atlantic two interglacial assemblages are separated by a brief return to a glacial fauna within isotope stage 7 (Ruddiman and McIntyre, 1982). We hypothesize that the Holsteinian (*sensu stricto*) is the first light isotope peak in stage 7 (7c: 245–230 ka); most of our molluscan samples come from early within this interval. Substage 7b is represented by the niveo-eolian sands separating the Holsteinian (*sensu stricto*) from the overlying peat at Wacken, NW Germany. The latter peat, the Wacken Interglacial, can be correlated with substage 7a, or with the first peak of it, leaving room for an additional warm interval within the Saalian. If these correlations are correct, then the 'late Cromerian' beds can be no younger than stage 13 and no older than stage 17. Consequently a shallow-marine equivalent of at least stage 9 and 11 is missing in NW Europe.

Alternatively, if the Holsteinian (*sensu stricto*) is stage 9, the Wacken/Dömnitzian may be correlative with stage 7 and the 'late Cromerian' could be stage 15, 17, or 19. In this case, shallow-marine equivalents of at least isotope stages 7, 11 and 13 are missing (assuming Fjøsangerian is not stage 7).

The D/L ratios can be used similarly to support strongly a last-interglacial age for the Eemian. If the Eemian is older than stage 5e (e.g. stage 7), then the minimum age for the Holsteinian is stage 11 and the 'late Cromerian' would have to be considerably older than 700 ka, again in contradiction to the established paleomagnetic stratigraphy.

Several recent campaigns have been directed at providing independent dates on terrestrial interglacial sequences across NW Europe. A number of U-series dates have been reported recently (e.g. Hennig, 1983; Brunnacker *et al.*, 1983) primarily on travertines and speleothems. The ages of these deposits show a strong grouping that correlates with isotope stage 5. In addition, a number of pre-Eemian sites yield dates that cluster between 300 and

350 ka. However, correlation of the localities dated with the classical interglacial sequence is problematic due to the scarcity of pollen in the carbonate deposits. We conclude that these correlations cannot yet be securely established independently of such dates.

There have also been attempts to date molluscs directly in well studied interglacial sites in the region. Stremme (1983) reports U-series dates on shell from the Herzeele Formation (Holsteinian) in northern France that cluster around 330 ka. More recently Linke *et al.* (1985) report 17 ESR dates on marine molluscs from the same Holsteinian sites in NW Germany that were included in our amino acid survey. The ESR dates average 220 ± 20 ka, supporting our interpretation that the Holsteinian correlates with isotope stage 7.

CONCLUSIONS

We have identified a suite of several pelecypod genera from interglacial sites in NW Europe in which the isoleucine epimerization reaction proceeds at a similar, moderate rate. D/L ratios can be used more or less interchangeably between these taxa in developing a chronostratigraphy for the region. It is necessary to use several taxa in such a regional survey because no single taxon is present at all sites due to strong differences in local environments of deposition. In addition to the moderate-rate group that forms the basis of the interpretations, supplemental information has been obtained through a few additional taxa that produce reliable results, but have different epimerization rates. The relationship between the D/L ratios obtained from these taxa to those from the moderate-rate group is not constant over time, complicating conversion of all measurements to a single number of universal applicability.

Based on our analysis of more than 1,000 individual shells for this project we offer the following guidelines for future studies of this nature: (1) reliable amino acid data require the analysis of at least three, and preferably five individuals of an established taxon at each site; (2) improved confidence can be obtained by similarly analysing additional primary species; (3) sites for which the mean D/L ratio differs from an established interglacial group mean by more than one standard deviation require supplemental analyses of either the same species or another well constrained taxon before recommending that a 'new' interglacial be introduced; (4) occasionally aberrant individuals and possibly even sites may occur.

The following conclusions can be drawn from the interpretation of the measured D/L ratios:

(1) A first order verification of the validity of the D/L data is the correct ordering of shells from modern, Lateglacial, Middle Weichselian and interglacial sites as shown for Denmark and western Norway (Figs 8 and 9).

(2) The amino acid survey essentially verifies that sites in NW Europe previously labelled 'Eemian' are all of a single age and that they correlate with the interglacial beds in the Amersfoort boring in the Netherlands. We argue that the type locality for the Eemian Interglacial, the Amersfoort boring, is demonstrably the last interglacial in NW Europe and can be correlated with the marine beds of the Tychnowy Sea that underlies the type Weichselian till in Poland.

(3) All sites analysed that contain the typical Eemian pollen stratigraphy (Amersfoort, Castricum, Bergen, Zunderdoorp, Rödemis, Schnittlohe, Ristinge Klint) have yielded secure Eemian ratios. Sites that contain the classical Eemian index molluscs *Bittium reticulatum* and/or *Venerupis senescens* also produced Eemian ratios (with the possible exception of Fjøsanger, Norway).

(4) Marine beds in the vicinity of Esbjerg and Rögle, Denmark, that have been correlated previously with the Holsteinian of NW Germany, yielded D/L ratios in molluscs that are consistently higher than ratios in the same taxa from secure Holsteinian deposits. The amino acid data suggest a correlation with a pre-Elsterian interglacial in the Netherlands. This correlation implies that the till below the Esbjerg marine beds is of pre-Elsterian (*sensu stricto*) age; the first reported widespread occurrence of such a till in NW Europe.

(5) We accept the previous correlations of the Eemian to isotope substage 5e and an age of 120 ka. Using this as a control, the amino acid data imply that the Holsteinian probably correlates with isotope stage 7, less probably with stage 9 but cannot be as old as stage 11. If the Holsteinian (*sensu lato*) does correlate with isotope stage 7 then the Holsteinian (*sensu stricto*) must represent substage 7c and the Wacken and other intra-Saalian warm periods represent later peaks of stage 7.

(6) D/L ratios in shells from some localities on the Belgian coastal plain are significantly lower than values predicted for an Eemian age, suggesting the possibility of a post-Eemian (Early Weichselian) high sea-level event. A similar age high sea-level event has been identified in an amino acid survey of Mediterranean shoreline deposits (Hearty *et al.*, *in press*).

(7) One of the few remaining controversies is the amino acid correlation of interglacial sites in western Norway. The amino acid data remain open to interpretation whether Fjøsanger is the same age or is older than the interglacial at Bö, and by inference, the Eemian of NW Europe.

(8) Interglacial sites in the U.S.S.R., Svalbard and Greenland cannot be securely correlated with the Eemian sites in NW Europe by D/L ratios alone because of temperature differences. But by assuming that the postulated correlations are correct this provides a framework for evaluating the temperature-sensitivity of the isoleucine epimerization reaction. Last interglacial localities that have been sampled span a temperature range of more than 20°C (−12 to +10°C). The D/L ratios measured in shells from these sites demonstrate an exponential increase in reaction rate with increasing temperature.

Part 2 — Description of the Sites and Measured D/L Ratios

Sites from which molluscan samples were obtained are briefly described and the D/L ratios obtained for all species analysed at each site are presented. References for detailed site descriptions are given, as are the bases for previous age ascription. The sites, described in order from north to south, are shown in Figs 3 and 4.

The tables follow a standard format, in which results are presented alphabetically for each relative age group from each country. The analyses are listed by their laboratory identification number and species; the D/L ratio is given as the arithmetic mean of all analyses for a given Lab ID (Mean), the standard deviation of the measurements (σ) and the number of specific preparations on which the mean was based (n). Some collections were limited in size and our results include multiple analyses of individual shells. Such collections are designated by a number in parentheses following the number of analyses (n) that designates the number of *different* individuals utilized. Multiple laboratory identification numbers for the same collections are indicated as footnotes where appropriate.

SOVIET UNION

We have concentrated our analyses of interglacial molluscs from the U.S.S.R. on several regions that represent a large range in current thermal regime. Most analyses were on *Arctica islandica* and *Mya truncata*. *Arctica* is presently limited to areas influenced by water of the North Atlantic Drift (the present northeastern limit lies in the White Sea) and its presence in Pleistocene deposits along the Arctic coast of the Soviet Union is an indication of interglacial conditions. The localities (Fig. 3) are discussed from west to east; measured D/L ratios are given in Table 9.

Kola Peninsula

Yevzerov and Koschechkin (1977, 1981) describe two series of sub-till marine sediments that occur in the lower courses of river valleys on eastern Kola Peninsula. The age of these deposits has been long debated, but it now seems to be agreed (Faustova, 1984) that the lower of these, the Ponoy beds, were deposited during the Mikulino Interglacial, assumed to be correlative with the Eemian. The Ponoy beds contain a boreal mollusc fauna suggesting marine temperatures as high as today. Several finite radiocarbon dates between 34 and 47 ka were obtained from shells in the Ponoy beds, whereas U/Th dates on molluscs from the same beds range between 86 and 114 ka (Yevzerov and Koschechkin, 1977; Arslanov *et al.*, 1981). The upper marine Strel'ninskiye beds are separated from the Ponoy beds by erosional surfaces, and in one case, a till (Yevzerov and Koschechkin, 1977). The fauna in the Strel'ninskiye beds suggest colder marine conditions than in the Ponoy beds. Through pollen stratigraphy the Strel'niskiye beds are correlated with the Peräpohjola interstadial of Finland (e.g. Hirvas *et al.*, 1981). All of the samples we have analyzed from Kola Peninsula came from the Ponoy beds.

The Ponoy type locality, situated on the SE coast of Kola Peninsula, contains interglacial marine sediments that are currently 20 to 25 m above the sea. Samples of *Arctica islandica* were submitted by V. Yevzerov in 1980 and 1981 from the Ponoy beds exposed in sections

TABLE 9. D/L ratios in molluscs from sites in the Soviet Union. An explanation of the format for Tables 9 through 19 is given in the introduction to Part 2 of the text

Lab ID	Species	Mean	σ	n	Locality/sample number
		Kola Peninsula			
AAL-2596	*Arctica islandica*	0.035	0.002	3	Ponoy River, S of Village*
AAL-2786	*Arctica islandica*	0.034	0.004	6(3)	Malaya Kachkovka 5.8 m*
AAL-2785	*Arctica islandica*	0.037	0.001	3	Malaya Kachkovka 4.2 m*
AAL-3753	*Arctica islandica*	0.040	0.000	2(1)	Malaya Kachkovka 4.2 m
AAL-3752	*Arctica islandica*	0.042	0.004	2	Malaya Kachkovka 4.2 m
AAL-2787	*Arctica islandica*	0.042	0.004	3	R. Chapoma*
AAL-3754	*Arctica islandica*	0.050	0.006	2(1)	R. Chapoma
*Submitted by Yevzerov, others submitted by Punning.					
		Zaton, Archangeslk District			
AAL-3917	*Arctica islandica*	0.046	0.005	3(1)	R. Mezen
AAL-3751	*Arctica islandica*	0.053	0.008	2(1)	R. Mezen
AAL-3921	*Hiatella arctica*	0.054	0.006	2(1)	R. Mezen
AAL-3750	*Mya truncata*	0.044	0.000	2(1)	R. Mezen
AAL-3920	*Mya truncata*	0.089	0.006	2	R. Mezen
AAL-3192	*Arctica islandica*	0.094	0.005	2(1)	R. Divina*
AAL-3192	*Mya truncata*	0.082	0.005	2(1)	R. Divina*
*Submitted by Gudina, others submitted by Punning					
		Kanin Peninsula			
AAL-3190	*Arctica islandica*	0.036		1	3018-3
		Yenisey Bay			
AAL-2586	*Arctica islandica*	0.022	0.000	2(1)	A-262
AAL-2584	*Arctica islandica*	0.025	0.000	2(1)	B-192-4
AAL-2587	*Arctica islandica*	0.026		1	B-271
AAL-2585	*Arctica islandica*	0.027	0.001	2(1)	A-252/1
AAL-2590	*Arctica islandica*	0.027	0.000	2(1)	T-989
AAL-2589	*Arctica islandica*	0.035	0.004	2(1)	A-323
AAL-2595	*Mya truncata*	0.015		1	G-260
AAL-2588	*Mya truncata*	0.019	0.000	2(1)	G-27011
AAL-2591	*Mya truncata*	0.020	0.003	3(1)	G-122
AAL-2593	Mya truncata	0.031	0.001	2(1)	D-21
AAL-2592	*Mya truncata*	0.035	0.001	2(1)	G-203/1
AAL-2594	*Cardium edule*	0.027	0.004	6(1)	121/5
		Arctic Islands			
AAL-3191	*Mya truncata*	0.021		1	Novaya Zemlaya: 482-3
AAL-3189	*Mya truncata*	0.022	0.000	2(1)	Novaya Zemlaya: K-3
AAL-3187	*Mya truncata*	0.028		1	New Siberian Islands: 1083

along the Ponoy River, from correlative beds on the Chapoma River 150 km to the SW, and from the Malaya Katchkovka River, 50 km to the north. At the M Katchkovka site, 7.8 m thick marine beds occur below till at ca. 140 m asl. In 1983 Punning submitted additional *Arctica islandica* from the sections on the Malaya Katchkova River and Chapoma River.

