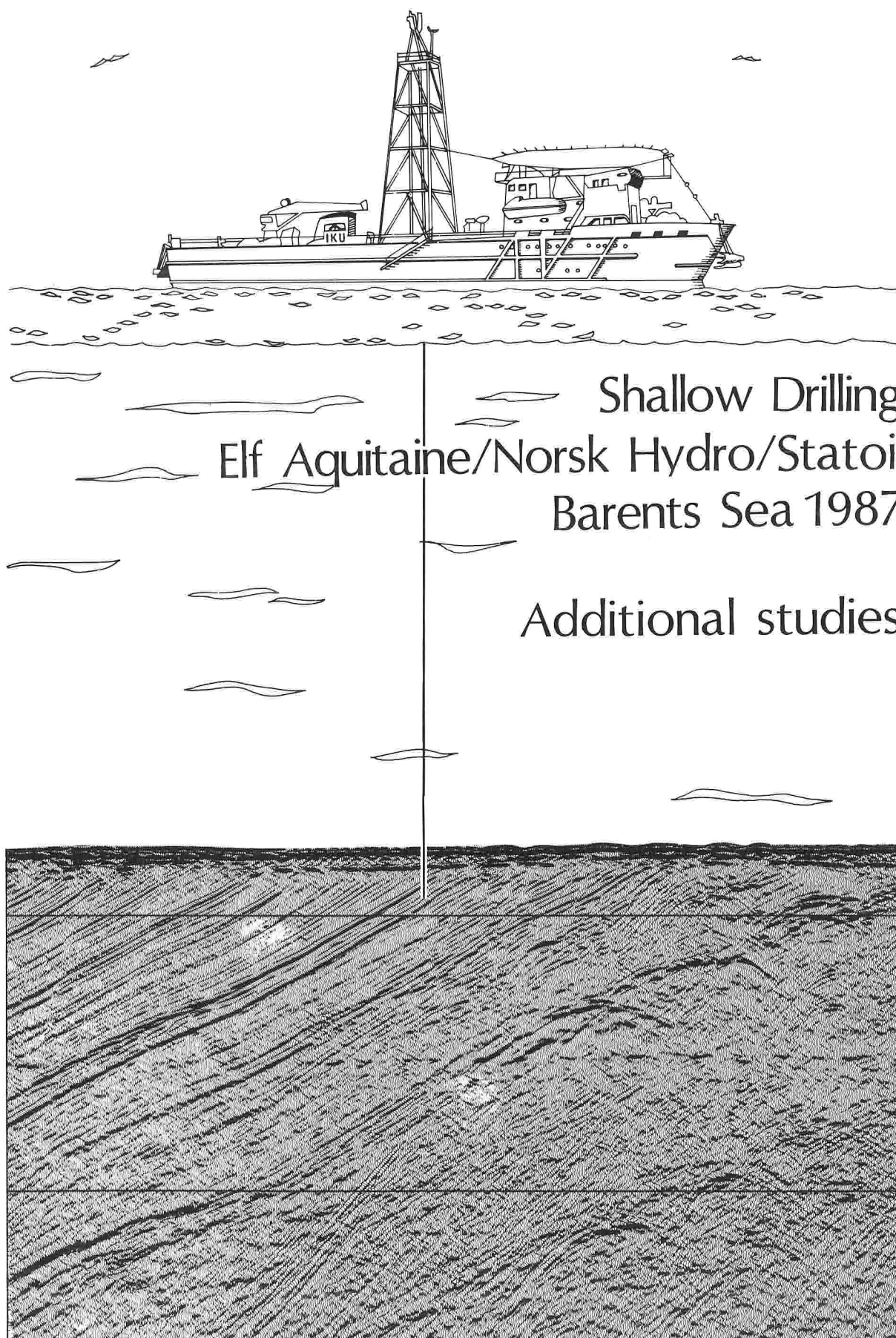




Shallow Drilling
Elf Aquitaine/Norsk Hydro/Statoil
Barents Sea 1987
Additional studies

PREFACE

This volume contains three separate reports which are additional studies to what was reported in the main data report called "Shallow drilling Elf Aquitaine/Norsk Hydro/Statoil Barents Sea 1987".

They comprise:

- Bivalve studies of four of the cores and a correlation between one of the cores and two other IKU cores in the Nordkapp Basin of the Late Jurassic black shale unit.
- Isotope analysis of glauconite in the cores 7231/07-U-01 and 7324/07-U-01.
- Rock mechanical studies of core 7323/12-U-01. (Reported together with other analyses within the project "Shallow drilling Barents Sea 1987". (See Appendix 17.8).

All results in the present project are thus reported in the "Main data report" of 22 December 1987 and this report.

REPORT

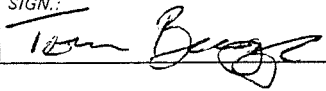
REG. NO.:
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REPORT TITLE:

Bivalve fauna, biostratigraphical comments and black shale correlation of some Barents Sea Late Jurassic-Cretaceous boreholes

REPORT NO.: **21.3435.00/03/88**
AUTHORS:

Nils Aarhus, Simon Kelly and Andrzej Wierzbowski

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CLIENT: Elf Aquitaine Norge A/S, Norsk Hydro a.s, Den norske stats oljeselskap a.s. (Statoil)				
SUMMARY: This report is a part of the project: "Shallow drilling Elf Aquitaine/Norsk Hydro/Statoil Barents Sea 1987". It deals with two items; bivalve macrofossils from some of the cores and correlation of Late Jurassic black shales in core 7231/01-U-01 with similar shale intervals in two other cores in the Nordkapp Basin. Bivalve macrofossils from the following cores were examined: Core 7231/01-U-01, 7231/04-U-01, 7230/05-U-09, 7324/07-U-01. Specimens of stratigraphic value have only been found in 7231/01-U-01 and 7324/07-U-01, and the biostratigraphy of these cores is commented and slightly revised. Late Jurassic black shale intervals in three shallow coreholes from the Nordkapp Basin have been correlated. The Late Oxfordian is thinning from approximately 10 m in 7227/08-U-03 and 7230/05-U-02 to about 3 m in 7231/01-U-01 whereas the thickness of the Early Kimmeridgian is more uniform around 5 m (somewhat thinner in the west, in 7227/08-U-03). The total thickness of the Late Kimmeridgian <i>A.mutabilis</i> and <i>A.eudoxus</i> Zones is between 5.25 and 7.42 m in the west (7227/08-U-03) and minimum 12.28 m in the east (7231/01-U-01).				

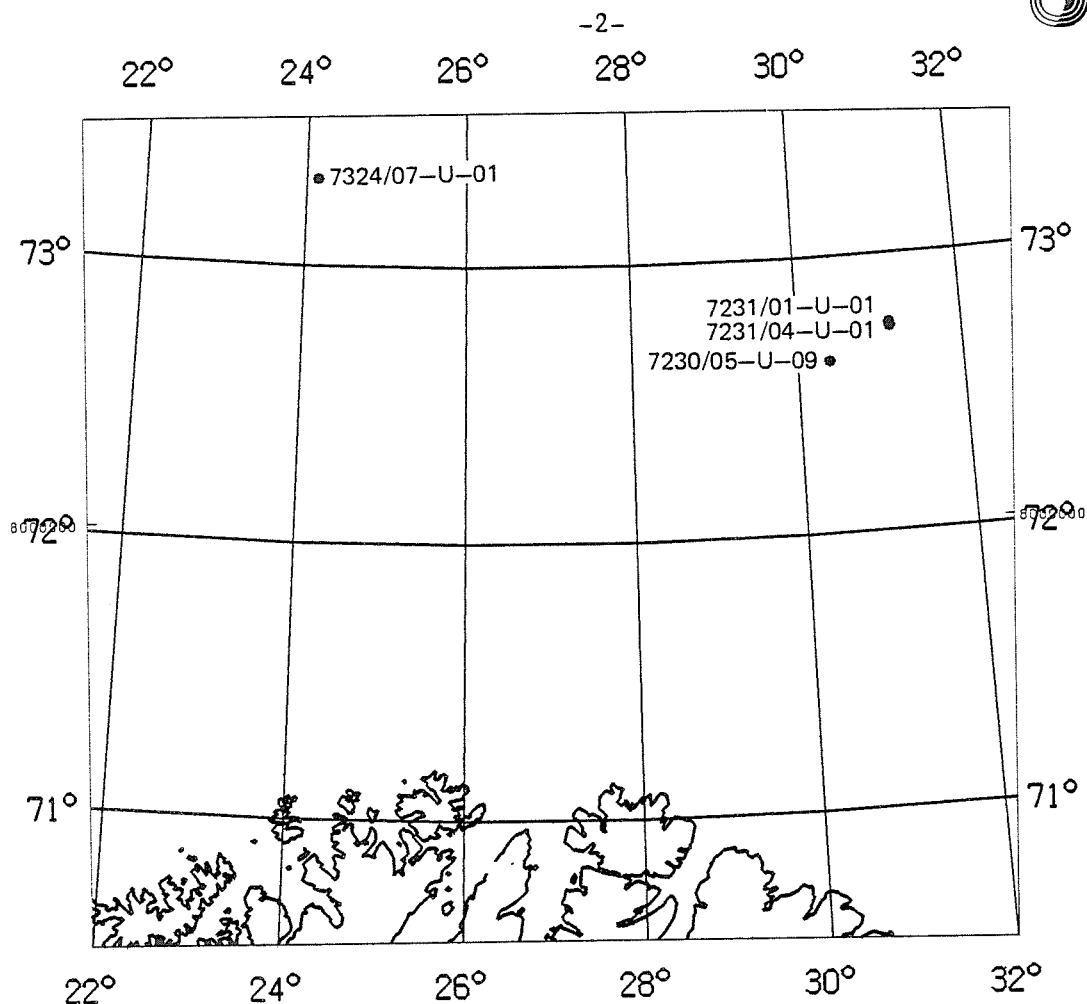
KEY WORDS:	
Barents Sea	Oxfordian
Bivalves	Kimmeridgian
Biostratigraphy	Cretaceous

