Foraminiferal stratigraphy and amino acid geochronology of Quaternary sediments in the Norwegian Channel, northern North Sea

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Based on isoleucine epimerization in benthonic foraminifera and the investigation of benthic and planktonic foraminiferal assemblages, it is concluded that the upper c. 120 m of the sediment sequence in the middle of the Norwegian Channel west of Bergen, Norway, spans the last approximately 300 ka. Most of these sediments consist of relatively coarse grained glacigenic material (tills and glacial marine sediments). These sediments usually contain foraminiferal faunas with low numbers of individuals and arctic and boreal species occur in mixed assemblages together with relatively high numbers of pre-Quaternary foraminifera. Between 62 and 72 m and 110 and 120 m in core 5.1/5.2, sorted sediments with *in situ* foraminiferal faunas occur. The uppermost of these units contains a planktonic and benthonic foraminiferal fauna indicating marine conditions at least as temperate and favorable as those prevailing in the area today. This period is designated the Troll Interglacial and is correlated with the last interglacial, the Eemian. The lowermost of these sorted units contain benthonic and planktonic faunas which suggest marine conditions at least as temperate as those prevailing in the low arctic to high boreal regions today. All available evidence suggests an age between 200 and 300 ka for this unit. The complexity of the glacigenic sedimentary units recorded in the core between and above these interglacial sediments and seismic data suggest that further examination of the sequence may give new information on the glacial history of the northern North Sea.

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The chronology and genesis of the late Cenozoic sediments in the Norwegian Channel west of southern Norway have so far been given little attention. Even though considerable effort has been put into the investigation of the upper layers while prospecting for hydrocarbons in this region, few papers have appeared. The investigation of the upper sedimentary sequence in the Norwegian Channel is important for purely scientific reasons but also for more practical reasons related to the industrial interest in the area. Among the more scientific aspects, information within these sequences will be important for a better understanding of the tectonic relationship between the Fennoscandian Shield and the North Sea Basin and for the possibility of linking the relatively complex Late Quaternary history which is evolving from studies in western Norway (among others, Andersen et al. 1981; Mangerud 1981; Sejrup 1987) with that of the North Sea and the Norwegian Sea. Of special interest is the possibility to extend the known depositional record and improve the chronology of glacial advances during the Late Quaternary which have been recorded in western Norway.

This paper is based on amino acid diagenesis studies on foraminifera from three shallow corings and on foraminiferal micropaleontology performed on one of these, from the Troll Field in the Norwegian Channel northwest of Bergen, Norway, at 61°N (Figs. 1, 2). In a paper by Brigham-Grette & Sejrup (in prep.) the amino acid chronology for the northern North Sea will be compiled and the discussion of absolute age estimates more thoroughly treated.

Materials and methods

The coring technique (Ardus et al. 1982) applied favored sampling of relatively fine-grained sediments and poorly sorted sediments. Sorted sands, if present, were not easily sampled. The relatively large gap between each of the analyzed samples

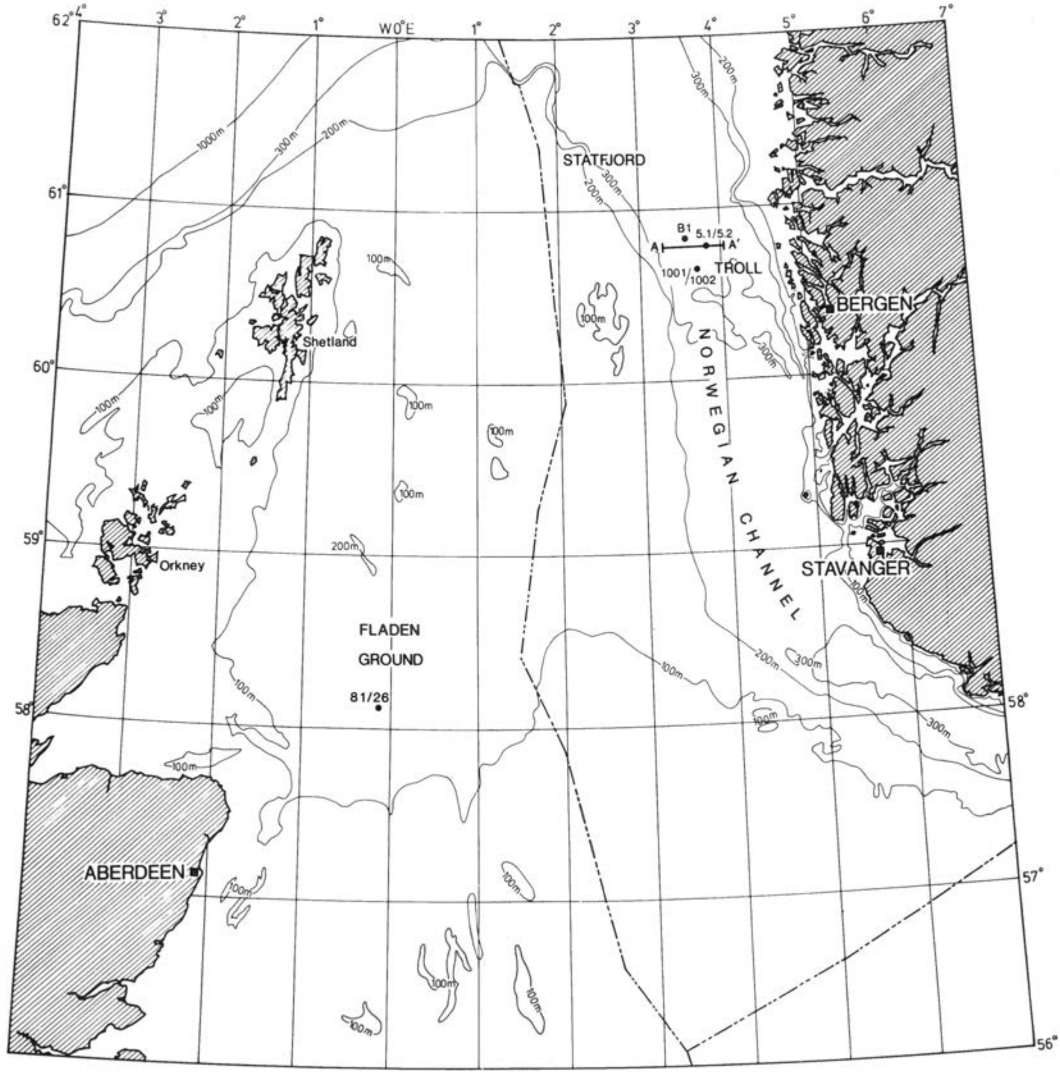

Fig. 1. Location of the investigated cores and some of the localities referred to in the text.

may well have resulted in that major sedimentary units have not been studied. However, to a certain degree the seismic and amino acid data can help in the identification of major hiatuses. The data presented here provide the first clue to what more detailed stratigraphic work in the region might yield.