The mean D/L ratio in 21 shells of *Arctica islandica* in 7 collections from Kola Peninsula is 0.039 ± 0.005 (Table 9), suggesting the localities represent a single interglacial event. We assume that this interglacial is correlative with the Eemian/Mikulino interglacial, and that the high elevation of some of the deposits is a result of uplift (Yevzerov, *written comm.* 1985).

Zaton, Archangelsk District

In 1983, Punning sent well preserved valves of *Mya*, *Hiatella* and *Arctica* from interglacial marine beds exposed along the River Mezen, near V. Zaton close to the White Sea coast. The shells were excavated from marine sands 4.4 to 6.0 m below the ground surface and were overlain by additional sandy beds. The fauna suggests conditions as warm as present and the deposit is considered to be Eemian by Punning (*written comm.*, 1983). Recent TL dating of sands beneath the early Weichselian (Valdai) till in the Archangelsk district gave an age of 93 ka (Hütt *et al.*, 1985). *Arctica* and *Mya* from an interglacial site on the River Divina were supplied by Gudina in 1980.

All but one of the valves submitted by Punning yielded similar D/L ratios. The anomalous valve (AAL-3920; *M. truncata*) gave a ratio twice as high as the other samples, but similar to the ratios in both samples from the River Divina. These results suggest that beds from two discrete interglacials occur in the Archangelsk district. The mean D/L ratio of the other four samples is 0.051 ± 0.006 (Table 9), slightly higher than on Kola Peninsula. The current MAT is about the same as on Kola Peninsula (0 to -1°C). The Zaton ratios are slightly higher than expected, but we suggest the shells are probably Eemian.

Kanin Peninsula

We have analyzed a single valve of *Arctica islandica* from Kanin Peninsula, at the juncture of the Barents and White seas. The shell was supplied by V. Gudina, Novosibirsk. The D/L ratio is 0.036 (Table 9), compatible with the correlation to the Kola and Archangelsk samples.

Yenisey Bay

In 1980, Gudina submitted a suite of samples from deposits around the mouth of the Yenisey River (MAT -10°C). Most of the samples were collected within a 100 km N–S strip in the inner reaches of Yenisey Bay, between Golchikka and Ladygrig Yar, except sample B-192, which was collected 150 km west of the river mouth, sample G-122 collected midway between B-192 and the river mouth and sample A-323 from the vicinity of lake Oz Khaseynto, 60 to 70 km west of the inner part of the bay. It is our understanding that all of the samples are considered to be of last (Kazantsevo) interglacial age. Certainly the occurrence of *Arctica islandica* in this area suggests much warmer inshore marine conditions than exist today. The interglacial beds are locally overlain by till of an Early Weichselian glaciation and Late Weichselian glacial-lacustrine sediment, separated by Middle Weichselian non-glacial deposits (Isayeva, 1984).

The D/L ratios in *Arctica* (Table 9) clearly indicate that all collections are of a similar age. The spread in ratios is greater for *Mya*, possibly suggesting some age differences. However, all samples consist of a single shell from which one to three preparations were made for analysis. At present we assume all samples are of approximately the same age. The mean D/L ratio from eleven preparations of *A. islandica* is 0.027 ± 0.004 and in ten preparations *M. truncata* is 0.024 ± 0.008.

Taimyr Peninsula

In 1979 D.M. Hopkins obtained molluscs from deposits on the Taimyr Peninsula (MAT −15°C). These samples were processed by J. Brigham-Grette and are included here for comparison with the samples from the more western localities along the Arctic coast of the Soviet Union. The mean D/L ratio in 8 shells of *M. truncata* and 11 shells of *H. arctica* that we believe are last interglacial in age is 0.023 ± 0.008.

Arctic Islands

We have processed a few shells from Novaya Zemlaya and the New Siberian Islands supplied in 1980 by Gudina. Both areas are high arctic sites with MATs averaging about −12°C. Only *M. truncata* has been analyzed, but these are from sites where the microfauna indicates an interglacial age (Gudina, *written comm.* 1980). The mean D/L ratio in 4 preparations is 0.023 ± 0.004 (Table 9).

GREENLAND

An *in situ* marine unit a few meters above sea-level on the west coast of Jameson Land, East Greenland contains a thermophilous fauna similar to that of the mid-Holocene marine optimum but includes taxa that did not live in the area during the Holocene as well as some that have since migrated out of the region (Petersen, 1982; Funder, 1984). The sandy shell-bearing beds lie on sediment of glacial origin. Based on the faunal composition, infinite radiocarbon dates and relatively low amino acid ratios, the beds, which define the Langelandselv Interglacial, are correlated with the Eemian interglacial and isotope substage 5e (e.g. Funder, 1984).

D/L ratios have been measured in *Mya truncata* from three levels in the interglacial beds. The mean ratios for each level are 0.047, 0.049 and 0.045. The mean D/L ratio for the sequence is 0.047 ± 0.02 (5).

SVALBARD

The Svalbard archipelago preserves a large variety of raised marine deposits, many of which contain a rich and diverse fauna. Many of the deposits found along the north and west coasts of Spitsbergen are beyond the range of radiocarbon and may be of last interglacial age or older. Lacking a diagnostic pollen stratigraphy that can be used as a basis for correlating with the standard European sequence, most workers have relied on 'extra-limital' mollusc or foraminifers to differentiate the last interglacial from interstadial events. Amino acid ratios supplement the biostratigraphy.

Miller (1982) identified two marine depositional episodes that might be correlated with the Eemian; episode B or C. Recent micropaleontological analysis of these sites has demonstrated that although both units are indicative of relatively warm nearshore marine waters, only the older (episode C) contains faunal elements suggestive of temperatures warmer than present (H.P. Sejrup and S.J. Lehman, *unpublished data*). Consequently, we argue that episode C is the most reasonable correlative of the Eemian deposits of Europe. The mean D/L ratio in *Mya truncata and Hiatella arctica is* 0.044 ± 0.005.

NORWAY

Fjøsanger

A complete glacial–interglacial–glacial marine sequence was uncovered in excavations at Fjøsanger near Bergen (Mangerud *et al.*, 1979, 1981a). At the base of the section is a till, overlain by silt with a cold-water mollusc and foraminifera fauna. In the overlying sands and gravels the fauna grades into an assemblage requiring sea-surface temperatures higher than at present. At the top of the interglacial beds the fauna changes back to a high arctic assemblage enclosed in glacial-marine sediment. The interglacial (the Fjøsangerian) has been correlated with the Eemian because of the strong similarity in the pollen stratigraphies. An Eemian age is supported by the occurrence of the index gastropod *Bittium reticulatum* and a series of thermoluminescence dates (Hütt *et al.*, 1983).

Fjøsanger was the first European mainland interglacial site to be studied by the amino acid method and a large number of analyses have already been published (Mangerud *et al.*, 1981a; Miller *et al.*, 1983). The assumption that the Fjøsangerian is the last (Eemian) interglacial has been the basis for estimating the ages of younger depositional events from their D/L ratios (Mangerud *et al.*, 1981b; Miller *et al.*, 1983). The average D/L ratios in Fjøsangerian taxa are given in Table 10.

Bø

An excavation at Bø on the island of Karmöy, revealed interglacial nearshore marine sediments in the lower 3 m of the 21 m section. The interglacial beds (Avaldsnes Interglacial: Andersen *et al.*, 1981, 1983) are overlain by two marine interstadial deposits separated by a till, and the section is capped by a Late Weichselian till. The interglacial beds have been correlated with the Fjøsangerian (see above) and the Eemian of NW Europe based on the interglacial character of the floral and faunal elements and amino acid ratios in foraminifera (Andersen *et al.*, 1983; Miller *et al.*, 1983). The marine gastropod *Bittium reticulatum*, common in the interglacial beds at Bø, is generally regarded as an index taxon for the Eemian. The upper interstadial marine unit, the Bø marine sands, is of Middle Weichselian age.

The interglacial beds are overlain by Early Weichselian marine sands, although the contact, which is either erosional or represents a prolonged period of slow sedimentation, was not obvious in the field, and molluscs are not available from this bed. A new excavation at the site has revealed a more complete stratigraphy of the interglacial beds (B.G. Andersen, *oral comm.*, June 1985) and additional analyses are underway at our laboratories.