Mesozoic bivalves from Barents Sea 1987 boreholes, with some stratigraphical comments

Introduction

The three cores in the Nordkapp Basin (7231/01-U-01, 7231/04-U-01 and 7230/05-U-09) and one of the two cores at the Dia-Structure (7324/07-U-01) have been examined for bivalves. The work was carried out by Dr. Simon Kelly, Department of Earth Sciences, Downing Street, Cambridge CB2 3EQ, England at a visit to IKU, Trondheim during the period 13-18 January 1988. Many specimens had been recognised and placed aside prior to Kelly's examination, but in a few cases he went back to see cores and obtained further specimens from horizons where it was potentially possible to obtain a more refined stratigraphy. The identifications were based mainly on previous identifications made on similar cores from the Barents Sea, and there was only a minimal amount of literature examined during the course of the visit. Since returning back to England, Kelly has been able to confirm these identifications by comparing latex casts with published photographs and determinations of other largely Arctic faunas.

For each core the macrofauna is identified at specific levels and at the end of each core section conclusions are drawn about the stratigraphy and any other general remarks are made.



Location of shallow coreholes here examined for bivalves.

Onychites which are interpreted as the hooks from the arms of belemnites or other coleoids are particularly common at some levels and specimens from Core 7231/01-U-01 at 70.99 and 82.97 m were borrowed for examination by Dr. Peter Doyle, British Antarctic Survey, High Cross, Madingley Road, Cambridge. The only bivalve material that was borrowed were heterodonts from 7230/05-U-09 at 30.67 m, so that Kelly could attempt better identification after preparation of the hinge regions.

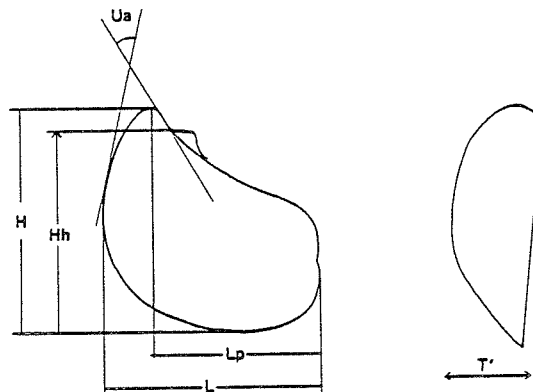
The following abbreviations or symbols have been used:

LV = Left Valve
RV = Right Valve

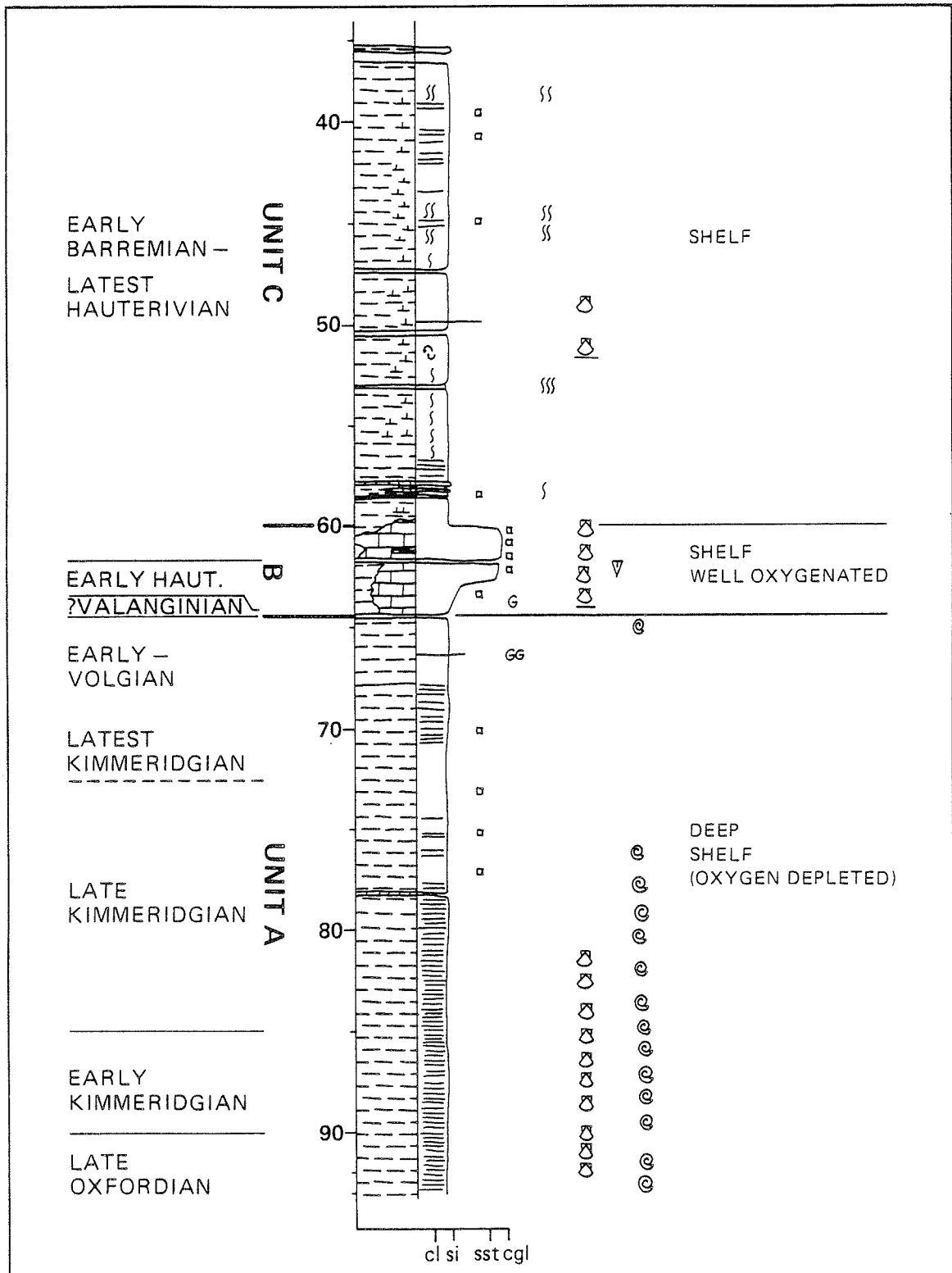
Dimensions (see figure):

All values are given in millimetres

L = Length
Pl = Posterior Length
Ol = Oblique Length
H = Total Height
Hh = Height of hinge
T' = Thickness (single valve)
Ua = Umbonal angle



CORE 7231/01-U-01



- 62.21 *Buchia keyerlingi/sublaevis*. Inflated, articulated LV & RV, incomplete, H 45, in limestone facies.
RV smooth to 15 mm from umbo.
LV moderately inflated, regular strong commarginal folds
L, 26, H 34.
- 62.46 Belemnite, approximately mid-rostrum, subcylindrical, diameter c9 mm.
- 63.28 *Buchia sublaevis*. Incomplete distal part of large LV & RV in occlusion, ornament low and commarginal.
- 63.36 *Buchia sublaevis* Incomplete large valve and two juveniles LV & RV.
- 63.40 *Buchia sublaevis*. LV, slightly elongate and crushed internal mould. L25, H 29+, Ua 80.
- 63.43 *Buchia* sp. Fragments of several individuals.
- 63.49 *Buchia* sp. RV, small, smooth (?*sublaevis*) Fragments of three large valves, poorly preserved.
- 63.57 Terebratulid brachiopod. Smooth, with slight plication, articulated, L 12, T 15 (both valves). Shell with traces of fine bryozoan borings - *Talpina*
- 63.62 *Buchia* sp. LV, smooth with trace of commarginal ornament close commissure. L 9.5, H 12.5
- 63.98 *Buchia* cf. *keyserlingi*. LV, large, moderately ribbed.
- 64.08 *Buchia keyerlingi* LV coarsely ribbed umbonal region of broken individual.
- 64.10 *Buchia* sp. RV, fragment of large valve, H 38+.
- 64.17 *Buchia* sp. LV, poor, H <10.
- 64.27 *Buchia* sp. Broad, coarsely ribbed, crushed. Bottom of limestone facies.
- 64.64 *Onychites* sp. in black shale
Fish remains
- 64.65 Fish remains in black shale
Onychites sp.
- 70.99 Fish remains in black shale
Onychites. At least 6 good hooks. Sample borrowed for P. Doyle (British Antarctic Survey, Cambridge).