Foraminifera

The foraminiferal samples have been processed in accordance with the technique described by Feyling-Hanssen (1964). The fraction between 0.125 and 1 mm have been counted, and CCl_4 with specific gravity 1.59 was used for separation. In each sample 300 benthonic individuals were counted. For the planktonic taxa, 100 specimens were counted when enough individuals were present. The percentages of selected species are presented in the vertical distribution diagrams (Figs. 4, 5). The number of foraminifera relative to weight sediment has not been determined, but samples containing less than 300 benthonic or 100 planktonic (each sample approximately 30 g) are indicated on the diagrams. The results of the foraminiferal investigations are presented in Figs.

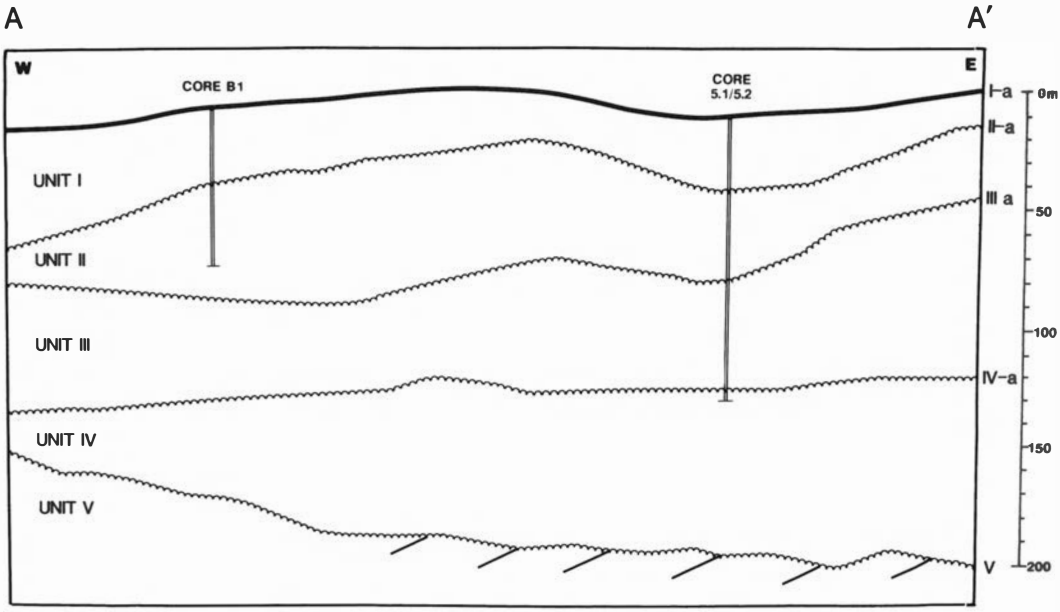

Fig. 2. Interpreted seismic profile from the Troll area (modified after Butenko et al., in press). Note location of the investigated cores. Location of profile in Fig. 1.

4 and 5 and in Tables 1, 2 and 3. The taxonomy is mostly according to Knudsen (1971). For *Elphidium excavatum* we refer to Miller et al. (1982) and for *Cassidulina reniforme* to Sejrup & Guilbault (1980).

Amino acids

To contribute in the cross-core correlation and in an effort to establish an absolute chronology, amino acid analyses on benthonic foraminifera were performed on three shallow cores from the Troll region (Fig. 1). In this study the isoleucine epimerization reaction was utilized and the degree of epimerization is given as the peak height ratio between D-alloisoleucine (aIle) and L-isoleucine (Ile) (Miller & Hare 1980; Wehmiller 1982). The epimerization of isoleucine is highly species dependent as well as temperature dependent. In this region a recent sample has a ratio close to 0.01 and equilibrium (aIle/Ile = 1.3) will be reached after some 2–3 million of years (Miller et al. 1983). Isoleucine epimerization studies on Quaternary benthic foraminifera from the North Sea region have been reported by Miller et al. (1983), Sejrup

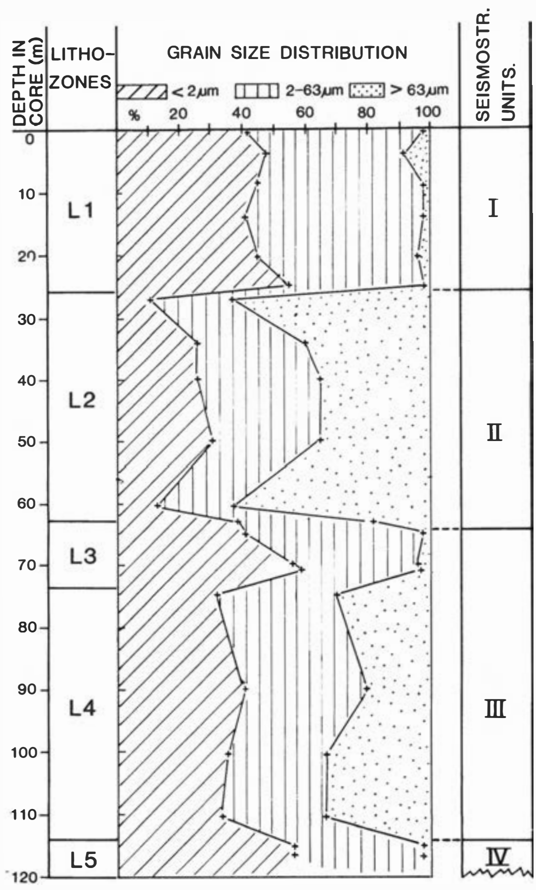

Fig. 3. Lithological units and grain-size data of core 5.1/5.2 from the Troll Field (after Forsberg, pers. comm., 1987). The correlations to the seismic units are indicated.