TABLE 10. D/L ratios in shells from marine sites in Western Norway

Lab ID	Species	Mean D/L	σ	*n*	Bed	Sample no.
		Fjøsanger Site				
AAL-2181	*Mya truncata*	0.180	0.000	2	F	235
AAL-2864	*Mya truncata*	0.193	0.021	2(1)	G1	1150
AAL-3684	*Hiatella arctica*	0.222	0.008	4(2)	G2	847
AAL-4564*	*Hiatella arctica*	0.238	0.008	3(2)	G2	847
AAL-2865	*Mya truncata*	0.219	0.002	2	G2	1411
AAL-3678	*Littorina littorea*	0.108		1	H	1352
AAL-3680	*Turritella communis*	0.295	0.025	4(1)	H	1148
BAL-181	*Arctica islandica*	0.213	0.006	2	I	366i
AAL-3400	*Bittium reticulatum*	0.063	0.035	4	I	295
AAL-3398	*Bittium reticulatum*	0.130	0.059	4	I	333 GJ
AAL-3683	*Littorina littorea*	0.138	0.006	3(1)	I	372
AAL-3846	*Lucinoma borealis*	0.261	0.025	3(2)	I	357
AAL-3847	*Lucinoma borealis*	0.311		1	I	328
AAL-2866	*Mya truncata*	0.222	0.008	2(1)	I	381
AAL-2867	*Mya truncata*	0.223	0.005	2(1)	I	1293
AAL-3682	*Turritella communis*	0.140	0.004	3(1)	I	1189
AAL-3399	*Turritella communis*	0.157	0.004	3(1)	I	1199i
AAL-3401	*Turritella communis*	0.211	0.013	2	I	1462i
AAL-2829	*Turritella communis*	0.219		1	I	1271
AAL-2828	*Arctica islandica*	0.177		1	J	1240
AAL-3631†	*Arctica islandica*	0.197	0.018	2(1)	J	1240
AAL-4563†	*Arctica islandica*	0.191	0.003	4(1)	J	1240
BAL-182	*Arctica islandica*	0.208	0.002	2	J	1341
AAL-3675	*Bittium reticulatum*	0.154		1	J	1299
AAL-3679	*Littorina littorea*	0.123	0.007	4(1)	J	1208
AAL-3848	*Lucinoma borealis*	0.231	0.024	2(1)	J	663
AAL-3676	*Turritella communis*	0.285	0.026	4(1)	J	665
AAL-3228	*Venerupis rhomboides*	0.135	0.007	2	J	1350i
AAL-4562*	*Venerupis rhomboides*	0.162	0.027	5(2)	J	1350i
AAL-3227	*Venerupis rhomboides*	0.154	0.007	3(1)	J	1222i
AAL-4561*	*Venerupis rhomboides*	0.194	0.002	2(1)	J	1222i
AAL-3402	*Littorina littorea*	0.130	0.006	3	K	1465
AAL-3844	*Littorina littorea*	0.144	0.014	3	K	1290
AAL-3845	*Littorina littorea*	0.150	0.007	3	K	1237
AAL-3849	*Lucinoma borealis*	0.265	0.009	3(1)	K	1351
AAL-3850	*Lucinoma borealis*	0.255		1	K	849
AAL-3681	*Littorina littorea*	0.125	0.007	3(1)	K/L	1371i
AAL-3397	*Littorina littorea*	0.135	0.017	4(2)	K/L	1473
AAL-3677	*Littorina littorea*	0.153	0.008	5(2)	L	1461
AAL-3851	*Lucinoma borealis*	0.207		1	L	659
AAL-3685	*Hiatella arctica*	0.212	0.024	2(1)	M	848
AAL-4565*	*Hiatella arctica*	0.226	0.004	2(1)	M	848
AAL-2868	*Mya truncata*	0.264		1	M	1415
AAL-2869	*Mya truncata*	0.286		1	M	606
AAL-2870	*Mya truncata*	0.274		1	M	1302
AAL-3685	*Mya truncata*	0.282		1	M	848
AAL-4565*	*Mya truncata*	0.283	0.010	3(1)	M	848

TABLE 10 (continued)

Lab ID	Species	Mean D/L	σ	*n*	Bed	Sample no.
Bø Site						
AAL-2825	*Arctica islandica*	0.156	0.009	3	D	
AAL-3403	*Arctica islandica*	0.140	0.010	4	D	
AAL-3404	*Arctica islandica*	0.144	0.027	3	D	
BAL-183	*Arctica islandica*	0.130	0.026	2	D	
AAL-3278	*Bittium reticulatum*	0.064	0.022	4	D	
AAL-3277	*Corbula gibba*	0.139	0.023	4	D	
BAL-291	*Littorina littorea*	0.097	0.017	3	D	
AAL-3853	*Lucinoma borealis*	0.232	0.022	3	D	
AAL-2824	*Turritella communis*	0.150		1	D	
AAL-3276	*Turritella communis*	0.193	0.057	3	D	
Middle Weichselian Sites						
AAL-3630	*Arctica islandica*	0.083	0.005	3	Rogne, Ålesund	1977–16
AAL-3641	*Mya truncata*	0.090	0.007	3	Rogne, Ålesund	1977–122
AAL-3001	*Mya truncata*	0.090	0.006	4	Bø, unit B	
AAL-4528	*Mya truncata*	0.112	0.011	3	Vigra, Ålesund	
AAL-4528	*Hiatella arctica*	0.126		1	Vigra, Ålesund	
AAL-3755	*Mya truncata*	0.171	0.021	3	Eidsvik	1978–52

*Repreparation of same shell(s) as in preceding sample.
†Repreparations of same shell as AAL-2828.

Middle Weichselian Sites

Shelly tills commonly occur in the Ålesund area of western Norway (Fig. 3). The shells are assumed to have lived during the Middle Weichselian Ålesund Interstadial (Mangerud *et al.*, 1981b). For comparison, *Arctica islandica* and *Mya truncata* were re-prepared from the Rogne site, as were *Mya* from Eidsvik, a site that had previously yielded higher ratios than other sites in the Ålesund area, and new sets of *Mya* and *Hiatella* were analyzed from Vigra (Table 10). The new analyses from Rogne and Eidsvik are ca. 70% of the values reported previously (see earlier discussion). *Mya* and *Hiatella* from Vigra are slightly higher than at Rogne. The Eidsvik results suggest that some of the sites in the Ålesund area may date from Eemian or Early Weichselian time rather than from the Middle Weichselian.

SWEDEN

Marine interglacial deposits were recently discovered near Margareteberg along the west coast of south Sweden (Påsse *et al.*, 1984). Floral and faunal studies on this deposit are still in progress, but Påsse (*pers. commun.*, 1985) argues that the pollen stratigraphy suggests the site is probably Eemian. The palynology, however, has similarities with the Fjøsangerian, the age of which remains unresolved. Påsse supplied us with several valves of *Hiatella arctica* from the Margareteberg beds in 1984 and *Macoma balthica* in 1985. Ten individuals of *Hiatella* yielded a mean D/L ratio of 0.25 ± 0.01 and six *Macoma* gave a mean ratio of 0.26 ± 0.02 (Table 11). The ratios in both species are well above their counterparts at Eemian sites in Denmark, although only slightly higher than extreme ratios in other epimerizing Eemian moderate-rate taxa.

TABLE 11. D/L ratios in marine molluscs from the Margareteberg site, SW Sweden

Lab ID	Species	Mean	σ	n
AAL-4264	*Hiatella arctica*	0.254	0.012	5
AAL-3914	*Hiatella arctica*	0.252	0.015	5
AAL-4552	*Macoma balthica*	0.263	0.022	6

Analytically, it is certain that the ratios in Margareteberg are higher than in Danish Eemian sites. Whether this shows the site to be pre-Eemian is unresolved, particularly with the lack of resolution on the age of the Fjøsangerian beds in western Norway. Although we have suggested that an occasional 'aberrant' shell that yields anomalously high or low ratios can be encountered it is not yet known if an entire site can yield 'aberrant' ratios. If the Fjøsangerian is Eemian, then so might be Margareteberg, and any additional factors besides time and temperature which might be influencing the measured D/L ratio would require evaluation.

PRE-EEMIAN SITES IN DENMARK

Esbjerg

Near the city of Esbjerg in SW Denmark, shell-bearing marine sediments have been frequently observed in claypits (Hansen, 1965). The typical succession is till at the base, generally assumed to be of Elsterian age (Sjörring, 1983), overlain by glacial-fluvial sand and glacial-marine silt with a cold-water fauna (e.g. *Portlandia arctica*). Higher up in the silt/clay beds is a more boreal fauna, but warm-water species are absent, presumably because relative sea-level fell before the interglacial climatic optimum. The sequences are capped by a till or other glacial sediments, showing that the marine beds are older than the Eemian because this area lies outside the Weichselian ice limit. The marine sediments have been assumed to be of Holsteinian age (e.g. Hansen, 1965; Feyling-Hanssen and Knudsen, 1980; Sjörring, 1983).

Mya truncata fragments from the *Tellina* (*Macoma*) sands and *Hiatella arctica* from Maade clay pit, both at Esbjerg were submitted by K.S. Petersen in 1983; additional material from the Esbjerg area was supplied in 1984; all shells are from collections of the Geological Survey of Denmark, many from collections obtained late in the last century. All shells yielded D/L ratios indicating an age much older than Holsteinian. They are correlated with the 'late Cromerian' of the Netherlands.

Vognsbøl

The Vognsbøl boring, 2 km north of the town of Esbjerg, contains a Quaternary record similar to that at the Esbjerg localities. The shells come from the Vognsbøl Sand, a fossiliferous marine unit containing a fauna that grades from boreal–arctic to boreal in character. The marine beds in the Vognsbøl boring, which are overlain by 19 m of glacial-fluvial sediments and at least 22 m of till, are considered to be a different and later facies to the marine units at Esbjerg and Rögle (Nordmann, 1913, 1922).

The D/L ratios in 5 valves of *Mya truncata* from Vognsbøl are indistinguishable from ratios in the same species from the *Yoldia* clay at the Esbjerg localities, confirming Nordmann's local correlation. *Arctica* ratios from Vognsbøl give lower mean values than *Mya*, but are in statistically indistinguishable (Table 12), whereas six valves of *Littorina* are not unexpectedly substantially lower. The ratios in both *Mya* and *Arctica* are well above the ratios in the same taxa from Holsteinian deposits in the Schleswig-Holstein area of NW Germany, with which they had been previously correlated (e.g. Nordmann, 1913).

Røgle Klint

At the base of the Quaternary section at Røgle (Sjörring, 1983) on the western tip of Fyn, is a till and associated glacial-fluvial sediment, overlain by marine clay of supposed late Elsterian age (Feyling-Hanssen and Knudsen, 1980). Two till units overly the marine sediment: the first, a thick sequence of glacial-fluvial sediment and till is generally considered to be of Saalian age, although a Weichselian age has also been proposed; a younger overlying till is of Weichselian age. *Hiatella arctica* from the marine clay gave D/L ratios of 0.54 ± 0.08 (3), considerably above the expected Holsteinian ratios for this taxon. Although higher than the ratios in *Hiatella* and other moderate-rate taxa from the Esbjerg area, the rather large standard deviations overlap and the ratios from the two regions are not statistically different. We argue that the beds at Esbjerg, Vognsbøl and Røgle predate the Holsteinian interglacial by a considerable time interval based on the large differences between D/L ratios measured in these shells and those in the same taxa from the classical Holsteinian sites in NW Germany. Their correlation with the 'Cromerian' of the Netherlands is discussed in Part 1.

Slettenshage

Petersen (1973) described a unit of marine clay within the next-to-youngest till (till A) in a clay pit at Slettenshage on the southern side of the Røsnaes Peninsula, Sjaelland. Twenty

TABLE 12. D/L ratios in shells from pre-Eemian deposits in Denmark

Lab ID	Species	Mean	σ	n	Locality
AAL-3507	*Hiatella arctica*	0.438	0.025	4(2)	Esbjerg, Maade Claypit
AAL-4003	*Hiatella arctica*	0.502	0.054	4(2)	Esbjerg, Yoldia Clay
AAL-4026	*Macoma calcarea*	0.415	0.064	2	Esbjerg, Yoldia Clay
AAL-4023	*Macoma calcarea*	0.497	0.025	3	Esbjerg, Yoldia clay
AAL-4002	*Mya truncata*	0.504	0.007	5	Esbjerg, Yoldia Clay
AAL-4006	*Mya truncata*	0.412	0.044	5	Esbjerg, Maade Claypit
AAL-3506	*Mya truncata*	0.433	0.036	4	Esbjerg, Tellina Sand
AAL-4009	*Arctica islandica*	0.367	0.002	3(1)	Kaas Hoved
AAL-4010	*Mya truncata*	0.308	0.052	3	Kaas Hoved
AAL-4004	*Hiatella arctica*	0.535	0.078	3	Røgle Klint
AAL-2606	*Arctica islandica*	0.320	0.010	3	Slettenshage
AAL-2601	*Turritella communis*	0.308	0.008	5	Slettenshage
AAL-2602	*Turritella communis*	0.292	0.008	5	Slettenshage
AAL-4001	*Arctica islandica*	0.375	0.041	4	Vognsbøl, 13.8–14.8 m
AAL-3981	*Littorina littorea*	0.247	0.038	6	Vognsbøl, 13.8–14.8 m
AAL-4000	*Mya truncata*	0.435	0.023	5	Vognsbøl, 15.3–15.6 m

mollusc taxa were identified from the clay and Petersen (1973: p. 42) stated that all of the genera and most of the species are known from Eem Sea deposits. He therefore tentatively suggested an Eemian age for the clay and a Weichselian age for the younger tills. All of the shells analyzed were collected by Petersen and submitted by him in 1980.