- 72.02 Mollusc fragments, large, fragmentary, larger than width of core 45 mm.
Ribbed ammonite.
- 76.65 *Buchia concentrica/tenuistriata* group. 2 LVs with radial and concentric ribbing, very crushed with other *Buchia* fragments.
- 76.90-77.34 Black shale without benthos, occasional fish debris and *Onychites*
- 77.45-78.05 Black shale without benthos, occasional fish debris and *Onychites*
- 77.70 Lignite. 1-2 mm thick layer.
- 79.39 *Buchia* sp.
- 79.62 *Buchia* sp. Large
- 80.80 *Buchia concentrica/tenuistriata* group. Very squashed with radial and commarginal ornament.
- 81.02 *Inoceramus* sp. Fragment of large prismatic shell.
- 81.10 *Buchia concentrica* Fragments of large individual.
- 81.32 *Inoceramus* sp. Fragment of large prismatic shell.
- 81.33 *Inoceramus* sp. Fragment of large prismatic shell.
- 81.89 *Camptonectes (Mclearnia)* sp. juv.
LV L 10.5 H 10
RV L 6.5 H 7
- 81.99 *Inoceramus* sp. Fragment of large prismatic shell.
- 82.05 *Buchia concentrica* 4 RVs and other fragments.
- 82.06 *Buchia* sp.
Camptonectes (Mclearnia) sp. juv. RV L 13 H 14.5
- 82.29 *Inoceramus* sp. Fragment of large prismatic shell.
- 82.39 *Inoceramus* sp. Fragment of large prismatic shell.
Camptonectes (Mclearnia) sp. juv. LV L 5, H 5, RV L 8, H 7.
- 82.76 *Camptonectes (Mclearnia)* sp. juv. L 10, H 9,5.
- 82.97 *Onychites* sp. Large (Borrowed for P. Doyle)

- 83.20 *Buchia concentrica/tenuistriata* group. RV with other *Buchia* fragments.
Fish scale.
- 83.52 *Buchia concentrica/tenuistriata* group. RV and LV, poor.
- 84.11 *Amoeboceras* sp.
Campionectes (Mclearnia) sp juv. RV L 13.5, H 11,5.
- 85.82-85.84 *Buchia* sp. Incomplete large valve. *Oxytoma inequivalve*. LV
L 21, Lp 14, H 16
- 85.98 *Buchia concentrica* LV missing anterior and umbo, but part of
large individual L about 55 mm (estimate)
?Inoceramid. Fragments of prismatic shell.
- 86.32 *Buchia concentrica* RV, showing excellent contrast between
juvenile shell and adult shell at about 10mm from beak.
Radial ornament only in juvenile, then radial with
commarginal folds with well preserved lamellae in adult
portion of shell.
- 86.50 *Buchia* sp. LV distal portion
Nicaniella sp. LV compressed composite mould, L 3, strong
commarginal ribs, obliquely compressed lunule.
Ghost impressions of ?bivalve spat, poorly preserved.
- 87.40 *Buchia* sp. RV at centre with portions of 5 surrounding
individuals cut by drill bit. All articulated.
- 87.67 *Buchia* sp. LV, incomplete very large individual cut by
drill bit.
?Heterodonts, ghost traces.
Fish scales.
- 89.95 *Buchia concentrica* RV, complete internal mould L 24, Lp 16.5,
H 21.
- 90.06-90.1 *Buchia concentrica* Several LV & RVs maximum dimension 3.5 - 5
mm *Buchia* sp. marked #, incomplete internal mould of a
large LV with impressions of numerous small spat (<imm)
attached to surface. Benthic island assemblage.
- 90.45 *Buchia concentrica*. 2 LVs with several small valves <5mm and
some spat visible on large valves.
Fish scale.
- 90.57 *Buchia* sp. fragments.
Heterodonts, elongate cyprinids about L 12 mm. About 9
isolated poorly preserved valves.
Amoeboceratid fragments.
Fish scale.

- 91.29 *Liostrea plastica* (Trautschold). Exterior of two calcitic shells, smooth exterior.
Buchia sp. 2 LVs of young strongly ribbed valves with posterior auricle
- 91.68 *Buchia* sp. 2 RVs, large internal moulds with some shell attached, weak radial ribs at c10 mm from beak and commarginal ribs.
Cyprinids. 3 poor composite moulds
- 91.78 *Buchia* sp. 4 poorly preserved moulds
- 92.19 *Buchia* sp. About 5 LV and RVs in occlusion and compressed. LV & RVs with strong radial and commarginal ornament.
- 92.33 *Buchia concentrica*. Incomplete crushed LV interior with fragments of another valve.
- 92.38 *Buchia concentrica*. RV interior, crushed flat, radial and commarginal ornament. L 25, Lp 19, H 24, Hh 22.
- 92.43 *Buchia concentrica*. RV, damaged RV about 10 mm long.
Heterodont, RV
- 92.48 *Buchia concentrica*. Common
Heterodont, 10 mm
Ammonite fragment showing broad tubercles.

Stratigraphy

Buchia concentrica (J.de C. Sowerby 1829) has been recorded from the interval 92.48 - 81.10 m. The species therefore occurs throughout the Late Oxfordian, Early Kimmeridgian and into the lower part of the middle Late Kimmeridgian *A. eudoxus* Zone in this core. Zakharov (1981) gave the total range as *obliteratum* to *borealis* Zones (Early Oxfordian to end of Early Kimmeridgian), but the species is most typical of the latest Oxfordian and particularly the Early Kimmeridgian.