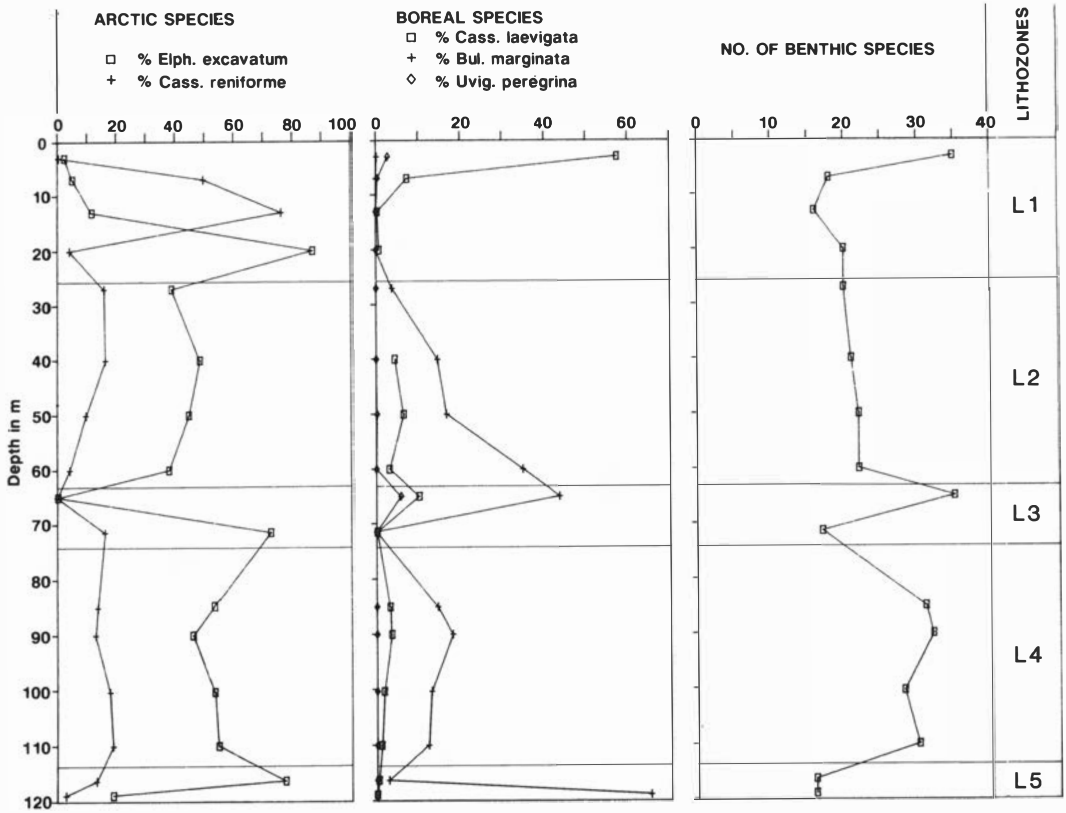

Fig. 4. Distribution of selected species of benthic foraminifera from Troll Field core 5.1/5.2.

et al. (1984), Sejrup et al. (1987) and Knudsen & Sejrup (1988).

The samples in the present study have been prepared after the method described in Miller et al. (1983) and then analyzed on an automatic HPLC amino acid analyzer. The peak height ratios (Table 4 and Fig. 6) have been determined using a Hewlett-Packard computing integrator. To eliminate taxonomic effects on reaction rate, each sample was monospecific and consisted of close to 100 specimens of the benthonic foraminifer *Elphidium excavatum* or *Bulimina marginata.* Because some of the foraminifera may be reworked the resulting ratio is interpreted as a weighted mean of the whole sample. Resedimentation will tend to produce ratios relatively higher than the age of the enclosing sediments. The amino acid data from core 5./5.2, B1 and 1001/1002 are presented in Table 4 and Fig. 6.

The Interlaboratory Calibration Standards (Wehmiller 1984) analyzed in July 1987 gave the following results (total fraction) in the laboratory in Bergen: 81 ILC A 0.158 ± 0.018(5), 81 ILC B 0.481 ± 0.0.008(4) and 81 ILC C 0.934 ± 0.018(3).

Parallel investigations

Seismostratigraphy on the Troll Field

Butenko et al. (in press) have divided the upper (down to approximately 200 m) sedimentary sequence from the coast of west Norway to the North Sea Plateau into five major seismic units. Fig. 2 shows the geometry of these units along an east–west profile across the Troll Field. The lower of these units (unit V) has westerly dipping internal reflectors and is composed of rocks of pre-Quaternary age. The boundary to the unit above (unit IV) is an angular unconformity which has been described by several authors (Sellevold & Sundvor 1974; Rokoengen & Rønningsland 1983). Unit IV is found between 125 and 200 m

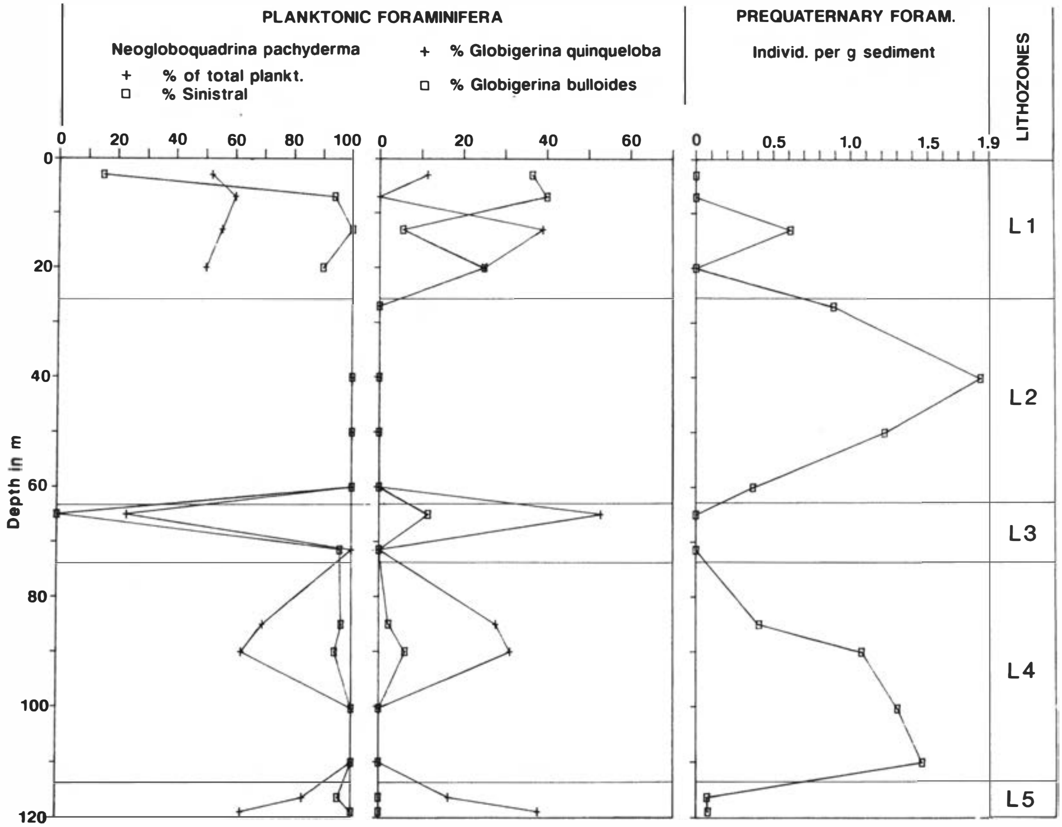

Fig. 5. Planktonic foraminifera and reworked pre-Quaternary foraminifera in Troll Field core 5.1/5.2.