The D/L ratios determined in *Arctica islandica* and *Turritella communis* (Table 12) clearly indicate an age older than Eemian, but younger than the marine beds at Esbjerg and Røgle. The shells may be of Holsteinian age; the ratios in *Arctica* are the same as in *Arctica* from the Holsteinian in NW Germany.

Kaas Hoved

The lithology and marine micropaleontology of the site at Kaas Hoved in the western part of Limfjord has recently been described by Jensen and Knudsen (1984). A marine unit below two tills (Units 2 and 3) and glacially tectonized glacial-fluvial sediments (Unit 4) contains boreal foraminifera indicative of full interglacial marine conditions. Based on the faunal composition and stratigraphic position, the marine bed is assigned an Holsteinian age. Marine units of similar age located nearby at Gyldenal (Jensen and Knudsen, 1984) and Hostrup (Knudsen, 1977) contain foraminiferal faunas of shallow arctic marine affinity that are considered to be of late Elsterian age, but marginally predating the Kaas Hoved beds.

Specimens of *Arctica islandica* and *Mya truncata* from the Leda Clay at Kaas Hoved were supplied by Petersen in 1984 from collections at the Geological Survey of Denmark. Three individuals of each species were analyzed; the *Arctica* ratios group tightly at 0.37 ± 0.01, but *Mya* gave rather conflicting results with two ratios at ca. 0.28 and a third at 0.37. We conclude that the samples are at least of Holsteinian age but are more probably older.

EEMIAN SITES IN DENMARK

Assumed Eemian marine sequences in Denmark have been previously sub-divided into two paleontological groups, based on differences in their mollusc faunas (Ødum, 1933; Hansen, 1965). The distribution of these two faunal groupings is geographically distinct. Sites in southwestern Denmark are characterized by the extinct *Venerupis senescens* (Nordmann, 1908) and several species that today only live south of Denmark (e.g. *Divaricella divaricata*, *Syndesmya ovata* Phil., *Gastrana fragilis* L.). *Bittium reticulatum*, a species which is considered to be limited to the Eemian and the Holocene in NW Europe (Heide, 1957; Dechend, 1958; Mangerud *et al.*, 1981), is also frequent. This thermophilous fauna is similar to the Eemian faunas in NW Germany and the Netherlands, and the Danish sequences are considered to have been deposited in an arm of the sea extending from the English Channel. Of the sites included in this study, Ristinge Klint, Trappeskov Klint, Stensigmose, Mommark Faergegaard and Højer belong to this Eemian (*sensu stricto*) group.

The eastern Danish sites (Skaerumhede [interglacial portion], Strandegaards Dyrehave, Stubberup Have and Hjelm Nakke) are characterized by a boreal–arctic fauna (e.g. *Macoma calcarea*, *Nucula tennus*) and lack most of the Lusitanian (southerly) elements.

However, the index gastropod *Bittium reticulatum* does occur in some of these sites. The marine sequences in eastern Denmark are thought to have been deposited in a sea with an open connection to the ocean toward the north, between Denmark and Norway. This sea has been called the Skaerumhede Sea (Hansen, 1965), and the associated deposits have been suggested to represent a younger event during the last interglacial antedating the Eem Sea (e.g. Hansen, 1965).

This interpretation has been questioned by Petersen (in Bahnson *et al.*, 1974) who considers the two faunas to represent different facies of the same age a view supported by the geographic separation and lack of superposition of the two faunal groupings.

In contrast to the paleontological argument, maps of the distribution of Eemian marine sediments show that the Eem Sea did not extend across the Jutland-Schleswig Peninsula into the Baltic Sea (Krogh, 1979; Behre *et al.*, 1979; Oele and Schuttenhelm, 1979; color chart). On this basis all of the sites investigated in Denmark, the site at Holnis, Germany and the sites in Poland are associated with a paleo-Baltic Sea that was connected to the North Atlantic between Denmark and Norway, much as it is today.

To compare as many sites as possible we concentrated the analytical program on two of the most common taxa in Danish interglacial sites, *Arctica islandica* and *Turritella communis*. Most of the specimens were supplied by Petersen in 1980 and 1982 from collections housed at the Geological Survey of Denmark. *A. islandica* is a reliable species for amino acid geochronology, but D/L ratios in *Turritella* show considerable scatter in many sites, and we suggest that the mean D/L ratios in all *Turritella* analyzed in this study should be considered to have a confidence level no smaller than ±20% (1σ).

The analytical results for Eemian sites are summarized in Table 13; site locations are given in Fig. 4. Mean D/L ratios in *Arctica* range between 0.14 and 0.21, with most sites grouping between 0.15 and 0.17. There is no clear separation of the two faunal groups: the Eem Sea sites tend to be lower, although the single *Arctica* from Ristinge Klint gave some of the highest ratios (0.20). The Skaerumhede Sea group includes high (Strandegaard), and intermediate (Stubberup Have) ratios. The mean D/L ratio in the moderate-rate group (*Arctica, Macoma, Venerupis, Corbula, Mya*) is 0.17 ± 0.02 (80).

The implications are that if these deposits do not belong to the same interglacial, the time between the two extreme values is not great and does not appear to follow the established faunal/geographic grouping. At present the geological, biostratigraphic and amino acid evidence appears to support a strong case for a similar age for these deposits. Nevertheless, we acknowledge the fact that the evidence from some sites is debatable and accept the possibility that more than one age may be represented. None of the sites gave ratios as high as in Holsteinian deposits or as low as in Middle Weichselian deposits.

Ristinge Klint

At Ristinge Klint more than 30 glaciotectonically stacked floes occur, with a nearly identical lithostratigraphical sequence within each floe (Sjörring, 1983). From the base upwards, the stratigraphy is: (1) glaciolacustrine clay; (2) 10 cm sand with freshwater molluscs, assumed to be Early Eemian; (3) Eem '*Cyprina*-clay', with a brackish-water fauna at the base, and a more open-marine fauna higher up (Madsen *et al.*, 1908). This clay contains a rich, thermophilous marine fauna, including the species considered guide-fossils in the Eemian; (4) sand; (5) till; (6) glaciofluvial sand; (7) till. Unconformably overlying these units is a further till bed.

Together with the shells for amino acid analysis, we collected pollen samples that were counted by J.I. Svendsen (University of Bergen). The pollen stratigraphy (Fig. 12) is similar to the Eemian pollen stratigraphy in southern Denmark–northern Germany, and supports an Eemian age for the sequence. *Picea* rises to more than 8% at the top of the diagram, but the diagnostic *Carpinus–Picea* phase of the upper part of the Eemian is missing, which shows either erosion, and/or a regression well before the end of the interglacial. The significant rise of *Tilia* (to 6%) in the highest sample may be the start of the major *Tilia* phase known from nearby localities (S.T. Andersen, 1975). The marine transgression (the boundary between lacustrine and marine beds) took place before the *Corylus* rise, which according to Müller (1974a) occurred only 750 years after the start of the Eemian. This is in accordance with the results of Jessen and Milthers (1928, pp. 178–179) from Stensigmose and suggests that the Danish sites may include more of the interglacial than some of the Dutch localities.

Samples were collected by Mangerud in 1983, under the guidance of S. Sjörring from floe 15 (Sjörring, 1983). A single, whole specimen of *Arctica islandica* was recovered from the upper portion of the *Cyprina* (*Arctica*) clay and several individuals of *Venerupis* were collected from lower levels in the same bed. Nine separate preparations of the single *Arctica* specimen gave a mean D/L ratio of 0.20 ± 0.03. Although the mean ratio is higher than most other nearby Eemian sites (Table 13) the large standard deviation indicates that the

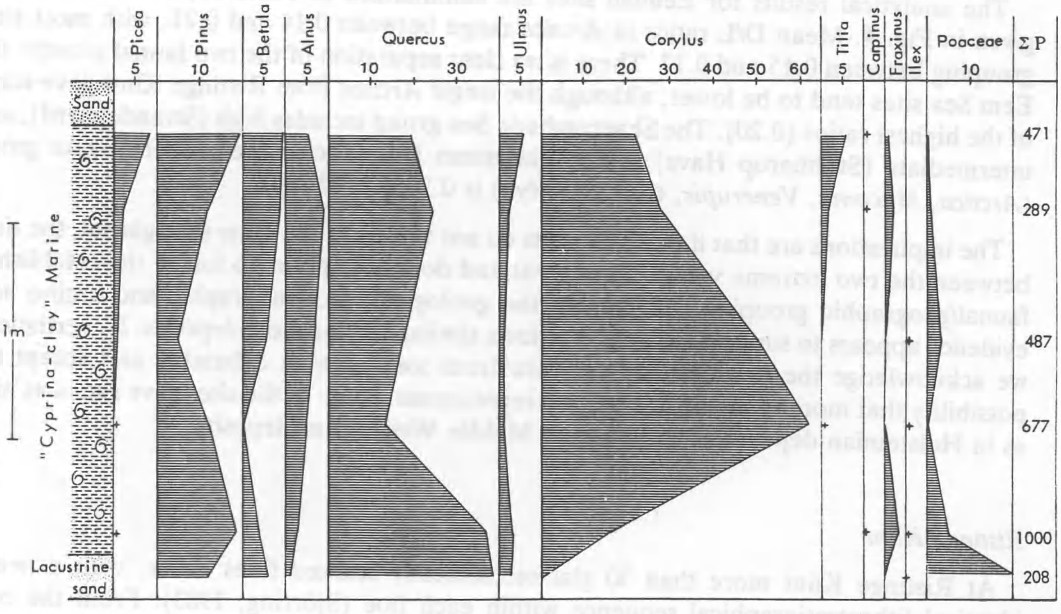

FIG. 12. Pollen diagram for the interglacial beds in floe 15 at Ristinge Klint, Denmark (J.I. Svendsen, Univ. of Bergen, *unpubl. data*).