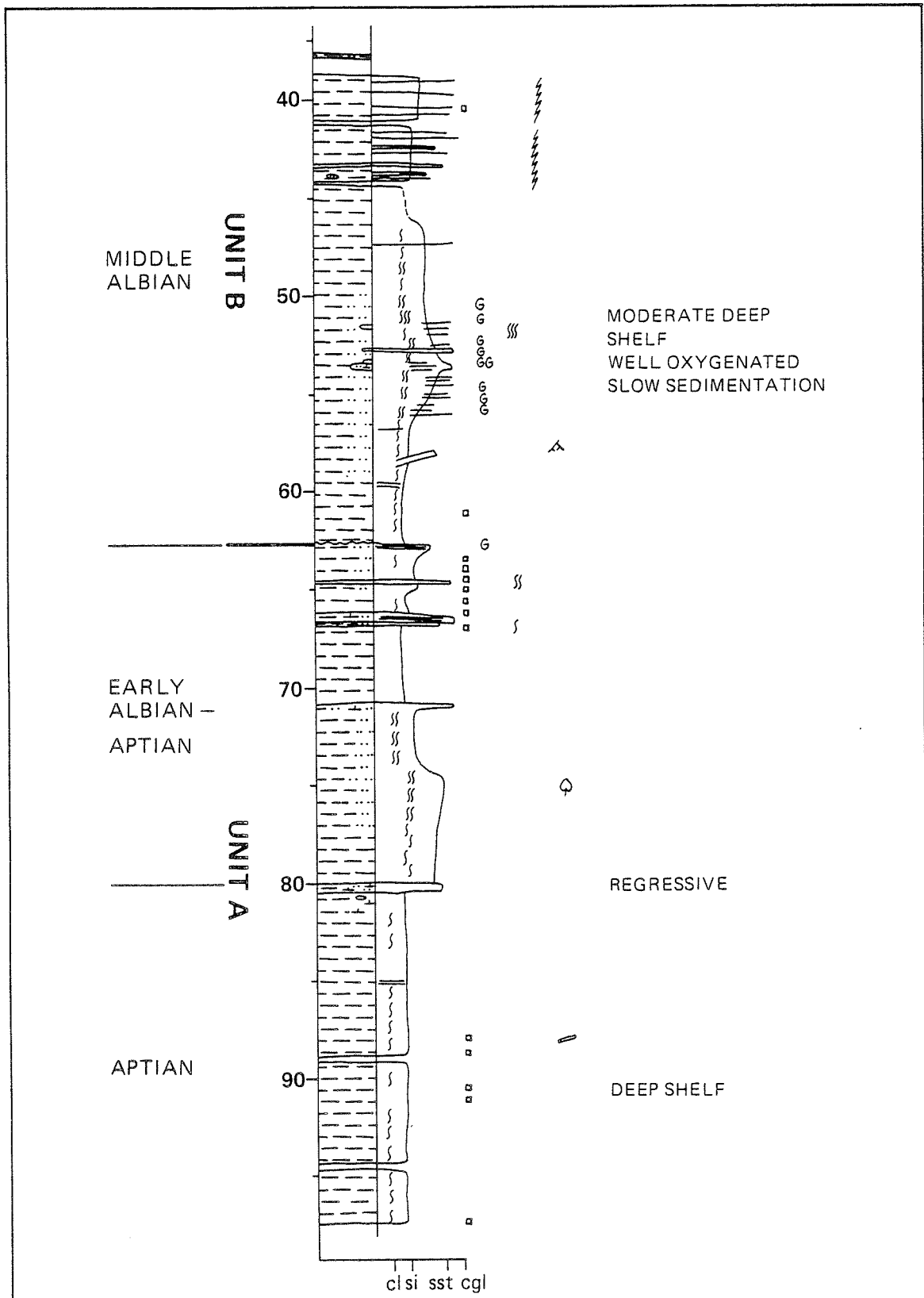
The record of *Buchia keyserlingi* (Trautschold 1868) at 64.08 m suggests that Valanginian strata are also represented by a few centimetres in the corehole. *B. keyserlingi* is a typical boreal Early Valanginian to Early Hauterivian indicator, (*klimovskiensis* to *versicolor* Zones), but most characteristic in the late part of the Early Valanginian.

Buchia sublaevis occurs between 63.40 and 63.28 m with a questionable specimen at 63.49 m and a representative of the *B. keyserlingi/sublaevis* group at 62.21 m. *B. sublaevis* ranges from the Late Valanginian to the Late Hauterivian, *Dichotomites*

to *decheni* Zones (Zakharov 1981). In Russian terms the overlap of the two species is typical of the Late Valanginian and Early Hauterivian, but in the margins of the southern North Sea Basin, the association is restricted to the Early Hauterivian.

Our Early Hauterivian dating based on foraminifera at 63.79 m is consistent with the observed change in the *Buchia* fauna from an assemblage exclusively with *B.keyserlingi* at 64.08 m (possibly late Early Valanginian) to an assemblage mainly with *B.sublaevis* from 63.49 m to 62.21 m. The stratigraphy on the simplified log above has been slightly changed from the version in the main report due to the possible presence of a thin slice of Valanginian strata.

CORE 7231/04-U-01

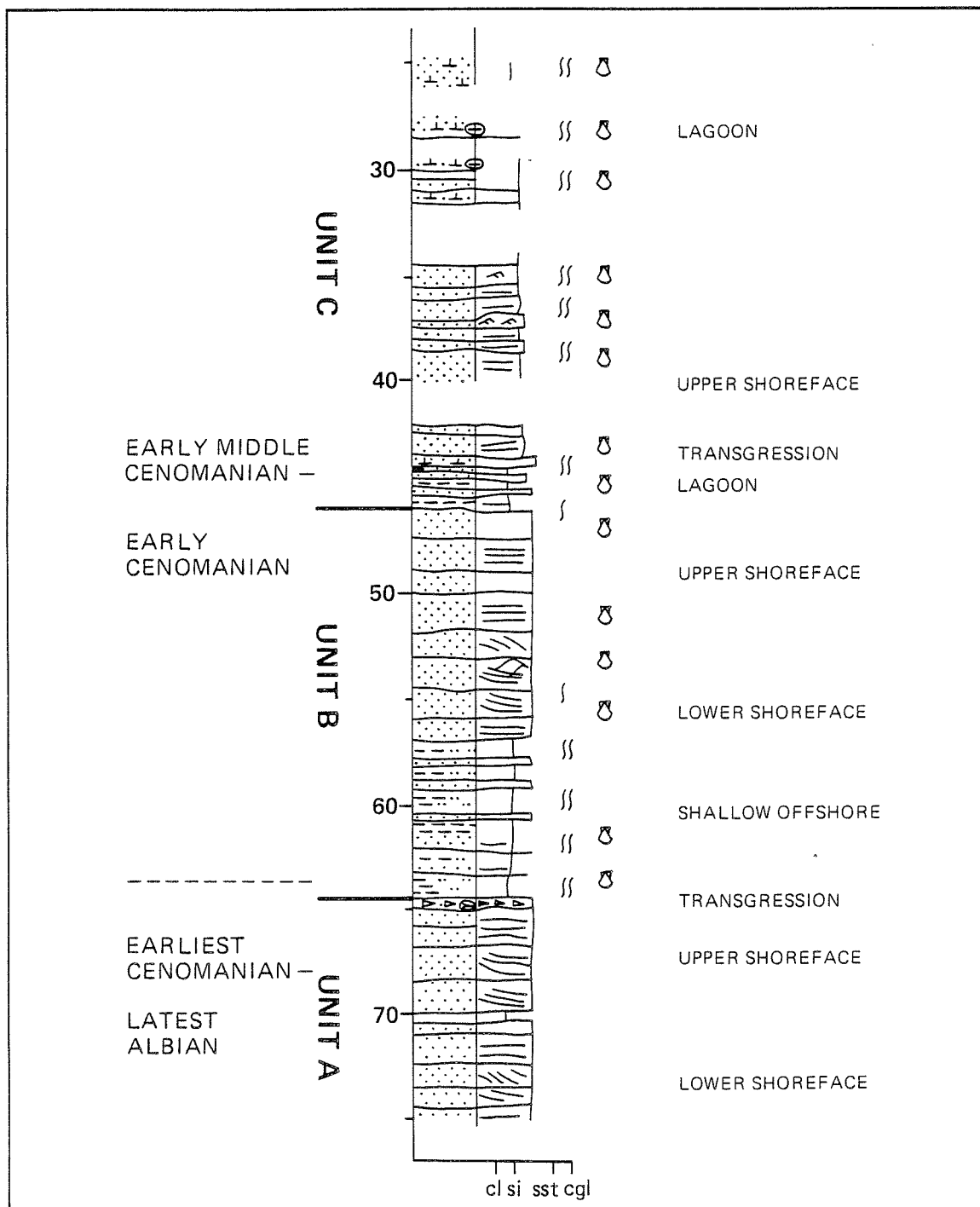


- 68.48 ?*Plagiosoma* sp. Large 50 mm fragment of shell, whole shell maximum dimension estimated 100 mm. Ornament of coarse radial ribs which have slight lateral irregularities. Homogeneous-weakly shaley clay mudstone with mica flakes.
- 74.40 Molluscan fragment, undetermined, but probably bivalve in bioturbated clayey siltstone.
- 76.77 ?Worm tubes with indeterminate shelly remains
- 77.89 Indeterminate shelly remains.

Stratigraphy

These additional studies have not brought forward any new evidences for the dating of the core, and the datings given in the main data report (Aarhus et.al. 1987) are still valid.

CORE 7230/05-U-09



- 25.74 Heterodont, LV, thick shelled and inflated, L 25, prosogyrate, with slightly overhanging umbonal infilling.
- 28.85 *Falcimylus* sp.
Undetermined heterodonts.
- 38.76 Serpulid? worm tubes in bioturbated glauconitic sandstone. Thin shelled bivalves.

- 30.67 Cyprinid, RV, thick shelled, elongate, umbo prosogyrate and located well to anterior, small beak, weakly differentiated lunule and escutcheon. Recrystallised aragonitic shell. L 53+, Lp 33?, H 42+, W' 15.
Falcimylus LV and RV in occlusion, partly destroyed by coring. Falcate with sharp carina, shell surface smooth.
Calcareous cemented fine glauconitic sandstone with glauconite concentrated in burrows. Many large whole shells.
- 43.90 Heterodonts. Thick shelled, medium sized, 2-3 cm. Too fragile for preparation. Fine dark glauconitic sandstone
- 44.22 Heterodont. Large aragonitic, 40 mm max dimension
Plastic mudstone.
- 46.95 Heterodont. Thick shelled
Fine muddy glauconitic sandstone, poorly consolidated

Stratigraphy

Nothing new has been noted of stratigraphic value. *Falcimylus* ranges from Middle Jurassic to Late Cretaceous.