depth in the Troll Field area and thins out toward the North Sea Plateau. The unit consists of several flat-lying sub-parallel reflectors and the upper boundary is defined by an erosional unconformity. The next two units (units III and II) consist partly of irregular and relatively less continuous reflectors. The boundary between these units, however, is more continuous and can be followed all the way from the North Sea Plateau to the coast of Norway. This boundary was interpreted to represent the top of the Late Pliocene by Rise et al. (1984), but this has later been questioned by Green et al. (1985), who suggested a Saalian age for unit III. The upper unit (unit I) consists of well-defined parallel reflectors. The unit is locally thin (even absent) close to the coast. In the Troll area it is between 20 and 30 m thick. Towards the plateau it pinches out.

Unit I corresponds to the Kleppe Senior Formation, unit II to the Norwegian Trench Formation and units III and IV to the 'Late Pliocene' in Rise et al. (1984).

Lithology of core 5.1/5.2

Lithologic changes in the cores partially mimic the seismostratigraphic units outlined above. None of the cores presented in this study penetrated into sediments below the regional angular unconformity, so this work will focus on the chronology and genesis of units I to IV. Core 5.1/5.2 (150 m long) is one of the most complete cores raised from the Norwegian Channel. Based on the grain-size distribution (Forsberg, pers. comm. 1986), the core can be divided into five informal lithozones (L1–L5) (Fig. 3).

Lithozone L1 (0–26 m) consists of pelitic sediments with a relatively high clay content (40–50%) and a small admixture of sand and gravel. The unit is very loose and characterized by shear strength values lower than 30 kPa. L1 has often

Table 1. Benthonic foraminifera in sample 4–A from 3 m depth in coring 5.1/5.2

Species	%
Cassidulina laevigata	57.5
Nonion grautelopi	12.4
Nonion barleeanum	4.1
Epistominella nipponica	3.7
Cibicides lobatulus	3.3
Cibicides pseudoungerianus	3.3
Uvigerina peregrina	2.8
Elphidium excavatum	2.4
Stainforthia loeblichi	1.3
Globobulimina turgida	1.3
Stainforthia fusiformis	1.1
Nonion labradoricum	0.9
Lagena laevis	0.4
Milliolinella subrotunda	0.4
Quinqueloculina seminulum	0.4
Pyrgo williamsoni	0.4
Pyrgo sp.	0.4
Pullenia osloensis	0.4
Cassidulina reniforme	0.4
Bulimina marginata	0.2
Fissurina marginata	0.2
Fissurina sp.	0.2
Globobulimina auricula	0.2
Textularia sagittula	0.2
Lagena mollis	0.2
Quinqueloculina stalkeri	0.2
Pateoris hauerinoides	0.2
Lagena striata	0.2
Trifarina angulosa	0.2
Hyalinea balthica	0.2
Rosalina sp.	0.2
Lenticulina sp.	0.2
Dentalina sp.	0.2
Sum	98.8

No. of benthonic species: 33.

Table 2. Benthonic foraminifera in sample 25–A from 65 m depth in core 5.1/5.2

Species	%
Bulimina marginata	43.6
Bolivina cf. *robusta*	14.6
Nonion barleeanum	12.6
Cassidulina laevigata	10.1
Uvigerina peregrina	5.8
Trifarina angulosa	3.9
Textularia saggitula	2.8
Cibicides pseudoungerianus	2.0
Bolivina pseudoplicata	1.1
Fissurina danica	0.4
Astrononion gallowayi	0.5
Fissurina laevigata	0.2
Fissurina marginata	0.2
Fissurina sp. A	0.2
Parafissurina lateralis	0.2
Lagena distoma	0.2
Stainforthia fusiformis	0.2
Stainforthia loeblichi	0.2
Epistominella nipponica	0.2
Elphidium excavatum	0.2
Allomorphina fragilis	0.2
Quinqueloculina seminulum	0.2
Lenticulina thalmani	0.2
Lenticulina sp.	0.2
Elphidium excavatum f. *alba*	0.2
Pullenia subcarinata	0.2
Pyrgo williamsoni	<0.2
Loxostomum porrectum	
Lagena semilineata	
Lagena striata	
Spirrilina latesepta	
Fissurina anectens	
Fissurina sp. B	
Fissurina sp. C	
Fissurina sp. D	

No. of benthonic species: 35.

Table 3. Benthonic foraminifera in sample 39–D from 118.9 m depth in coring 5.1/5.2

Species	%
Bulimina marginata	65.0
Elphidium excavatum	9.0
Bulimina ulata?	8.1
Islandiella norcrossi	3.1
Cassidulina reniforme	2.9
Stainforthia loeblichi	1.0
Bolivina cf. *robusta*	0.2
Elphidium incertum	0.2
Nonion orbiculare	0.2
Nonion germanicum	0.2
Lenticulina thalmanni	<0.2
Trifarina fluens	
Parafissurina tectulostoma	
Dentalina frobisherensis	

No. of benthonic species: 14.

been referred to as the 'soft clay of the Norwegian Trench' and it corresponds to seismostratigraphic unit I. Radiocarbon dates from the Troll Field (Butenko et al., in press) and also from the Gullfaks area (Carlsen et al. 1986) suggest that most of this unit was deposited between 10 and 13 ka ago. The Holocene sediments are usually less than a couple of meters thick in this area.

Lithozone L2 (26–62 m) is a much coarser, less sorted sequence; between 35 and 60% of the material is sand and gravel. The shear strength values vary between 150 and 30 kPa and are highest in the lower part. The unit corresponds to seismostratigraphic unit II.

Lithozone L3 (62–72 m) is a well-sorted mainly pelitic sediment. The upper samples contain more

Table 4.