TABLE 13. D/L ratios in shells from Eemian localities in Denmark

Lab ID	Species	Mean	σ	*n*	Locality
AAL-2604	*Turritella communis*	0.200	0.000	2	Hjelm Nakke
AAL-2600	*Turritella communis*	0.162	0.004	5	Højer
AAL-2599	*Turritella communis*	0.230	0.007	5	Højer
AAL-3698	*Arctica islandica*	0.134	0.003	3	Mommark
AAL-2612	*Arctica islandica*	0.144	0.030	5	Mommark
AAL-3615	*Arctica islandica*	0.208	0.020	6(1)	Ristinge
AAL-3916*	*Arctica islandica*	0.182	0.033	3(1)	Ristinge
AAL-3616	*Mya truncata*	0.223	0.002	3(1)	Ristinge
AAL-3913	*Nassarius reticulatus*	0.099	0.008	3(1)	Ristinge
AAL-3612	*Venerupis senescens*	0.150	0.025	3	Ristinge
AAL-3614	*Venerupis senescens*	0.160	0.024	3	Ristinge
AAL-3613	*Venerupis senescens*	0.172	0.006	2	Ristinge
AAL-3616	*Venerupis senescens*	0.204	0.023	3	Ristinge
AAL-2610	*Arctica islandica*	0.147	0.026	3	Stensigmose
AAL-3697	*Arctica islandica*	0.156	0.006	3	Stensigmose
AAL-3509	*Bittium reticulatum*	0.140	0.026	4	Stensigmose
AAL-2611	*Cardium edule*	0.174	0.046	4	Stensigmose
AAL-4005	*Divaricella divaricata*	0.261	0.030	4	Stensigmose
AAL-3982	*Littorina littorea*	0.086	0.008	3(1)	Stensigmose
AAL-4025	*Macoma balthica*	0.159	0.012	4	Stensigmose
AAL-4007	*Macoma balthica*	0.172	0.013	4	Stensigmose
AAL-4034	*Mactra subtruncata*	0.139	0.015	3	Stensigmose
AAL-3510	*Spisula subtruncata*	0.145	0.033	4	Stensigmose
AAL-3508	*Venerupis senescens*	0.149	0.006	4	Stensigmose
AAL-4035	*Venus gallina*	0.143	0.020	3	Stensigmose
AAL-3699	*Arctica islandica*	0.205	0.012	3	Strandegaard
AAL-2607	*Arctica islandica*	0.209	0.010	3	Strandegaard
AAL-4058	*Corbula gibba*	0.229	0.006	2	Strandegaard
AAL-2603	*Turritella communis*	0.190	0.019	5	Strandegaard
AAL-2795	*Arctica islandica*	0.156	0.019	8(4)	Stubberup
AAL-2605	*Turritella communis*	0.222	0.032	4	Stubberup
AAL-3915	*Arctica islandica*	0.171	0.015	5	Trappeskov
AAL-2608	*Arctica islandica*	0.174	0.012	3	Trappeskov
AAL-3983	*Littorina littorea*	0.114	0.014	5	Tønder
AAL-4008	*Venerupis senescens*	0.180	0.016	5	Tønder

*Repreparation of same shell as utilized in AAL-3615.

sample cannot be shown to be significantly different than *Arctica* from other Eemian sites. A single specimen of *Mya* also produced a mean ratio higher than expected for an Eemian site. To check the validity of the high ratios obtained from the single individuals of *Arctica* and *Mya*, 12 individuals of *Venerupis* collected from four levels in the marine clay bed were also analyzed, and produced a mean D/L ratio of 0.16 ± 0.02. The similarity in Ristinge Klint *Venerupis* ratios with other Eemian correlatives suggests that the *Mya* and *Arctica* results represent aberrant individuals, reinforcing our conclusions that reliable D/L values require the analysis of several individuals.

Trappeskov Klint

Trappeskov Klint is situated only 50 km west of Ristinge Klint. The entire sequence, described by Madsen *et al.* (1908), has been glaciotectonically upthrusted and moderately disturbed. Madsen *et al.* (1908) stress that the lithostratigraphy and biostratigraphy of the

Eemian beds (freshwater sand and '*Cyprina* clay') are nearly identical to the beds of Ristinge Klint. At the base is a freshwater sand, overlain by brackish water sediments and 1.5 m of '*Cyprina* clay'. The sequence is capped by two (?) tills and glaciofluvial sediments. Samples from the collection at the Geological Survey of Denmark were submitted by Petersen in 1980. Eight preparations of *Arctica islandica* gave a mean D/L ratio of 0.17 ± 0.01, which confirm an Eemian age for the site.

Mommark

This site was described by Johnstrup in 1882 and referred to by Madsen *et al.* (1908), who correlate it with Ristinge Klint, Trappeskov Klint and other Eemian sites on the basis of its mollusc fauna. Only *Arctica islandica* from the *Cyprina* (*Arctica*) clay was supplied by Petersen from the DGU collection. The first set of analyses, confirmed by a second series (Table 13), gave ratios lower than in *Arctica* from other Eemian sites. Citing Johnstrup (1982), Madsen *et al.* (1908, p. 128) indicate that neither of the classical Eemian index species *Bittium reticulatum* nor *Venerupis senescens* were found at Mommark. For the moment, we assume that the site is probably Eemian and that the ratios are simply at the lowest end of the Eemian range, but additional analyses would be important to test whether the site might be from a post-Eemian high sea-level event.

Stensigmose

The sequence at Stensigmose is glaciotectonically disturbed by thrust faults. According to Madsen *et al.* (1908) the lithostratigraphy is, however, clear: at the base are lacustrine sediments, overlain by marine clay ('*Cyprina* clay'), marine sand ('*Tapes* sand') and till. Most of the sequence is similar to Ristinge Klint, with respect to both lithostratigraphy and molluscan biostratigraphy. The main difference is the presence of sand at the top of the interglacial sequence at Stensigmose which indicates a marine regression. This sand also has an extremely rich mollusc fauna. Madsen *et al.* (1908) consider the Stensigmose site to represent a more complete sequence of the Eemian than at Ristinge or Trappeskov; both transgressive and regressive facies are confirmed by foraminifera-stratigraphy (Konradi, 1976). This interpretation also agrees with recent reconstructions of sea-level change during the Eemian (Mangerud *et al.*, 1981; Zagwijn, 1983). Although the foraminifera fauna from Stensigmose (Konradi, 1976) includes more cold-water species than the mollusc fauna it generally supports the proposed interpretations.

Samples from the collections at the Geological Survey of Denmark were submitted by Petersen in 1980 and 1982. Ten genera from the '*Tapes* Sand' have been analyzed for their D/L ratios (Table 13); most of them strongly support an Eemian age.

Tønder

Borings in the Tønder region of southwest Denmark were initially undertaken late in the last century (e.g. Madsen *et al.*, 1908). The area lies outside the Weichselian ice-limits and the interglacial deposits have not been glacially disturbed. The top of the marine beds are encountered 7 to 10 m below sea-level where they overlie Saalian till, and glacial-fluvial sediments, and are overlain solely by Weichselian meltwater sediments and Holocene deposits. Such marine interglacial beds are traditionally considered to be of last interglacial age based both on stratigraphic position and presence of Lusitanian molluscan elements such as *Venerupis senescens*, *Divaricella divaricata* and others (Hansen 1965).

Samples of *Venerupis senescens* and *Littorina littorea* from 11.2 to 12.7 m depth in Tønder boring 4 from the Geological Survey of Denmark collections were supplied by Petersen in 1984. The D/L ratios (Table 12) in *Venerupis* confirm the correlation of Tønder to other Eemian sites in Denmark and NW Germany and the *Littorina* values provide an important Eemian calibration point for this slow-epimerizing species.

Højer

Marine deposits of supposed Eemian age have been encountered in boreholes along the coast west of Højer where they rest on till, glaciofluvial sands or Eemian limnic deposits. The marine beds are clayey at the base, coarsening upward into sand at the top and are overlain by Weichselian glaciofluvial sands. The region lies beyond the limits of Weichselian ice in Denmark, and the deposits are considered to be *in situ*. They were first described by Nordman (1928) while the microfauna was described by Sorensen (1980). The foraminiferal faunas in the interglacial beds include boreal–lusitanian shallow-water assemblages of a composition similar to those found in Eemian sites in NW Germany and Denmark. In 1981 K.-L. Knudsen provided us with samples of *Turritella communis* from 19 and 24 m depth in the interglacial beds of a boring near Højer. D/L ratios (Table 13) are within the range of Eemian values.

Strandegaards Dyrehave

A clay rich in molluscs of interglacial aspect occurs at this site (Ødum, 1933). The interglacial clay is less than 1 m thick and is strongly folded and thrusted. According to Petersen and Konradi (1974), the clay is overlain by three till-beds, all separated by sand or gravel. They assume the clay is of Eemian age, from the characteristics of the mollusc and foraminifera faunas. Samples were collected by Petersen and submitted by him in 1980. *Arctica*, *Corbula* and *Turritella* have been analyzed from the site; all yield D/L ratios at the very highest end of the range for these taxa in nearby Eemian sites. The mean ratio in *Arctica*, in particular, lies above the other secure Eemian *Arctica* ratios from this region. Tentatively we consider the high ratios to indicate a slightly warmer thermal history than at other sites in the region, rather than indicating an older age.

Stubberup Have

A marine clay, rich in molluscs, is found beneath a till bed (ca. 5 m) at this site (Ødum, 1933). Well-sorted sand and clay without fossils lie below the clay and below these beds there is another till. Thrust-planes are frequent in the interglacial beds. The marine clay is correlated with the interglacial beds at Strandegaard on the basis of the mollusc fauna. *Arctica* and *Turritella* were submitted by Petersen in 1980; *Arctica* yielded typical Eemian D/L ratios.

Hjelm Nakke

Below a complex sequence of tills and glaciotectonically disturbed sediments occur beds of marine sand (10 cm) and clay (20–50 cm) which are also glaciotectonically up-thrusted. Berthelsen *et al.* (1977) correlated the sand and clay with Strandegaards Dyrehave and Stubberup Have by their similar mollusc faunas. *Turritella* collected by Petersen were submitted by him in 1980.

WEICHSELIAN SITES IN DENMARK

Skaerumhede Borings

The Skaerumhede borings from northern Jutland (Fig. 4) were taken from an elevation about 24 m asl. The first boring (Jessen *et al.*, 1910; Knudsen and Lykke-Andersen, 1982) penetrated 200 m of Quaternary sediment before reaching bedrock. Close to 20 m of till and glacial-fluvial sediments overlie bedrock at the base of the core and are in turn overlain by 123 m of marine sediment that are capped by ca. 57 m of glacial-fluvial sediment. The Skaerumhede II boring penetrated the upper 122 m of glacial-fluvial and marine sediment (Bahnson *et al.*, 1974). The fauna in the marine beds follows a generally cold–warm–cold sequence. Samples from the Geological Survey of Denmark from both borings were submitted by Petersen in 1980, 1983 and 1984.

A thorough study of isoleucine epimerization through the two borings is currently ongoing and will be reported in due course. Here we report only the analytical results of the upper 120 m of the two borings. Four preparations of a single fragment of *Arctica islandica* from a depth of 98 m (0.082 ± 0.002) and 5 preparations of *Macoma calcarea* fragments from 66 m below the ground surface (0.093 ± 0.007), both in the more recent boring, confirm that the levels above 100 m in the boring are probably of Middle Weichselian age and younger. Bahnson *et al.* (1974) suggested that the Eemian–Weichselian boundary might lie at 140 m in the original boring. Samples of *Turritella* from 95 to 120 m depth in both borings were analyzed. The similar ratios in both borings (Table 14), suggest that correlation is possible, but the ratios are lower than in *Turritella* from other secure Eemian localities suggesting that the upper 120 m of the borings are indeed post-Eemian.

Hirtshals

A sequence of glacio-tectonically thrusted and folded silt and sand beds occur at Hirtshals (Lykke-Andersen, 1981, 1982). Both the foraminifera and mollusc assemblages indicate that marine conditions colder than today persisted throughout the deposition of the silt and sand units. Lykke-Andersen subdivided the sequence into interstadials and stadials of supposed Middle Weichselian age.

Radiocarbon dates gave ages ranging from 14 to 47 ka. Lykke-Andersen (1982) concluded that the two dates from her zone C between 14 and 15 ka BP were severely contaminated, and that all shells were older than 34 ka.