The diagram illustrates a geological column for the latest Albian period, showing three main units: Unit C, Unit B, and Unit A. The column is marked with 'LATEST ALBIAN' and 'Inoceramus anglicus'. A scale bar at the bottom indicates 'clsi' and 'sstcgl'.

- Unit C (80-90):** Labeled 'DEEP SHELF' and 'TRANSGRESSION'. It contains a 'DEEP SHELF' section and a 'TRANSGRESSION' section.
- Unit B (90-100):** Labeled 'DEEP SHELF', 'TRANSGRESSION', and 'CURRENT INFLUENCED SHELF'. It contains a 'DEEP SHELF' section, a 'TRANSGRESSION' section, and a 'CURRENT INFLUENCED SHELF' section.
- Unit A (100-120):** Labeled 'REGRESSIVE DEEP SHELF', 'TRANSGRESSION', 'REGRESSIVE', 'STORM INFLUENCED', and 'SHELF'. It contains a 'REGRESSIVE DEEP SHELF' section, a 'TRANSGRESSION' section, a 'REGRESSIVE' section, a 'STORM INFLUENCED' section, and a 'SHELF' section.

The column is marked with 'LATEST ALBIAN' and 'Inoceramus anglicus'. A scale bar at the bottom indicates 'clsi' and 'sstcgl'.

Oxytoma pectinata. LV shell interior. Exterior visible through translucent shell. Fine ribbing and not strongly differentiated, large posterior auricle, oblique.

Bioclastic fine grained limestone with burrows of fine quartzose material, glauconite.

- 75.82 *?Inoceramus* sp. Small fragment of umbonal region of thin shelled (?small) individual, crushed. Grey mudstone, fine, with black <1 mm wide subhorizontal burrows, flattened.
- 78.72 *Inoceramus anglicus*. 4 specimens including:
LV, shell interior and internal mould
LV & RV, articulated but open, cut by drill bit.
LV, shell exterior
- 80.84 *Oxytoma pectinata*, LV & RV
- 89.54 *Oxytoma pectinata*
- 105.59 *Inoceramus anglicus*. Internal mould and shell interior, incomplete at ventral margin and umbo, bifurcation of coarse commarginal ribs towards posterior
Oxytoma pectinata. Juvenile
Grey claystone, fine <1 mm burrows with pyrite
- 106.83 *Inoceramus anglicus* LV & RV articulated, but open. Coarse commarginal folds.
Grey claystone as 105.59

Stratigraphy

In the main data report 21.3435.00/02/87 we had conflicting macrofossil and microfossil dating evidence. The recorded assemblages of nannofossils, foraminifera and dinoflagellate cysts pointed to a latest Albian age whereas some poorly preserved ammonites were suggestive of an age close to the Early/Middle Albian boundary. In the report we chose the younger alternative because three independent fossil groups supported this.

We informed Dr. Ryszard Marcinowski, Warsaw University, who did the ammonite work, about the controversy. In his reply Marcinowski rules out the possibility that our correlation problems could be of paleobiogeographical nature as the stratigraphic distribution of *Ottohoplites* and *Cleoniceras* seems to be independent of biogeography. He rather stresses the poor preservation and difficulties in determining the material. In addition homeomorphy between the Early/Middle Albian genera *Ottohoplites* and *Cleoniceras* and some representatives of the Late Albian genera *Pleurohoplites* and small slightly ornamented *Anahoplites* or *Lepthoplites* complicate stratigraphical conclusions. The specimens earlier determined as *Ottohoplites* sp. also show similarities to the Cenomanian schloenbachid *Styracoceras balduri* (Keyserling). The genus *Styracoceras* Hyatt 1903 is poorly known because it occurs only in the Pechora

Basin (Luppov & Drushchic 1958, p. 115, pl. 55, fig. 5).

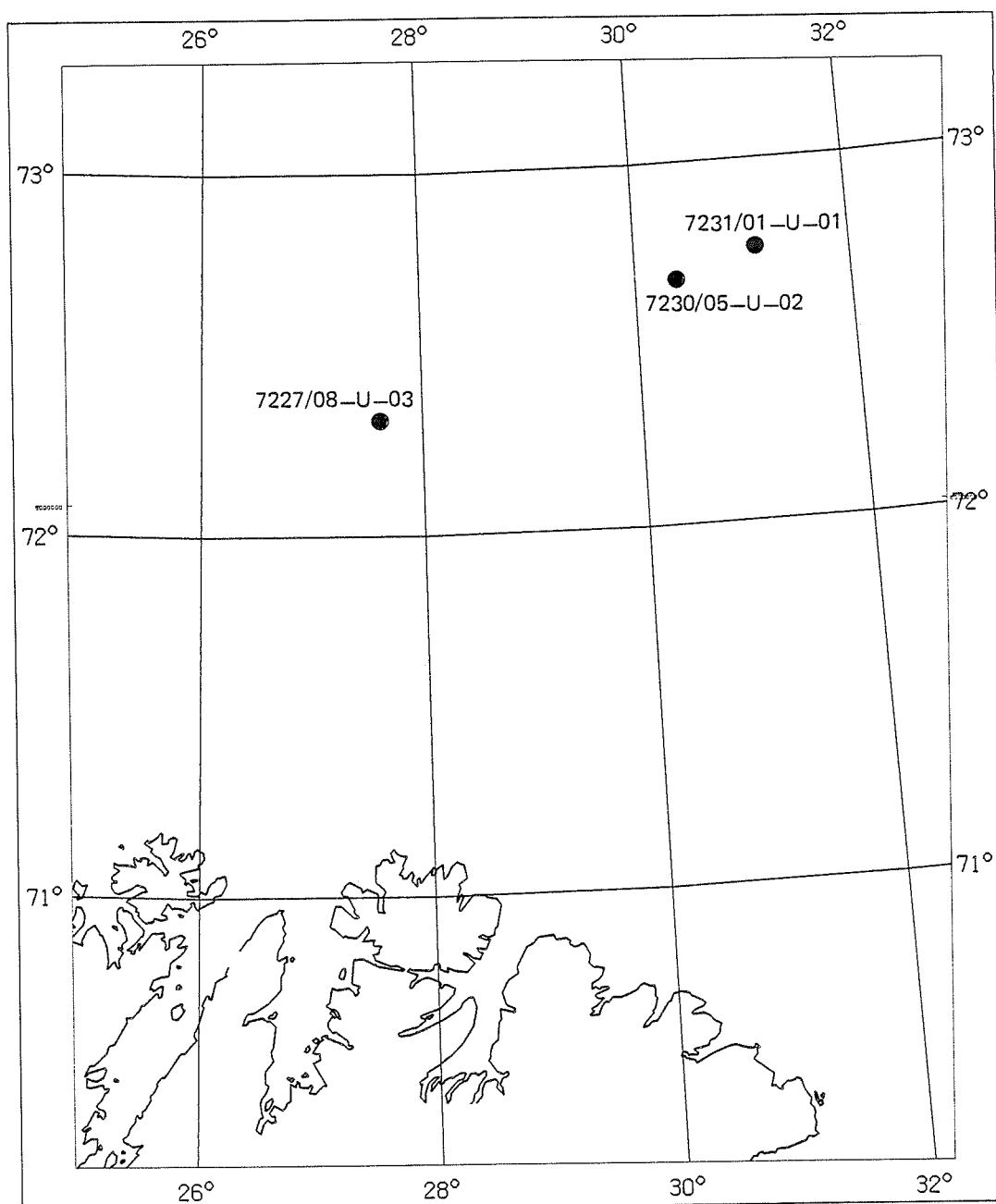
The Middle to Late Albian *Inoceramus anglicus* Woods (1911) occurs in the interval 106.83 - 78.72 m. *Inoceramus anglicus* is widely ranging in Middle to Late Albian deposits of England (type occurrence), Greenland, Alaska, Southern and Far Eastern USSR, Japan. There are some records of Cenomanian age from Japan, but they remain to be substantiated (Kauffman 1977). Imlay (1961) used the name *Inoceramus anglicus* in the systematic section of his article but on p. 3, he indicated that Matsumoto had regarded this species as a junior synonym of *Inoceramus comancheanus* Cragin. An initial investigation of the literature indicates that Cragin's name does not appear to have been accepted in later literature.