Lab. ID	Coring/sample	Depth (m)	Species	aIle/Ile
BAL 751	5.2/4B	25.05	*Elphidium excavatum*	0.048 0.052
BAL 750	5.2/7A	31.0	*Elphidium excavatum*	0.077
BAL 752	5.2/13A	37.0	*Elphidium excavatum*	0.120
BAL 753	5.2/13A	37.0	*Bulimina marginata*	0.137
BAL 754	5.2/21C	60.0	*Elphidium excavatum*	0.124
BAL 755	5.2/21C	60.0	*Bulimina marginata*	0.110
BAL 749	5.2/24	64.0	*Elphidium excavatum*	0.139
BAL 644	5.2/25D	65.45	*Bulimina marginata*	0.099
BAL 645	5.2/35B	105.15	*Elphidium excavatum*	0.218
BAL 646	5.2/37A	115.0	*Elphidium excavatum*	0.189
BAL 647	5.2/38B	116.1	*Elphidium excavatum*	0.220
BAL 392	1002	3.1	*Elphidium excavatum*	0.059
BAL 376	1002/6A	5.9	*Elphidium excavatum*	0.048
BAL 370	1002/9A	8.9	*Elphidium excavatum*	0.050
BAL 378	1002/T15A	14.9	*Elphidium excavatum*	0.047
BAL 372	1002/22F	21.0	*Elphidium excavatum*	0.108
BAL 379	1002/28A	27.9	*Elphidium excavatum*	0.090
BAL 373	1002/36A	35.9	*Elphidium excavatum*	0.075
BAL 377	1001/T7A	62.1	*Elphidium excavatum*	0.135
BAL 371	1001/T12B	70.15	*Elphidium excavatum*	0.225
BAL 380	1001/63	81.7	*Elphidium excavatum*	0.197
BAL 374	1001/71	92.02	*Elphidium excavatum*	0.39
BAL 381	1001/81	115.14	*Elphidium excavatum*	0.212
BAL 375	1001/84	118.75	*Elphidium excavatum*	0.299
BAL 394	1001	130.6	*Elphidium excavatum*	0.208
BAL 101	B1/7	10.5	*Elphidium excavatum*	0.043
BAL 103	B1/12	22.0	*Elphidium excavatum*	0.050
BAL 104	B1/14	30.0	*Elphidium excavatum*	0.084
BAL 102	B1/28	64.0	*Elphidium excavatum*	0.129

sand and silt than the lower ones, which have 60% clay. This unit corresponds to the upper part of seismostratigraphic unit III.

Lithozone L4 (72–112 m) is similar to L2 in grain-size distribution. The content of sand and gravel, however, is less in most of the samples. The unit is very stiff and has shear strength values around 450 kPa. L4 corresponds to the lower part of seismostratigraphic unit III.

Lithozone L5 (112–120 m) is a well-sorted pelitic sediment with shear strength values close to the superimposed unit. Lithozone L5 is found in the upper part of seismostratigraphic unit IV.

Foraminiferal stratigraphy

All the shallow cores analyzed for benthonic foraminifera from the Troll Field show a similar stratigraphy, even though none of the cores have been sampled closely. In core 5.1/5.2 the content of benthonic and planktonic foraminifera was studied in 16 subsamples (Figs. 4, 5). The distribution of the microfossils shows a surprising covariation with the lithology described above (Fig. 3).

L1 shows a nice faunal change upward from a low-diversity arctic assemblage dominated by *Elphidium excavatum* (mostly forma *clavata*) into a more diverse arctic fauna dominated by *Cassidulina reniforme*. The upper sample represents a boreal shelf fauna dominated by *Cassidulina laevigata*, with high diversity and number of individuals (Table 1). The planktonic fauna in the lower and middle parts of L1 is dominated by *Neogloboquadrina pachyderma* (sin.) and in the upper sample by *N. pachyderma* (dex.) (more than 80% of this species). Similar evolution in the late glacial–Holocene fauna has been reported by several authors from the Norwegian shelf (Vorren et al. 1978; Nagy & Ofstad 1980; Sejrup et al. 1980; Jansen et al. 1983; Hald & Vorren 1984, 1987; Mackensen et al. 1985). Of special interest is that faunas very similar to the one recorded in

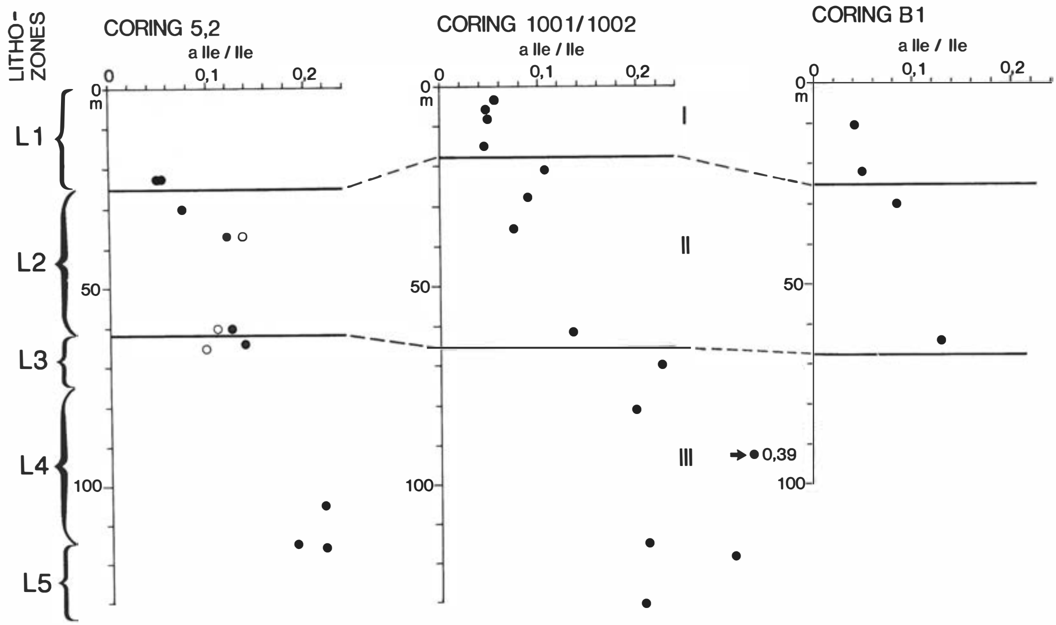

Fig. 6. Isoleucine epimerizaion in *Elphidium excavatum* (closed circles) and *Bulimina marginata* (open circles) in three cores from the Troll area. The seismostratigraphic correlation is indicated.

the lower part of L1 have been suggested to represent an environment close to a retreating glacier (Osterman & Andrews 1983).

The relatively coarse sediments in L2 contain foraminiferal faunas different from those of L1. The most striking feature is the mixture of arctic and boreal species (*Elphidium excavatum* and *Bulimina marginata*). Moreover, the relatively high number of pre-Quaternary species suggests that this unit contains foraminifera representing different ages and environments. The sequence represents either a glacial marine environment and/or deposition more directly at the base of the glacier (lodgement till).