We analyzed shells from zone C partly to obtain Middle Weichselian D/L ratios, but also in part to test whether the young radiocarbon dates could be due to mixed populations, in

TABLE 14. D/L ratios in Middle Weichselian shells from Denmark

Lab ID	Species	Mean	σ	*n*	Locality
AAL-3704	*Hiatella arctica*	0.099	0.007	4	Hirtshals, zone C
AAL-3114	*Hiatella arctica*	0.085	0.008	3	Hirtshals, lower zone C
AAL-3726	*Macoma calcarea*	0.098	0.009	3	Hirtshals, zone E
AAL-3304	*Zirphaea crispa*	0.134	0.030	3	Hirtshals, zone E
AAL-3115	*Zirphaea crispa*	0.119	0.021	3	Hirtshals, zone E
AAL-4050	*Macoma calcarea*	0.110		1	Holmstrup
AAL-4057	*Macoma calcarea*	0.318	0.083	2	Holmstrup
AAL-4036	*Macoma calcarea*	0.260	0.071	5	Holmstrup
AAL-4050	*Macoma calcarea*	0.193	0.059	2	Holmstrup
AAL-4051	*Macoma calcarea*	0.076		1	Holmstrup
AAL-3113	*Hiatella arctica*	0.074	0.002	3	Nørre Lyngby
AAL-3112	*Hiatella arctica*	0.097	0.017	4	Nørre Lyngby
AAL-2968	*Turritella communis*	0.125	0.006	2	Skaerumhede I, 115 m
AAL-3306	*Turritella communis*	0.148	0.001	2	Skaerumhede I, 125 m
AAL-3511	*Arctica islandica*	0.082	0.002	4(1)	Skaerumhede II, 98 m
AAL-4022	*Macoma calcarea*	0.093	0.007	5	Skaerumhede II, 66 m
AAL-2598	*Turritella erosa*	0.116	0.030	2(1)	Skaerumhede II, 96 m
AAL-2597	*Turritella communis*	0.129	0.002	2(1)	Skaerumhede II, 118 m

which case the glacial-tectonics would post-date 14 ka BP. However, we did not have shells from the same collections that were radiocarbon dated.

Hiatella arctica from zone C (193 m in Fig. 1 of Lykke-Andersen, 1982) gave a mean D/L ratio of 0.085 (Table 14). *Macoma balthica* from zone E (ca. 185 m), underlying zone C, yielded a mean ratio of 0.098. Both samples were collected by A.-L. Lykke-Andersen and submitted by her in 1982. Samples from the same site of *Zirphaea* were analyzed but are difficult to interpret because of the lack of comparative specimens. Additional *H. arctica* collected by Mangerud in 1983 under guidance of Lykke-Andersen from a site in zone C have a mean ratio of 0.099 similar to the earlier analyses. None of the shells analyzed from the Hirtshals sequence yielded a ratio within the range of Lateglacial samples from Denmark (0.052 ± 0.007 for *Hiatella*, Miller, 1985). Our results support a Middle Weichselian rather than a 14 ka age for the Hirtshals collections.

Nørre Lyngby

In 1982, Knudsen sent two samples of *Hiatella arctica* from interstadial deposits at Nørre Lyngby, N Jutland. The sites have been radiocarbon dated and in both cases the results are slightly older than 14 ka (Knudsen, 1978). The mean D/L ratio in one of the collections based on four different individuals is 0.097 whereas in the other collection, three individuals gave a ratio of 0.074. The higher ratio strongly suggests a Middle Weichselian age, whereas the lower ratio is significantly higher than ratios obtained in the same taxon dated 1 to 2 ka younger. There remains some question whether the ^{14}C age is correct, or if the deposits are of Middle Weichselian age as favored by the amino acid results (see also discussion of the Hirstshals samples).

Holmstrup

Dislocated marine sediments at Holmstrup on the island of Sjaelland have been described by Petersen and Buch (1974). They overlie a till correlated with the Early Weichselian Old Baltic till that overlies Eemian sediments at Ristinge Klint and Strandegaard. The foraminiferal assemblage in the Holmstrup marine sediment is correlated with the Middle Weichselian zone C assemblage at Skaerumhede.

Amino acid analyses have been completed on eleven individuals of *Macoma calcarea* submitted from the Holmstrup locality by Petersen in 1984 (Table 14). The measured D/L ratios scatter widely, ranging from ca. 0.08 to ca. 0.4, suggesting that the fauna has been derived from deposits of more than one age. Three of the shells gave Weichselian ratios, averaging 0.11 ± 0.03. The remaining individuals all contained ratios similar to or greater than in Eemian representatives of this taxon. These samples demonstrate the importance of analyzing individual shells in dislocated sediments.

The three shells with a mean D/L ratio of ca. 0.11 support the contention of Petersen and Buch (1974) that the Holmstrup deposit was emplaced during the Weichselian. However, the apparent mixed ages of the *Macoma* population analyzed in this study, raises the question of whether the microfauna in the same sediment is similarly of a mixed origin. If the stratigraphic interpretations of Petersen and Buch (1974) and Petersen (1973, 1984) are correct, then glaciers must have reached Denmark before the Late Weichselian, contrary to the common view of the last decade that the area was glaciated only during the Late Weichselian.

POLAND

In the lower Vistula valley two series of marine sediments of assumed Eemian age are stratigraphically separated by continental sediments (Makowska, 1980, 1982). According to pollen stratigraphy, the lowermost (Sztum Sea) is from early Eemian, whereas the upper (Tychnowy Sea) is from around the climatic optimum. All the analyzed samples (Table 15) are from the Tychnowy Sea beds, and were obtained from A. Makowska in 1982; insufficient mollusc remains were present in the Sztum Sea layers for this project. The mollusc fauna are diminutive and relatively rare, suggesting stressed environmental conditions.

TABLE 15. D/L ratios in shells from Tychnowy Sea Sediment in cores from the Vistula Valley, Poland

Lab ID	Species	Mean	σ	*n*	Core, Depth
AAL-3175	*Nassarius reticulatus*	0.121	0.020	4	Kwidzyn XXI, 30 m
AAL-3666	*Nassarius reticulatus*	0.179	0.004	2	Kwidzyn XXI, 30 m
AAL-3719	*Bittium reticulatum*	0.101	0.017	3	Kwidzyn XIX, 38 m
AAL-3179	*Corbula gibba*	0.189	0.010	5	Nowiny boring, 62 m
AAL-3177	*Divaricella divaricata*	0.243		1	Nowiny boring, 62 m
AAL-3176	*Spisula subtruncata*	0.131	0.023	4	Nowiny boring, 62 m
AAL-3174	*Venerupis senescens*	0.177	0.034	3	Nowiny boring, 62 m
AAL-3665*	*Venerupis senescens*	0.219	0.037	3	Nowiny boring, 62 m

*Repreparation of AAL-3174.

Nowiny Boring

The lower marine Eemian beds (Sztum Sea) occur at ca. 70 m below the surface, overlain by ca. 5 m continental and lacustrine sediments and the upper (Tychnowy Sea) marine beds (Makowska, 1980). More than 50 m of Weichselian sediments overlie the younger marine beds. Ratios in five individuals of *Corbula gibba* (0.19) and six analyses of three *Venerupis* (0.20) confirm a correlation to the type Eemian. A single speciman of *Divaricella divaricata* gave a ratio of 0.24, whereas four *Spisula subtruncata* produced a mean ratio of 0.13, but with considerable scatter.

Kwidzyn

From the Tychnowy Sea beds (Makowska, 1980), *Nassarius reticulatus* and *Bittium reticulatum* were analyzed (Table 15).

PRE-EEMIAN SITES IN NORTHWEST GERMANY

The oldest glacial sediments identified in NW Germany are tills of Elsterian age (Ehlers, 1983; Ehlers *et al.*, 1984); the Holsteinian beds overlying the Elsterian tills are the oldest known Pleistocene marine deposits. The top of the Holsteinian marine beds are generally 20 to 25 m below sea-level, except where upthrusted (Ehlers, 1983). They are wide-spread and are considered to be an important marker horizon (Duphorn *et al.*, 1973; Behre *et al.*, 1979).

We have determined D/L ratios from molluscs at six sites of Holsteinian age (Table 16). Unfortunately, except for Wacken, most sites are represented by only a single genus, reducing the power of the amino acid method for correlation. With the exception of Hummelsbüttel, the results do support the assumption of a similar age for all deposits, and that they are clearly older than the Eemian.

Wacken

The glaciotectonically upthrusted sequence at Wacken consists of 3 m of marine clay and sand overlain by 'flaser sand' and 'white sand' followed by a peat. Pollen stratigraphy of the lower marine beds indicates initial accumulation early in the Holsteinian (Menke, 1968, 1980). The overlying 'white sand' is interpreted as niveofluvial-eolian (Dücker, 1969). The palynology of the overlying peat demonstrates the development from a *Betula–Pinus* phase into full interglacial vegetation, the Wacken Interglacial.

The main stratigraphic significance of this site is that it documents a cold phase between the Holsteinian (*sensu stricto*) and the overlying Wacken Interglacial. Many workers (e.g. Duphorn *et al.*, 1973; Müller, 1974b; Menke, 1968, 1980) consider the Holsteinian (*sensu stricto*) and Wacken to be a single interglacial complex, containing a short-lived cool interval between two warm intervals, all of which underlies the entire Saalian (*sensu lato*). Others (e.g. Cepek and Erd, 1982) consider the Wacken Interglacial (correlated with the Dömnitzian of East Germany) to be separated from the Holsteinian (*sensu stricto*) by the first glaciation of the Saalian complex.

TABLE 16. D/L ratios in pre-Eemian shells from West Germany

Lab ID	Species	Mean	σ	*n*	Locality
AAL-3724	*Littorina* sp	0.263	0.041	6(3)	Halstenbek
AAL-3852*	*Littorina* sp	0.213	0.047	3	Halstenbek
AAL-4061	*Spisula subtruncata*	0.309	0.021	5	Billbrook
AAL-3182	*Spisula subtruncata*	0.280	0.015	2	Heide-Holtex, 37 m
AAL-2613	*Cardium edule*	0.278	0.024	4	Hummelsbüttel
AAL-4062	*Macoma balthica*	0.382	0.016	5	Hummelsbüttel
AAL-3183	*Portlandia arctica*	0.315	0.007	2(6)	Müldsberg
AAL-3405	*Macoma balthica*	0.289	0.004	3	Scharhörn 55, 34 m
AAL-3406	*Macoma balthica*	0.289	0.002	3	Scharhörn 57, 34 m
AAL-3909	*Arctica islandica*	0.305	0.008	5(1)	Wacken
AAL-3617	*Arctica islandica*	0.286	0.020	4	Wacken
AAL-3911	*Corbula gibba*	0.263	0.027	5	Wacken
AAL-3721	*Littorina littorea*	0.224	0.030	6(3)	Wacken
AAL-3912	*Macoma calcarea*	0.293	0.013	2	Wacken
AAL-3910	*Macoma* sp	0.274	0.048	5	Wacken
AAL-3725†	*Mya truncata*	0.223	0.057	3	Wacken
AAL-3919†	*Mya truncata*	0.245	0.052	3	Wacken
AAL-2943†	*Mya truncata*	0.253	0.015	3	Wacken
AAL-3618	*Nucula* sp	0.377	0.045	3	Wacken

* Repreparation of the same three shells utilized in AAL-3724.
† All three preparations utilized the same three individuals.

Molluscs from the marine Holsteinian at Wacken were submitted by B. Menke in 1982 and additional specimens were collected by J. Mangerud in 1983 under guidance of Menke. The analyzed taxa include *Arctica*, *Corbula*, *Littorina*, *Macoma* and Mya. The average D/L ratio in moderate-rate taxa is 0.28 ± 0.02 (43) compared to a ratio of 0.17 ± 0.01 (29) in nearby Eemian representatives of the same taxa.

Heide

Hinsch submitted *Spisula subtruncata* from assumed Holsteinian beds at 37 to 38 m depth. The mean D/L ratio is 0.28 ± 0.02 (Table 16), similar to other members of the moderate-rate taxa.

Muldsberg

The Holsteinian marine sediments at Muldsberg began to accumulate during late Elsterian as indicated by the cold-water fauna; the fauna becomes increasingly thermophilous upward. *Portlandia arctica* submitted by Menke in 1982 from the late Elsterian beds gave a mean ratio of 0.32 ± 0.01 (2).