This new information is in good agreement with our latest Late Albian dating based on calcareous nannoplankton, foraminifera and dinoflagellate cysts, but we will still not exclude the possibility that this core straddles the Albian/Cenomanian boundary.

Correlation of Late Oxfordian and Kimmeridgian black shales in three Barents Sea shallow coreholes.

Introduction

Late Jurassic black shales have been penetrated in the IKU shallow boreholes 7227/08-U-03, 7230/05-U-02 and 7231/01-U-01 drilled in 1986 and 1987.



Location of shallow IKU 1986 and 1987 coreholes with Late Jurassic black shale intervals.

The cores contain numerous ammonites determined by Andrzej Wierzbowski, Warsaw University, and these faunas allow ammonite zonation and detailed correlation of the cores. Some natural gamma radiation and organic geochemical data are also taken into consideration, but do not seem to be very useful for this correlation.

Since the natural γ -radiation detector instrument set up was changed between the measurements on the 1986 core 7227/08-U-03 and the cores drilled in 1987, the absolute γ -activity cannot be directly compared with the absolute γ -log of the two other cores. The patterns and the variations can, however, still be tools for correlation. The density of the measurements complicates the correlation since we do not get a continuous log of the γ -radiation.

Lithology

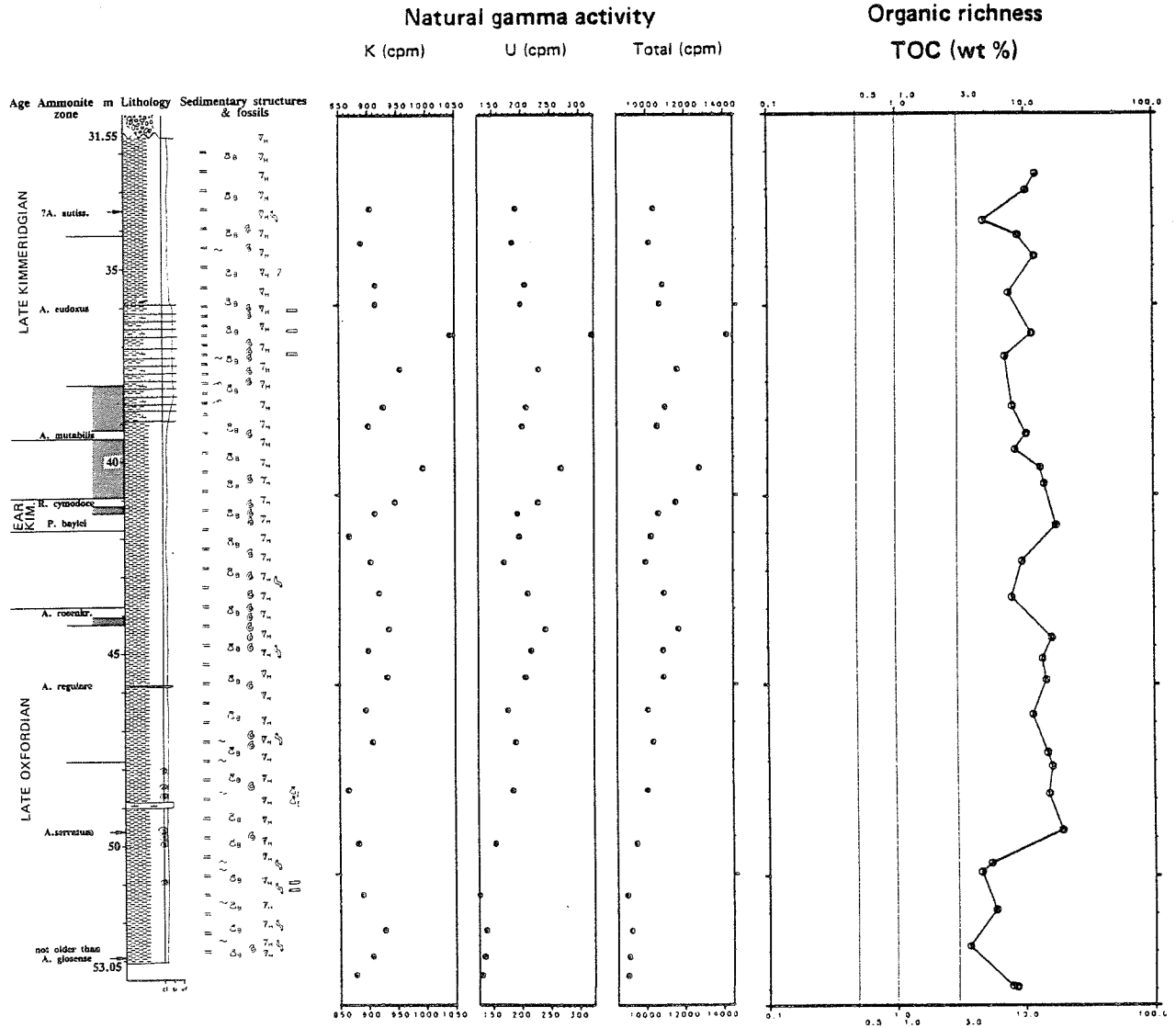
7227/08-U-03

In core 7227/08-U-03 two thin carbonate beds/concretions have been penetrated around 49 and 45.85 m in the Late Oxfordian *A. serratum* and *A. regulare* Zones. There is a sudden increase in the TOC content at 49 m.

Between 39 and 35.75 m in the *A. mutabilis* and lower half of the *A. eudoxus* Zone numerous up to 2 mm thick graded siltstone to very fine-grained calcite cemented sandstone laminae occur. In this interval also some up to 5 mm thick laminae of belemnite hooks are observed.

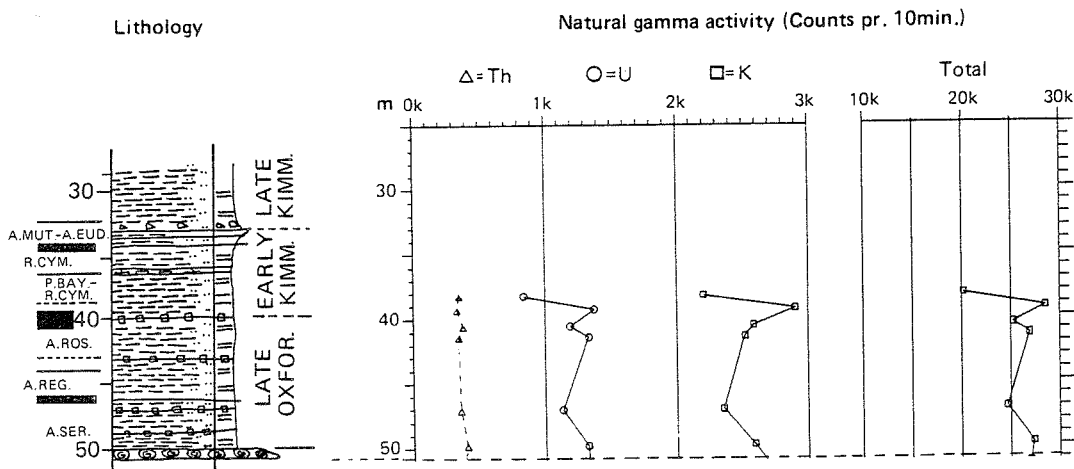
Representatives of a benthic fauna (*Buchia*, worm tubes) are most common in the latest Late Oxfordian and in the Early Kimmeridgian. Belemnite hooks and ammonites are also quite numerous, although absent in the uppermost 2 m of the core above 33.5 m in the latest Late Kimmeridgian.