Two samples from L3 have been analyzed for their foraminiferal content, and both contain relatively rich faunas. The upper sample has a high diversity boreal benthonic fauna dominated by *Bulimina marginata, Bolivina* cf. *robusta, Nonion barleeanum* and *Cassidulina laevigata* (Table 2). The planktonic fauna is dominated by the subpolar species *Globigerina quinqueloba* and *N. pachyderma* (dex.). Both the benthonic and planktonic assemblages consist mainly of species common in the North Sea region today (Jarke 1961; Murray 1971; Sejrup et al. 1981; Jansen et al. 1983). The assemblages from L3 are similar to the interglacial fauna described by Feyling-Hanssen (1981) from coring 2501 in the Statfjord area (Fig. 1). In that paper *Bulimina marginata* has been distinguished from the less spinose form *B. gibba*. In the present contribution both these taxa are included in *B. marginata*. However, the present authors are not convinced that the interpretation of a fauna from c. 20 m sediment depth in coring 3506 at Statfjord as interglacial is correct, because this fauna is dominated by the two arctic species *Elphidium excavatum* forma *clavata* and *Cassidulina reniforme*. As the fauna in L3 is associated with a well-sorted sediment, and contains a rich boreal benthonic assemblage and a planktonic assemblage dominated by subpolar species, we believe that this level represents one of the most convincing interglacial deposits recorded in cores from the North Sea. As the interglacial sequence is represented by only one sample and the upper and lower boundaries are not recovered, we only give it an informal climatostratigraphic notation (Hedberg 1976); the Troll Interglacial.

The lower sample in unit L3 has an arctic benthonic fauna without any admixtures of boreal or pre-Quaternary elements. This fauna is similar to those recorded in the lower part of L1 and both the benthonic and planktonic (95% *N. pachyderma* (sin.)) components indicate an arctic environment without the presence of warm Atlantic water in the area.

Both the benthonic and planktonic foraminiferal assemblages in the relatively coarse-grained sediments in L4 are almost identical to those recorded in L2. The number of individuals is generaly low, warm and cold species occur mixed together, and a high number of pre-Quaternary species are present. The same possibilities for interpretation of the genesis also exist; till and/or glacial marine.

The two samples analyzed from the well-sorted pelitic sediment in L5 contain quite different faunas. The upper sample has an arctic benthonic fauna similar to the one recorded in the lower part of L3. The lower sample contains 60% of the thermophileous species *Bulimina marginata*; however, the diversity and number of other boreal species is much lower in this sample (Table 3) than in the interglacial sample from L3 (Table 4). The planktonic fauna is dominated by the polar *N. pachyderma* (sin.) in both samples. Another common feature is that both samples have low numbers of reworked pre-Quaternary specimens. The lower sample is interpreted to represent deposition in an open marine environment under high boreal to low arctic conditions and the upper may represent a full arctic situation.

Amino acid stratigraphy and geochronology

Correlation of cores

Amino acid analyses have been performed on three cores from the Troll Field (Fig. 1). The degree of isoleucine epimerization in the benthonic species *Elphidium excavatum* and *Bulimina marginata* is presented in Table 6 and Fig. 6 as the ratio between D-alloisoleucine and L-isoleucine (aIle/Ile) in the total fraction. The mean value of eight analyses of *Elphidium excavatum* from seismostratigraphic unit I is 0.050 ± 0.005, of ten analyses from unit II is 0.108 ± 0.024 and of eight from units III and IV is 0.221 ± 0.033. The difference in mean ratios suggests that the seismic boundaries between Unit I/Unit II and Unit II/Unit III do, in fact, represent major unconformities in deposition. These results support the conclusion of Sejrup et al. (1984) that isoleucine epimerization in benthic foraminifera is a valuable tool in the correlation of Quaternary shelf sediments.

The general trends of the ratios in the three cores are that they increase with depth. Another feature is that the downcore changes seem to occur in a stepwise fashion. A similar stepwise change in the aIle/Ile-ratios has been recorded in several other cores from the northern North Sea (Sejrup et al. 1987; Brigham-Grette & Sejrup 1988) reflecting a very episodic style of sedimentation with large hiatuses. From the micropaleontological investigations of core 5.1/5.2 it was concluded that the fauna in L2 and L4 consist of mixed assemblages of different ages and environments. Since the relatively large variations in amino acid ratios from these stratigraphical levels support this conclusion, we will mostly rely on the ratios obtained from units L1, L3 and L5 in our discussion of the chronology of the sediments.

Late glacial–Holocene (lithozone 1)

Two preparations of a single sample from L1 in core 5 gave aIle/Ile ratios of 0.048 and 0.052 in *Elphidium excavatum*, similar to what was obtained on this species from seismostratigraphic unit I in other parts of the Norwegian Channel. Radiocarbon-dated late glacial samples from the Norwegian shelf have produced ratios between 0.03 and 0.05 (Sejrup et al. 1984; Sejrup et al. 1987). The fact that the ratios from seismic unit I in the Troll area are at the higher end of this range might suggest that the deeper burial (24 m) has resulted in higher temperatures for these samples than those analyzed by Sejrup et al. (1984), which were all shallower than 3 m below the seabed. There is therefore a good agreement between the amino acid data and the radiocarbon dates, which suggest an age younger than c. 13 ka for lithozone 1.

The Troll Interglacial

Two samples have been analyzed from lithozone L3. One of them consisted of *Bulimina marginata* from the interglacial fauna recorded at 65.45 m depth in core 5.1/5.2 and yielded an aIle/Ile ratio of 0.099. A sample (which has not been examined for its foraminiferal content) of *Elphidium excavatum* from 64.0 m depth gave 0.139. From the interglacial locality at Fjøsanger, western Norway

Table 5. aIle/Ile ratios in benthonic foraminiferal samples of known age from the North Sea region (partly from Sejrup et al. 1987).

Lab. no.	Area	Field no.	Spec.	aIle/Ile	Age
BAL 224	Norwegian Sea	16118	*Cibicides wuellerstorfi*	0.009 0.008	Living
BAL 635	Nor. Trench	C.1/1A 0.0 m	*Bulimina marginata*	0.008	Recent
AAL–1831	Off Ålesund	B77–139	*Elphidium excavatum*	0.032	12,930 ± 240 (T–2647 Sejrup et al. (1984)
AAL–1933	Off Tromsø	C76–113	*Elphidium excavatum*	0.036	11,770 ± 170 (T–2528 Sejrup et al. (1984)
BAL 430	n. North Sea	A79–156, 52 cm	*Elphidium excavatum*	0.055	29,430 ± 390 (T–4221)
BAL 429		A79–156, 84 cm	*Elphidium excavatum*	0.054	29,930 ± 450 (T–4222)
BAL 428		A79–156, 93 cm	*Elphidium excavatum*	0.059	30,190 ± 360 (T–3827)
BAL 277	Statfjord C	2501, 52 m	*Elphidium excavatum*	0.086 0.093	ca. 120,000 (last interglacial, Feyling-Hanssen (1981)
BAL 651	Statfjord C	2501, 52 m	*Bulimina marginata*	0.078 0.078	ca. 120,000 (last interglacial Feyling-Hanssen (1981)
BAL 650	Statfjord B	3506, 23 m	*Elphidium excavatum*	0.036	Last interglacial (Feyling-Hanssen 1982). Questioned by present authors
BAL 106	Statfjord B	3506, 23 m	*Cibicides lobatulus*	0.048	
BAL 716	Fjøsanger Gravel K	256	*Bulimina marginata*	0.088	ca. 120,000 (last interglacial, Sejrup (1987)