Scharhörn

Specimens of *Macoma balthica* from borings on the island of Scharhörn in the German Bight just outside the river Elbe, were provided by G. Linke in 1983. Pollen analysis of the cores confirms an early Holsteinian age for levels from which the shells were obtained (below the *Abies* and *Carpinus* increase; Linke, 1970). Three individuals of *Macoma* from

33.10 to 34.10 m depth in Boring 55 and an additional three individuals of the same species from 33.15 to 34.0 m depth in Boring 57 gave identical results (0.29 ± 0.01; Table 16).

Hamburg Region

From Hamburg, the type area for the Holsteinian, we have analyzed shells from two sites: Hummelsbüttel and Billbrook. The palynology of the Holsteinian beds at Hummelsbüttel (Hallik, 1960) demonstrates the difference in vegetation changes between Holsteinian and Eemian interglacials, and the typical Holsteinian pollen stratigraphy is used for regional correlation. Whether the Holsteinian pollen stratigraphy is unique and was never repeated in another interglacial is difficult to show. We assume that the similar palynology of the 'Holsteinian' sites we have analyzed shows them to be the same age.

Hummelsbüttel

The Hummelsbüttel locality is situated in the city of Hamburg. It is in an old clay pit cut into glacial-lacustrine clay of late Elsterian age. The interglacial beds comprise 0.7 m of freshwater gyttja overlain by 3 m of fossiliferous marine sands, all of which is capped by Saalian till (Grube, 1959, 1963). The entire complex has been upthrusted from its original position by subsequent glacial tectonics. Both the pollen (Hallik, 1960) and foraminiferal assemblages (Knudsen, 1979) indicate full interglacial conditions during deposition of the marine beds. The late Elsterian arctic–subarctic faunas found below other Holsteinian marine layers in NW Germany are not present in the Hummelsbüttel sequence, presumably because of the freshwater sedimentation at the start of the interglacial.

Analysis of five individuals of *Macoma balthica* supplied from this site by Linke gave a mean D/L ratio of 0.38 ± 0.02, well above the ratios measured in the same taxon from Holsteinian beds in the nearby Scharhörn borings (0.29) or at Wacken (0.29). Because the Hummelsbüttel site is Holsteinian by definition, we can only note the discrepancy at present. Additional amino acid analyses are required to verify whether the difference apparent on the few analyses available is real or an artifact of analytical errors.

Billbrook

The Billbrook locality, also from the Hamburg area, is an object of ongoing research. It is considered to represent the same sedimentary sequence that is exposed in the Hummelsbüttel section except in an undisturbed position. The late Elsterian clay (Lauenberg Clay) is overlain by freshwater gyttja and 25 m of Holsteinian marine silt and sand. The marine beds represent the lower portion of the temperate stage of the interglacial (Linke, *written comm.* 1985). *Spisula subtruncata* from the marine beds were supplied by Linke from a depth of 42 to 44 m below the surface; none of the primary moderate-rate taxa were present. The D/L ratio measured in 5 individuals is 0.31 ± 0.02, similar to that in the same taxon from the Holsteinian beds at Heide.

Halstenbek

Littorina were collected 15 m asl from the Halstenbek site, where marine beds, presumed to be ice-thrusted upwards, occur between 6 and 12 m below ground level. The sequence was thought to be of Holsteinian age, but recent U/Th dates suggest they are Eemian (Stremme, *personal comm.* 1982). The specimens were provided by Hinsch in 1982. The mean D/L ratio derived from nine preparations of three individuals of *Littorina* sp. (0.25 ± 0.05) indicate a Holsteinian (or possibly even older) age; the deposit is certainly older than Eemian.

EEMIAN SITES IN NORTHWEST GERMANY

The end moraines of the Weichselian glacial maximum run through Schleswig-Holstein (NW Germany). Outside that boundary, the marine Eemian beds are not disturbed by ice. However, the top of these beds lie approximately 5 to 7 m below present day sea-level (Duphorn *et al.*, 1973; Behre *et al.*, 1979) probably due to general subsidence of the region since the Eemian and samples are therefore only obtained by coring. A paleogeographical map indicating the Eemian shoreline is given in Behre *et al.* (1979). The samples from Rödemis, Schnittlohe, Offenbüttel and Südermarsch are all from cores in the lowlands outside the Weichselian glacial limits. For Rödemis and Schnittlohe an Eemian age is shown by pollen stratigraphy. For the others, an Eemian age is assumed by correlation. Holnis lies inside the Weichselian boundary and provides a link between the Danish sites and the other West Germany localities. The samples from Rödemis were submitted by Menke in 1980; all others were provided to Miller by Grube, Menke and Hinsch during a visit to Geologisches Landesamt Schleswig-Holstein, Kiel, in 1982.

Rödemis

In the Rödemis IV coring, marine silt from 11.2 to 14.7 m depth is assigned an upper Eemian age from the pollen stratigraphy (Menke, 1985). *Littorina littorea* from 12.3 to 12.6 m depth were supplied by Menke in 1980. The measured ratios in this slow-epimerizing genus (0.098; Table 17) support an Eemian age.

Schnittlohe

The Schnittlohe I coring site is situated 1 m asl; Eemian marine sediments were encountered between 12.3 and 17.7 m below ground surface. The guide fossil for the Eemian, *Bittium reticulatum*, occurs through most of the core (Hinsch, 1985), and *Venerupis senescens* is also common.

The D/L ratios determined in *V. senescens*, *B. reticulatum* and *Corbula gibba* from 13, 15 and 16 m depth in the core are listed in Table 17. Pollen stratigraphically (Menke, 1985), the 13 m sample is from the upper part of the *Picea* — lower part of the *Abies* zone, the 15 m sample is from the base of the *Tilia* zone, and the 16 m sample predates the *Corylus* zone. The lack of a clear increase in ratios down-core is discussed in Part 1. Nevertheless, the mean ratios in *Venerupis* [0.17 ± 0.02 (9)] and *Corbula* [0.19 ± 0.02 (9)] are as expected for Eemian sites.

TABLE 17. D/L ratios in shells from Eemian deposits in West Germany

Lab ID	Species	Mean	σ	*n*	Locality, Depth in core
AAL-3180	*Arctica islandica*	0.153	0.010	4	Holnis
AAL-3008	*Arctica islandica*	0.165	0.008	4	Holnis
AAL-3723	*Arctica islandica*	0.161	0.014	4	Holnis
AAL-3181	*Spisula subtruncata*	0.111	0.019	2	Offenbüttel
AAL-2581	*Cardium edule*	0.137		1	Rödemis IV, 14.5 m
AAL-2580	*Cardium edule*	0.106	0.010	4	Rödemis IV, 12.5 m
AAL-2582	*Hydrobia ulvae*	0.105	0.033	4	Rödemis IV, 14.5 m
AAL-2583	*Hydrobia ulvae*	0.103	0.012	6	Rödemis IV, 12.5 m
AAL-3635	*Littorina littorea*	0.098	0.004	3	Rödemis IV, 12.5 m
AAL-2580	*Turritella communis*	0.128	0.001	2	Rödemis IV, 12.5 m
AAL-3184	*Bittium reticulatum*	0.099	0.007	4	Schnittlohe I, 14.8 m
AAL-3632	*Bittium reticulatum*	0.104	0.016	2	Schnittlohe I, 14.8 m
AAL-3633	*Bittium reticulatum*	0.093	0.019	3(5)	Schnittlohe I, 16.2 m
AAL-3003	*Corbula gibba*	0.185	0.007	2	Schnittlohe I, 13.2 m
AAL-3185	*Corbula gibba*	0.191	0.004	2	Schnittlohe I, 14.8 m
AAL-3005	*Corbula gibba*	0.204	0.035	3	Schnittlohe I, 14.8 m
AAL-3007	*Corbula gibba*	0.165	0.000	2	Schnittlohe I, 16.2 m
AAL-3002	*Venerupis senescens*	0.155	0.008	3	Schnittlohe I, 13.2 m
AAL-3004	*Venerupis senescens*	0.184	0.019	3	Schnittlohe I, 14.8 m
AAL-3006	*Venerupis senescens*	0.157	0.006	3	Schnittlohe I, 16.2 m
AAL-3720*	*Mya truncata*	0.164	0.024	4	Südermarsch
AAL-2941	*Mya truncata*	0.157	0.008	4	Südermarsch
AAL-2942	*Turritella communis*	0.162	0.002	4	Südermarsch

*Repreparation of same four individuals used in AAL-2941.

Offenbüttel

This site is located close to Schnittlohe (Menke, 1985; Hinsch, 1985). Two individuals of *Spisula subtruncata* from a depth of 14.0 to 14.3 m gave a mean D/L ratio of 0.11 ± 0.02. This ratio is lower than expected for an Eemian site; however, only two valves were analyzed and the taxa has not been thoroughly studied for its reliability in amino acid geochronology. At present we can safely conclude that the site is no older than Eemian.

Südermarsch

From the Südermarsch 29 boring the following samples were analyzed: four large fragments of *Turritella communis* from 20.5 to 21.5 m depth and four umbo fragments of *M. truncata*. The mean D/L ratios (Table 16) support an Eemian age.

Holnis

This site is assumed to be Eemian from its sedimentary (clayey) facies. It is situated within the Weichselian glacial boundary, close to the Danish sites Stensigmose and Mommark. Our main interest in the site was the occurrence of *Arctica islandica* at a depth of 24 to 27 m. Nine individual fragments of this species were prepared at three different times over a two year period. The results are consistent in all preparations averaging 0.16 ± 0.01 (9), similar to the ratio in *Arctica* from most Danish Eemian sites.

THE NETHERLANDS

Amersfoort

Interglacial deposits near Amersfoort were named Eemian after the nearby river Eem (Harting, 1874; referenced in Zagwijn, 1961). A description of the stratotype near the city of Amersfoort is given in Zagwijn, 1961. The lower part of the Eemian beds, including the *Quercus* (oak) zone, consists of peat and lacustrine gyttja. Brackish-water sedimentation began during the *Corylus* (hazel) increase and marine sedimentation continued through the *Carpinus* (hornbeam) zone ending with a return to brackish sedimentation during the *Picea* (spruce) zone.