7227/8-U-3



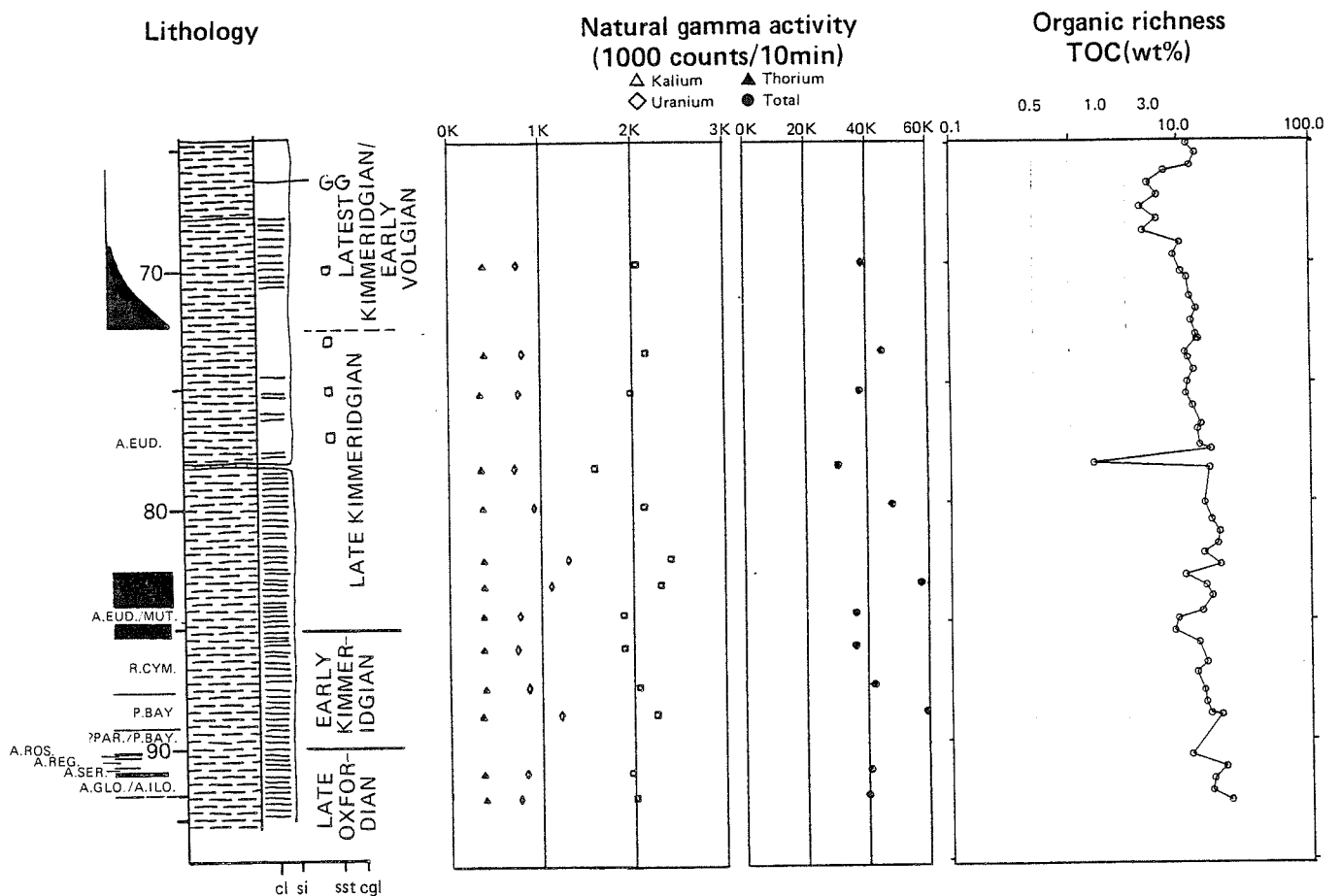
7230/05-U-02

The lowermost metre of the dark shale interval of this core in the early Late Oxfordian *A. serratum* Zone contains thin beds of glauconite pebbles up to 1.5 cm in diameter. The darker black shale interval up to the 33 m level is rich in *Buchia* and ammonites, and belemnite hooks and fish remains also occur. Pyritic and bioclastic laminae are present below 40 m (in the Late Oxfordian) and some silty laminae between 34 and 33 m in the lowermost part of the Late Kimmeridgian is followed by a 1 cm thick greyish mud flake conglomerate at 33 m. Cone-in-cone calcite concretions are common. The claystone above 33 m is less fissile than below, and fossils are much more scarce.



7231/01-U-01

The thinly laminated black shales of this core are more uniformly developed than in core 7227/08-U-03. *Buchia* and ammonites are common up to about 76.5 m in the *A. eudoxus* Zone although some intervals are without benthos. A calcitic bed or nodule is penetrated around 78.4 m also in the *A. eudoxus* Zone.



Correlation

Late Oxfordian

This substage is approximately 10 m thick in cores 7227/08-U-03 and 7230/05-U-02 whereas it is reduced to around 3 m in the more easterly hole 7231/01-U-01. The earliest Late Oxfordian *A. glosense* Zone does not seem to be penetrated in 7230/05-U-02. Natural γ -radiation is lower than in the Kimmeridgian mainly due to lower uranium contents except in core 7231/01-U-01 where the values are of similar size.

A. glosense Zone

In core 7231/01-U-01 this zone is minimum 0.85 m thick. The unit seems to be missing in 7230/05-U-02, and in 7227/08-U-03 we did not penetrate the entire zone.

TOC values in 7231/1-U-1 are very high with values between 15 and 21% in the zone itself and in the transitional beds to the zone above. Samples at 52.94 and 52.92 m from 7227/08-U-03 have TOC values around 8% and are considerably richer than the interval 51.86 to 49.67 m. Thus it may be reasonable to assume that we are close to the upper boundary of the *A. glosense* Zone at the base of core 7227/08-U-03 and that most beds between 91.92 and 91.04 m in 7231/01-U-01 belong to the *A. glosense* Zone.

A. serratum Zone

The zone is maximum 5.15 m thick in 7227/08-U-03, but may be considerably thinner. In 7230/05-U-02 the minimum thickness is 4.04 m and in 7231/01-U-01 the zone is somewhere between 0.29 and 1.32 m thick.

The unit is poorly defined in 7227/08-U-03, but a measured increase in TOC contents from around 5 to 15-20% may take place within the zone. This is associated with an increase in hydrogen index and a decrease in Tmax from about 420 to 410°C.

TOC contents vary between 13 and 23% in the *A. serratum* Zone in 7230/05-U-02. When compared to TOC data from 7227/08-U-03 this suggests that only the upper part of the zone is represented in 7230/05-U-02.

From 7231/01-U-01 we have organic geochemical data only from the transitional beds to the zones below and above. Samples from about 10 cm below and above the zone contain 19 and 10% TOC respectively.

A. *regulare* Zone

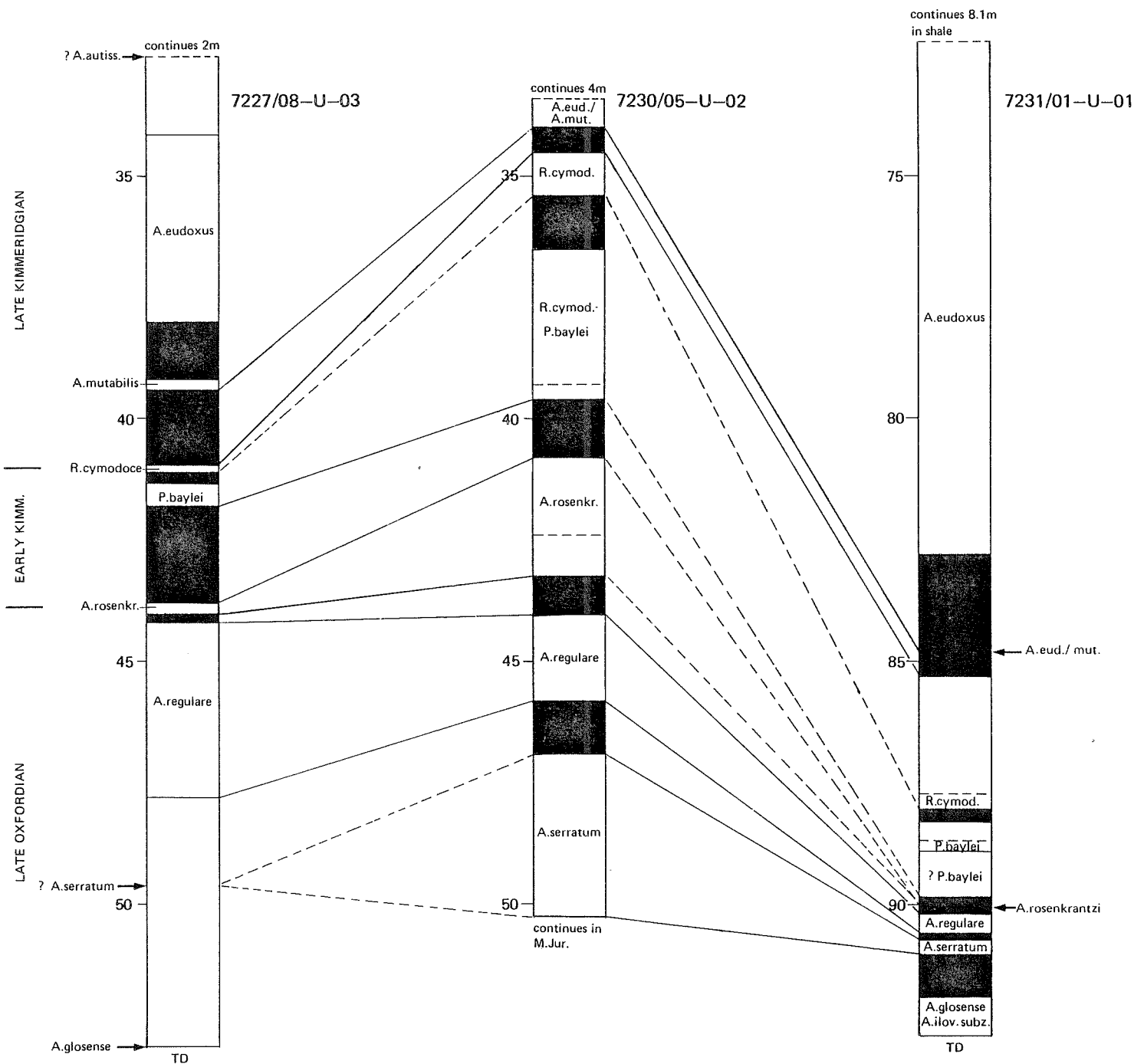
In 7227/08-U-03 this zone is somewhere between 3.55 and 5.58 m thick, in 7230/05-U-02 between 1.80 and 2.94 m and in 7231/01-U-01 between 0.33 and 0.71 m. The zone is thinning towards the east.