(Mangerud et al. 1981) a sample of *B. marginata* gave 0.088 (Table 5). From the interglacial recorded by Feyling-Hanssen (1981) in core 2501 on Statfjord *B. marginata* gave 0.078 and *E. excavatum* 0.09. Because the arctic species may have been reworked into these interglacial assemblages we rely mostly on *B. marginata*, which provide a good correlation between the sites. Similar ratios have also been obtained in samples of *B. marginata* from several sites of last interglacial age in Denmark (Knudsen & Sejrup 1988). However, the samples analyzed from core 3506 at Statfjord B (Table 5) contradict the conclusion of Feyling-Hanssen (1982) that the fauna recorded at 23 m depth could be of last interglacial age. The ratios from this core, 0.036 in *Elphidium excavatum* and 0.048 *Cibicides lobatulus*, rather suggest a Late Weichselian age.

Subpolar planktonic fauna like that recorded in the Troll Interglacial has only been recorded in sediments of Holocene or 5e age in Norwegian Sea core (Kellogg 1976, 1980) which possibly span the last 450 ka. The degree of isoleucine epimerization measured in the late glacial samples from the Troll area strongly suggest that the ratios obtained on the Troll Interglacial cannot represent interglacial sediments older than 5e. This, together with the similar ratios obtained on sediments of last interglacial age in Denmark (Knudsen & Sejrup 1988), bring the present authors to conclude that the Troll Interglacial is correlative with both 5e *and* the Eemian. This supports the correlation of these stages by Mangerud et al. (1979).

Lithozone 5

Two samples of *Elphidium excavation* have been analyzed from lithozone 5 in core 5.1/5.2 (0.189 and 0.220). The assemblages in both of these

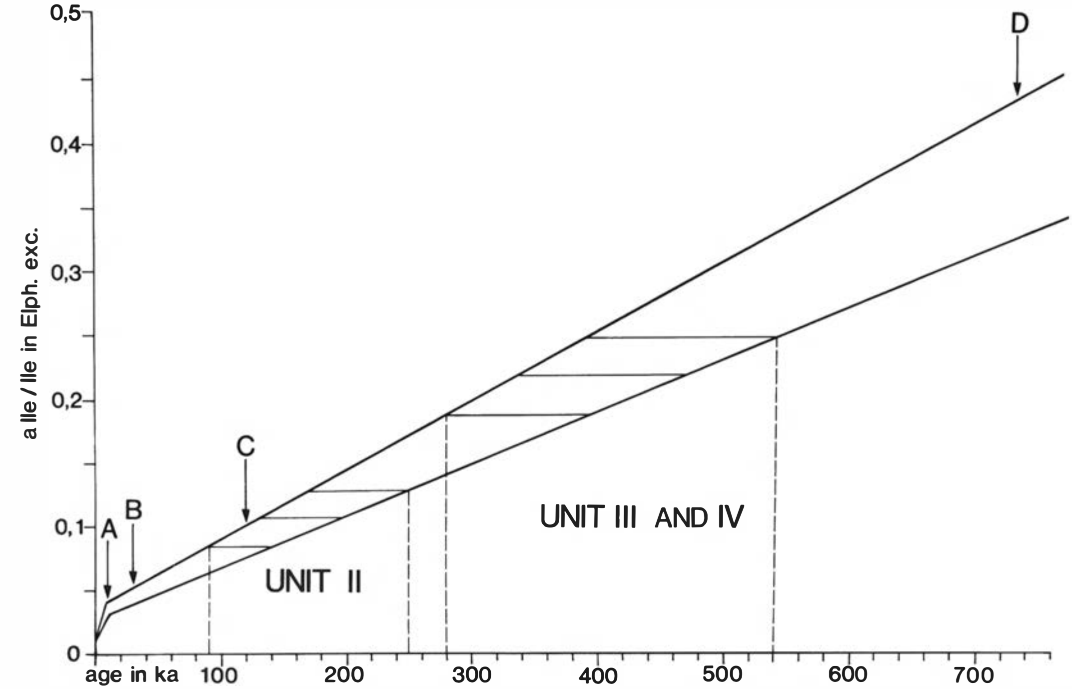

Fig. 7. Age estimates based on calibrated samples of *Elphidium excavatum*. The mean values obtained on samples of *Elphidium excavatum*, with one standard deviation, from seismostratigraphic units II and III + IV in the Troll area are marked. It is emphasized that *Elphidium excavatum* in these sediments is largely influenced by reworking, so these estimates should only be regarded as maximum estimates. The calibration points are as follows: A – radiocarbon-dated samples from gravity cores raised from the Norwegian shelf (Sejrup et al. 1984). B – radiocarbon-dated samples from the North Sea Plateau (Sejrup et al. 1987). C – analysis of material of last interglacial age from the North Sea (this work Table 5) and Denmark (Knudsen & Sejrup 1988). D – highest ratio obtained on sediment of Bruhnes age and lowest of Matuyama age in core 81/26 from the Fladen Ground (Sejrup et al. 1987).

samples were dominated by arctic taxa and lay above the ameliorated fauna dominated by *Bulimina marginata*. Assuming that these ratios are derived mostly from *in situ* specimens, it is possible to make preliminary age estimates by comparing with deposits of known age in the North Sea region. Sejrup et al. (1987) recorded ratios between 0.3 and 0.4 close to the Bruhnes/Matuyama boundary (730 ka) in the Fladen Ground area. These ratios suggest that an inflection point in the apparent rate of the isoleucine epimerization reaction must occur at ratios between 0.1 and 0.4. Such inflection points have been observed in both long cores from the deep sea and in pyrolysis experiments (King & Neville 1977; Müller 1984; Jansen & Sejrup 1986). This indicates that direct extension of the rate of epimerization observed up to 0.1 (last interglacial) further back in time on the Troll Field can only serve as a rough approximation of a minimum age. Linear extrapolation will always predict ages younger than the actual age. The effect of the geothermal gradient will also tend to cause age estimates to be too high if we use calibration points obtained on material closer to the surface. In Fig. 7 the mean values with one standard deviation for all the analyses done on *Elphidium excavatum* in Units III + IV are plotted on a graph based on four calibration points within the region. This suggests an age between 280 and 540 ka for the reworked fauna in L4 and *in situ* fauna in L5. If we assume that the *B. marginata* assemblage just below (the sediment composition is very similar) was deposited in the same marine episode, the age of this part would not be much higher. Samples of *Elphidium excavatum* from Holsteinian deposits in Denmark have yielded ratios close to 0.145 (Knudsen & Sejrup 1988). Taking into account the variable temperature history experienced by samples within lithozone 5, we cannot exclude a Holsteinian age. The fauna does not contradict a Holsteinian age, because typical Holsteinian marine faunas in NW-Europe usually appear to be colder than either the Eemian or the Holocene.