This sequence is, by definition, the Eemian. For this project it was essential to obtain reliable D/L ratios from a variety of taxa from the type locality. Existing shell collections had been heated during processing and were not suitable for the method (note the higher ratios for *Venerupis* and *Divaricella* in the heated material; Table 18). Under the direction

TABLE 18. D/L ratios in shells from interglacial sites in The Netherlands

Lab ID	Species	Mean	σ	*n*	Locality, depth
AAL-2791	*Bittium reticulatum*	0.162	0.021	3(6)	Amersfoort, 17–18 m
AAL-3637	*Bittium reticulatum*	0.179	0.021	5(8)	Amersfoort, 17–18 m
AAL-3638	*Bittium reticulatum*	0.165	0.022	5(8)	Amersfoort, 18–19 m
AAL-2792	*Bittium reticulatum*	0.174	0.012	3(9)	Amersfoort, 20 m
AAL-2789	*Cardium edule*	0.175	0.029	3	Amersfoort, 17–18
AAL-2790	*Cardium edule*	0.147	0.067	3	Amersfoort, 20 m
AAL-2794	*Divaricella divaricata*	0.290	0.024	3	Amersfoort, 20 m
AAL-4218	*Hiatella arctica*	0.196	0.019	4	Amersfoort, 26 m
AAL-2788	*Nassarius reticulatus*	0.140	0.017	3	Amersfoort, 20 m
AAL-2793	*Venerupis senescens*	0.201	0.031	6	Amersfoort, 17–18 m
AAL-3394	*Venerupis senescens*	0.210	0.022	4	Amersfoort, 17–18 m
AAL-3224	*Divaricella divaricata*	0.355	0.037	4	Amersfoort (heated)
AAL-3395	*Divaricella divaricata*	0.368	0.051	4	Amersfoort (heated)
AAL-3390	*Spisula subtruncata*	0.173	0.025	4	Amersfoort (heated)
AAL-3225	*Spisula subtruncata*	0.189	0.039	3	Amersfoort (heated)
AAL-3393	*Venerupis senescens*	0.256	0.019	4	Amersfoort (heated)
AAL-3640	*Bittium reticulatum*	0.160	0.022	5(8)	Bergen 19A/263, 66 m
AAL-3391	*Corbula gibba*	0.229	0.011	4	Bergen 19A/263, 77 m
AAL-3387	*Macoma balthica*	0.172	0.012	4	Bergen 19A/263, 59 m
AAL-3386	*Macoma balthica*	0.179	0.017	4	Bergen 19A/263, 66 m
AAL-3223	*Mya truncata*	0.176	0.021	5	Bergen 19A/263, 68 m
AAL-3226	*Spisula subtruncata*	0.181	0.041	3	Bergen 19A/263, 66 m
AAL-3396	*Spisula subtruncata*	0.164	0.039	4	Bergen 19A/263, 66 m
AAL-3389	*Spisula subtruncata*	0.154	0.022	4	Bergen 19A/263, 77 m
AAL-3392	*Venerupis senescens*	0.210	0.036	4	Bergen 19A/263, 68 m
AAL-3222	*Mya truncata*	0.200	0.014	3(1)	Bergen boring
AAL-4230	*Macoma balthica*	0.035	0.002	3	Castricum, 21 m (4.5 ka)
AAL-4221	*Littorina littorea*	0.122	0.013	5	Castricum, 38–39 m
AAL-4223	*Macoma balthica*	0.162	0.016	4	Castricum, 38–39 m
AAL-4227	*Macoma balthica*	0.165	0.020	4	Castricum, 45–46 m
AAL-4224	*Macoma balthica*	0.216	0.060	4	Castricum, 38–39 m
AAL-4220	*Mya truncata*	0.155	0.016	4	Castricum 38–39 m
AAL-4228	*Mya truncata*	0.180	0.019	4	Castricum, 46–47 m
AAL-4215	*Littorina littorea*	0.119	0.007	5	Zunderdorp, 46–47 m
AAL-4216	*Macoma balthica*	0.189	0.018	5	Zunderdorp, 46–47 m
AAL-3388	*Macoma balthica*	0.458	0.062	4	Noord Bergum 6D/38, 59 m

of W. Zagwijn, the Geological Survey of the Netherlands undertook a special boring for this project at Amersfoort. According to de Jong (*written comm.*, 1981) the lithostratigraphy of the Eemian beds in the new core is similar to that of the Amersfoort boring I of Zagwijn (1961). The molluscs were identified by G. Spaink and the samples, all of which were from the *Carpinus* zone, were submitted by de Jong and Zagwijn in 1981.

The Eemian marine beds at the type locality were deposited far inland from the coast near the head of an estuary during the highest stand of the Eem Sea. Consequently, the local marine environment was of reduced salinity and the fauna is restricted with several open-marine species conspicuous by their absence. The only representatives of the core taxa used in this survey are *V. senescens* (0.21), and a few diminutive shells of *Hiatella* (0.19).

Bergen Boring

Because of the limited fauna in the Amersfoort boring at the type Eemian locality, we chose to analyze additional shells from nearby borings that penetrated deeper water, more open-marine conditions from the last interglacial and for which the shell material had not been heated during the extraction procedure. Zagwijn submitted molluscs of several taxa in 1983 from a boring near the city of Bergen (boring 19A/263, unpublished) in which fossiliferous marine beds were located between 59 and 80 m depth where they directly overlie Saalian fluvial-glacial sediment. The boring is situated in an old tidal inlet that connected Ijsselmer with the Eem Sea; a similar inlet also existed during the Holocene but was later abandoned. Pollen analysis of a nearby boring indicates that the marine beds are of late Eemian age (pollen zone E6b, Zagwijn, *personal comm.*, 1984). The ratios in *Venerupis* and *Spisula* substantiate the biostratigraphic correlation of the two borings. Two other important species analysed from the Bergen boring, *Macoma balthica* and *Mya truncata*, gave D/L ratios similar to those in *Venerupis* (Table 18).

A single whole valve of *Mya truncata* was also submitted from a different boring in the same region (AAL-3222, Table 18). Although the precise location of the boring and depth from which the shell came are not known, the regional similarity in subsurface sediment around Bergen allows us to correlate to the Eemian marine beds of boring 19A/263.

Castricum

The boring at Castricum (19C/648), 15 km south of the Bergen boring, was selected for additional analysis because the Eemian marine beds that were encountered between 38 and 46 m depth contained specimens of several taxa used in other localities in this study, and the shells had not been heated above 50°C during their extraction. Samples of *Littorina littorea* and *Mya truncata* were given to Miller by Zagwijn and Meijer during a visit to Rijks Geologische Dienst, Haarlem in 1984.

Zunderdorp

The boring at Zunderdorp (25E/344), north of Amsterdam, contained Eemian deposits correlative with pollen zone E4/5 and a molluscan fauna indicative of an environment in the intertidal zone. Of particular interest was the occurrence of *Littorina* and *Macoma*. Samples were provided by Zagwijn and Meijer, Haarlem, in 1984. The measured D/L ratios (Table 18) support the Eemian correlation.

Noord Bergum

In an attempt to provide limiting values on the older interglacial sequences, we analyzed *Macoma balthica* from a boring near Noord Bergum (Boring 6D/38, *unpublished*). In this boring a Saalian till overlies a marine valley fill which contains a Holsteinian pollen spectra. The valley had been eroded into glacial-lacustrine beds of the Elsterian glaciation. These beds in turn fill a valley, at the base of which are 'Cromerian' marine sediments; the shells analyzed came from these beds at a depth of 59 to 60 m. The shells may have been heated during extraction. The site has been known since the 1930s, but the marine beds were originally thought to be Holsteinian; only recently have they been reinterpreted to be 'Cromerian' (e.g. Ter Wee, 1983), more specifically 'Cromer IV' (Zagwijn, *written comm.* 1980). They will be referred to here as 'late Cromerian'. The measured D/L ratio [0.46 ± 0.06 (4)] supports a pre-Holsteinian age.

BELGIUM AND NORTHERN FRANCE

Interglacial marine deposits have been penetrated in borings in the Flemish Valley and along the coastal plain of Belgium. The Oostende Formation includes the tidal flat deposits that contain *Venerupis senescens* (Paepe, 1965), generally considered to be a guide fossil for the last interglacial and *Corbicula fluminalis*, an interglacial freshwater bivalve (see e.g., Paepe *et al.*, 1981 for a review). Pollen spectra within peat deposits overlying the marine sands of the Oostende Formation indicate a correlation with the Eemian (pollen zones E4a to E6b) in the Netherlands, but a detailed treatment of the molluscan assemblages has not yet been published. The implication is that the molluscan assemblages are from middle Eemian time. However, Spaink's (Denys *et al.*, 1983) recent survey of molluscs extracted from a boring through supposed Eemian marine sediments near De Panne, on the Western Belgian Coastal Plain less than 2 km from the French border indicated a lack of diagnostic faunal elements that characterize the Eemian deposits in the Netherlands and the presence of numerous taxa not present in the Dutch Eemian beds. Spaink raised the question whether these deposits were actually of Eemian age.

We have analyzed *Macoma balthica* and *Venerupis* sp. obtained from a boring near Brugge in the Flemmish Valley (Koolkerke 3, Boring #368), in which marine shells were encountered between 10.5 and 14.8 m depth in the boring (shells were obtained from R. Paepe in 1981). The measured D/L ratios in these two taxa support a correlation to the Eemian sites in the Netherlands (Table 19).

Deposits of the Herzeele Formation, an older interglacial unit, underlie the Oostende Formation, but adequate molluscan material for amino acid analyses have yet to be obtained from Belgium. Instead, we have analyzed *Macoma balthica* from the Heem Brickyard located a few km west of the Belgian border near the town of Herzeele, northern France. *Cardium lamarcki* from the same deposit gave a consistent set of analytical results (unlike *C. edule*), with measured D/L ratios similar to those in *Macoma* (Table 19). The Herzeele shells were collected by J. Hollin guided by R. Paepe and J. Sommé. The D/L

TABLE 19. D/L ratios in shells from Belgium and Northern France

Lab ID	Species	Mean	σ	*n*	Locality
AAL-2976	*Macoma balthica*	0.163	0.028	4	Koolkerke 3
AAL-3664*	*Macoma balthica*	0.201	0.004	4	Koolkerke 3
AAL-4090	*Macoma balthica*	0.164	0.025	4	Koolkerke 3
AAL-3302	*Macoma balthica*	0.179	0.041	2	Koolkerke 3
AAL-3301	*Venerupis senescens*	0.157	0.063	2	Koolkerke 3
AAL-2970	*Venerupis senescens*	0.178	0.037	6(4)	Koolkerke 3
AAL-3117	*Venerupis senescens*	0.136	0.014	4	Koolkerke 3
AAL-3296	*Corbicula fluminalis*	0.343	0.044	3	Zeebrugge
AAL-4094¶	*Glycymeris* sp	0.201	0.012	2(1)	Zeebrugge
AAL-3297	*Glycymeris* sp	0.207		1	Zeebrugge
AAL-3298	*Macoma balthica*	0.312	0.012	2	Zeebrugge
AAL-4095	*Macoma balthica*	0.275	0.011	2(1)	Zeebrugge
AAL-2940	*Mya truncata*	0.116		1	Zeebrugge
AAL-3299†	*Mya truncata*	0.137	0.011	2(1)	Zeebrugge
AAL-4091†	*Mya truncata*	0.153		1	Zeebrugge
AAL-3299	*Hiatella arctica*	0.132		1	Zeebrugge
AAL-3634‡	*Hiatella arctica*	0.120		1	Zeebrugge
AAL-4103	*Cardium lamarcki*	0.280	0.033	5	Herzeele
AAL-4102	*Macoma balthica*	0.250	0.085	2(1)	Herzeele
AAL-4098	*Macoma balthica*	0.302	0.087	5	Herzeele
AAL-4104	*Macoma balthica*	0.306	0.018	3	Herzeele

*Repreparation of same four shells as AAL-2976.
†Repreparation of same shell as AAL-2940.
‡Repreparation of same shell as AAL-3299.
¶Repreparation of same shell as AAL-3297.

ratios suggest a correlation with the Holsteinian, supporting a similar conclusion based on the palynology (Sommé *et al.*, 1978). However, U/Th dating of shells has given an age of 326 ka (Stremme, 1983).

Additional shell material has been analyzed that was collected from an exposure at Zeebrugge on the Belgian Coastal Plain. The age of the deposit and stratigraphic association of the shells are obscure. The amino acid results suggest the shells are of several ages, including some that appear to be younger than the last interglacial, particularly individuals of *Hiatella arctica* and possibly *Mya truncata*. On the other hand, *Corbicula fluminalis* yielded D/L ratios suggestive of a Holsteinian age. We suggest that the deposit is complex and may contain shells of significantly different ages. Regardless of stratigraphic complexities, the presence of molluscs with D/L ratios significantly lower than in secure Eemian sites raises the possibility of a major post-Eemian marine transgression across the Belgian coast.

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