Amino acid ratios in lithozones L2 and L4

Because of the high content of reworked foraminifera the ratios obtained from these units may pre-date sedimentation. The relatively large variation in ratios within each of the units supports our interpretation that the faunal assemblages are of mixed ages. However, it is still possible to conclude that most of the reworked material in L2 must be of younger origin than the material in L4 because of the step in aIle/Ile ratios from c. 0.11 to c. 022 (Fig. 7). It should also be kept in mind that these units may represent several episodes of sedimentation. More detailed sedimentological investigation of lithozones L2 and L4 might give more conclusive evidence concerning the genesis of these units. However, the present authors would like to point out that both L2 and L4 are very different from the sediments in the lower part of L1, which undoubtedly must be of glacial marine origin. Therefore, we presently favor the interpretation that major parts of these units are true tills. The top of unit II (lithozone 2) possibly represents the retreat of the icefront from its maximum extent in the Late Weichselian on the North Sea Plateau (Sejrup et al. 1987). Green et al. (1985) and Godvik (1981) interpreted the top of seismic unit II as the change from the deposition of till to glacial marine sediments.

Conclusions

An amino acid stratigraphy is established for the upper c. 120 m of the sediment sequence in the Norwegian Channel NW of Bergen. The amino acid data support cross-core correlations based on the interpretation of seismic data. By comparing the degree of isoleucine epimerization in cores from the Troll Field with samples of known age in the region, it is concluded that the lower

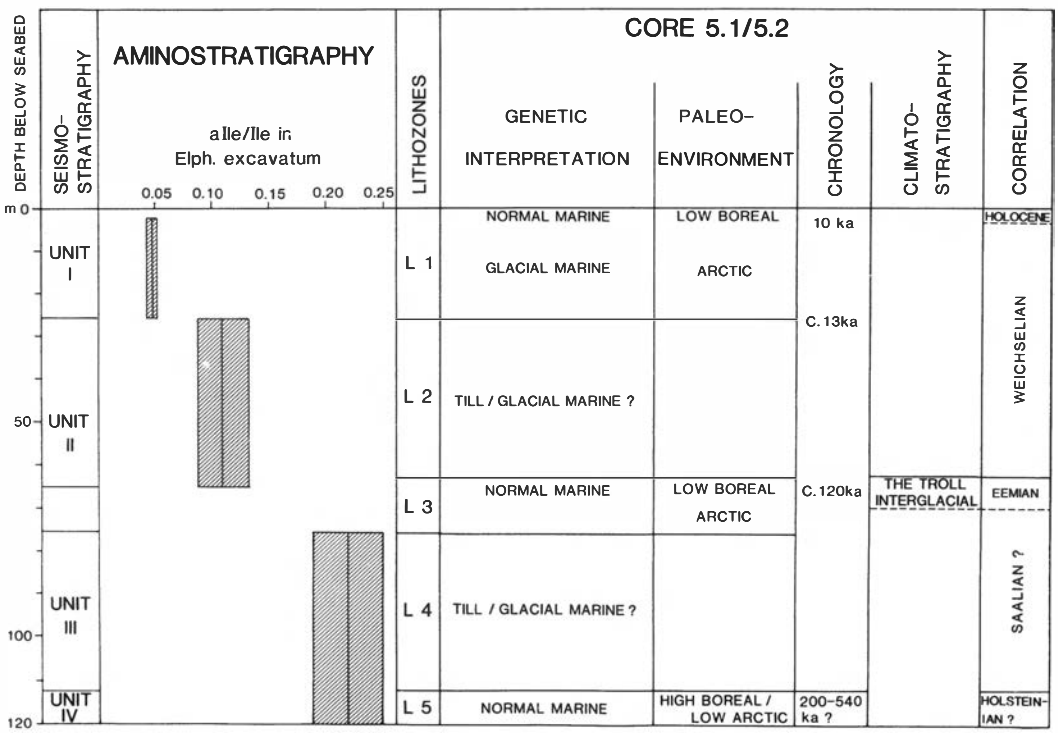

Fig. 8. Stratigraphy, paleoenvironment and correlation of the younger Cenozoic deposits in the Troll area.

units penetrated by core 5.1/5.2 cannot be much older than c. 540 ka and that they probably have an age closer to 200 ka. This conclusion contradicts the results of Rise et al. (1984), who proposed that the reflector found at c. 70 m represented the top of the Late Pliocene in the area. The form of the Norwegian Channel is primarily controlled by the regional unconformity, top unit V in Fig. 2. The data presented here and the results of Butenko et al. (in press) suggest that the erosion of this major topographical element dates to a period at least prior to 200 ka and after or during the Late Pliocene. The main results of the stratigraphical investigation of core 5.1/5.2 are given in Fig. 8.

Between c. 120 and 112 m a normal marine sediment with high boreal to low arctic foraminiferal assemblage was found. The age of this unit might be somewhere between 200 and 300 ka. A Holsteinian age cannot be excluded.

Between 112 and 72 m depth an unsorted sediment with mixed foraminiferal faunas suggests that the region was glaciated at some time between 400 and 120 ka. Parts of this unit may represent the same glacial advance as Diamicton D of probable Saalian age in core 81/26 from the Fladen area (Sejrup et al. 1987).

In a sorted fine-grained unit between 62 and 72 m a low boreal benthonic and subpolar planktonic foraminiferal fauna was recorded. This climatic event is informally designated the Troll Interglacial. Based on foraminiferal assemblages and amino acid ratios, the Troll Interglacial is correlated with the last interglacial; the Eemian.

Between 62 and 25 m a complex unit with coarse-grained sediments and mixed faunas is found. The upper part of this unit is interpreted to represent the retreat of the Scandinavian ice sheet close to 13 ka.

Most of the upper 25 m consists of glacial marine sediments deposited between 10 and 13 ka. The Holocene is only represented by a few meters of sediment on the top.

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