TOC contents vary between 11 and 16% in 7227/08-U-03 and seem to be 7-9% in 7230/05-U-02.

A. *rosenkrantzi* Zone

The thickness of this zone varies from 0.25-2.45 m in 7227/08-U-03 to 2.45-4.43 m in 7230/05-U-02 to 0.40 m or less in 7231/01-U-01.

In 7227/08-U-03 the TOC contents are in the same order of magnitude as in the *A. regolare* Zone. This is in contrast to 7230/05-U-02 where TOC contents are considerably higher than below, with one reading above 20%.



Ammonite zonation correlation chart for Late Oxfordian-Kimmeridgian black shale intervals of three Barents Sea shallow cores.

Early Kimmeridgian sensu gallico

P. baylei and R. cymodoce Zones

These zones have not been fully distinguished in core 7230/05-U-02 and they are therefore treated together. In 7227/08-U-03 the thickness of the Early Kimmeridgian is somewhere between 0.85 and 4.4 m, in 7230/05-U-02 5.06 to 6.82 m and in 7231/01-U-01 4.54 to 5.24 m. The thickness is thus more uniform than in the Late Oxfordian. The *P. baylei* Zone is maximum 2.65 and 1.98 m thick in 7227/08-U-03 and 7231/01-U-01, respectively and the *R. cymodoce* Zone is minimum 0.20, 0.92 and 0.28 m thick in 7227/08-U-03, 7230/05-U-02 and 7231/01-U-01.

TOC contents seem to be below 10% in the *P. baylei* Zone of 7227/08-U-03. In the two other cores values between 11 and 17% have been measured in the Early Kimmeridgian except for a less than 1 m thick interval close to the top of the *R. cymodoce* Zone in both cores with 2 to 8% TOC. The hydrogen indices are below 300 mg HC/g TOC in these last samples with relatively low TOC contents.

In 7227/08-U-03 there is an upward increasing trend in the γ -activity around the Oxfordian/Kimmeridgian and Early/Late Kimmeridgian boundaries. In 7230/05-U-02 a maximum is measured at the base of the Early Kimmeridgian and in 7231/01-U-01 there is a maximum in mid Early Kimmeridgian.

Late Kimmeridgian sensu gallico

A. mutabilis and A. eudoxus Zones

These early and middle Late Kimmeridgian zones have only been properly distinguished in 7227/08-U-03 where the *A. mutabilis* Zone is between 0.20 and 2.95 m thick. The minimum thickness of the *A. eudoxus* Zone in the same core is 3.85 m, in 7231/01-U-01 10.29 m. We have only been able to figure out a maximum thickness of the *A. eudoxus* Zone in 7227/08-U-03 where it is 5.67 m. The thickness of the two zones increases from somewhere between 5.25 and 7.42 m in the west to minimum 12.28 m in the east. This is surprising since the lower part of the Late Kimmeridgian is more silty in 7227/08-U-03.

In 7227/08-U-03 a TOC content of 13% for a sample in the *A.mutabilis* Zone is high compared to values between 7 and 11% in the *A.eudoxus* Zone. This may suggest that the undivided *A.mutabilis/eudoxus* Zone in 7230/05-U-02 with TOC contents between 14 and 23% belongs to the *A.mutabilis* Zone. The beds above 33.5 m without ammonites are less rich in TOC (9-10%). However, TOC data from 7231/01-U-01 show that correlation of black shales on the basis of organic richness is not always possible. In this core there does not seem to be any significant difference in TOC contents in the *A.mutabilis* and the *A.eudoxus* Zones. A reduction from a level between 13-17% to 9-12% rather takes place slightly above a limestone bed within the *A.eudoxus* Zone.

In 7227/08-U-03 there is a natural γ -radiation maximum in the middle part of the *A. eudoxus* Zone. An anomaly is observed in 7231/01-U-01 at a probably lower stratigraphic level in the same ammonite Zone.

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REPORT

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REPORT TITLE:
**Rb-Sr ISOTOPIC STUDIES OF GLAUCONIES FROM
THE NORDKAPP BASIN AND THE DIA-STRUCTURE
SHALLOW DRILLING 1987**

REPORT NO.: **21.3437.07/01/88**
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DATE: 19-MAY-88	NO. OF PAGES: 22	NO. OF APPENDICES: -	PROJECT MANAGER: T. Bugge	SIGN.: <i>Tom Bugge</i>
CLIENT: Elf Aquitaine Norge a/s, Norsk Hydro a.s., Den norske stats oljeselskap a.s. (Statoil)				
SUMMARY: Glaucouies were used for Rb-Sr isotopic dating of Cretaceous sedimentary wedges at two locations in the project "Shallow drilling Elf Aquitaine/Norsk Hydro/Statoil Barents Sea 1987". The glaucouies examined from the Dia-Structure have anomalous Rb-Sr isotopic compositions and low Rb and Sr contents and were not suitable for isotopic dating. Three of the glaucouy fractions from the Nordkapp Basin give model ages that are in accordance with the biostratigraphically determined deposition age. A later, post-depositional disturbance is indicated by an errorchron defined by all the glaucouy fractions from the Nordkapp Basin sample.				

KEY WORDS:	
Rb-Sr isotopes	Cretaceous
Radiometric dating	Nordkapp Basin
Glaucouy	Dia-Structure

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1. INTRODUCTION

Core material from IKU's shallow drilling project 1987 in the Barents Sea gives a possibility to study rock material in areas where the geology is poorly known, and mostly restricted to seismic profiling. Seismic profiles of Mesozoic successions combined with paleontological studies of core material have provided new and valuable geological information demonstrating the existence of Cretaceous sediment wedges both in the Nordkapp Basin and at the Dia-Structure (Aarhus et al. 1987). The drillings that form the basis for the present study (Aarhus et al. op. cit.) were parts of the project "Shallow drilling Elf Aquitaine/Norsk Hydro/Statoil Barents Sea 1987" and cover sedimentary sequences from Late Oxfordian to Santonian.

The presence of glaucony (terminology of Odin & Matter 1981) rich layers at several levels in the cores combined with the fossil control gives an opportunity for detailed comparisons with Rb-Sr isotopic ages. The application of glauconies for Rb-Sr isotopic dating of sediments is well established (cf. Faure & Powell 1972, Odin (ed) 1982). This method has the potential to reveal precise ages of the sedimentation and thus be a valuable supplement or test to the paleontological datings. However, the results of this method are strongly dependent on both the degree of evolution towards maturity of the glauconies during their formation (cf. Odin & Matter 1981) and on their post depositional history (cf. Morton & Long 1984). Smalley et al. (1987) report resetting of the Rb-Sr isotopic systems of glauconies and carbonate due to post-depositional equilibration with a fluid phase. By complete resetting of the isotopic systems, this provides a method to detect and date post depositional events. The interpretation of Rb-Sr isotopic results for glauconies therefore requires detailed knowledge of both the petrographic evolution and of the geological history.

In the present case glauconies have been selected from one core in the Nordkapp Basin (7231/04-U-01) and one from the Dia-Structure (7323/12-U-01) (Figure 1). The mineral separations and isotopic analyses were carried out in two periods. Both series are to be regarded as reconnaissance studies. Only the second series (Nordkapp Basin), benefitting from the first attempt (Dia-Structure), gave successful isotopic results for the glauconies. In general, selection of samples should be based on detailed knowledge of sedimentary and postdepositional evolution for the particular area (diagenesis, thermal evolution, tectonics) to get optimal results.

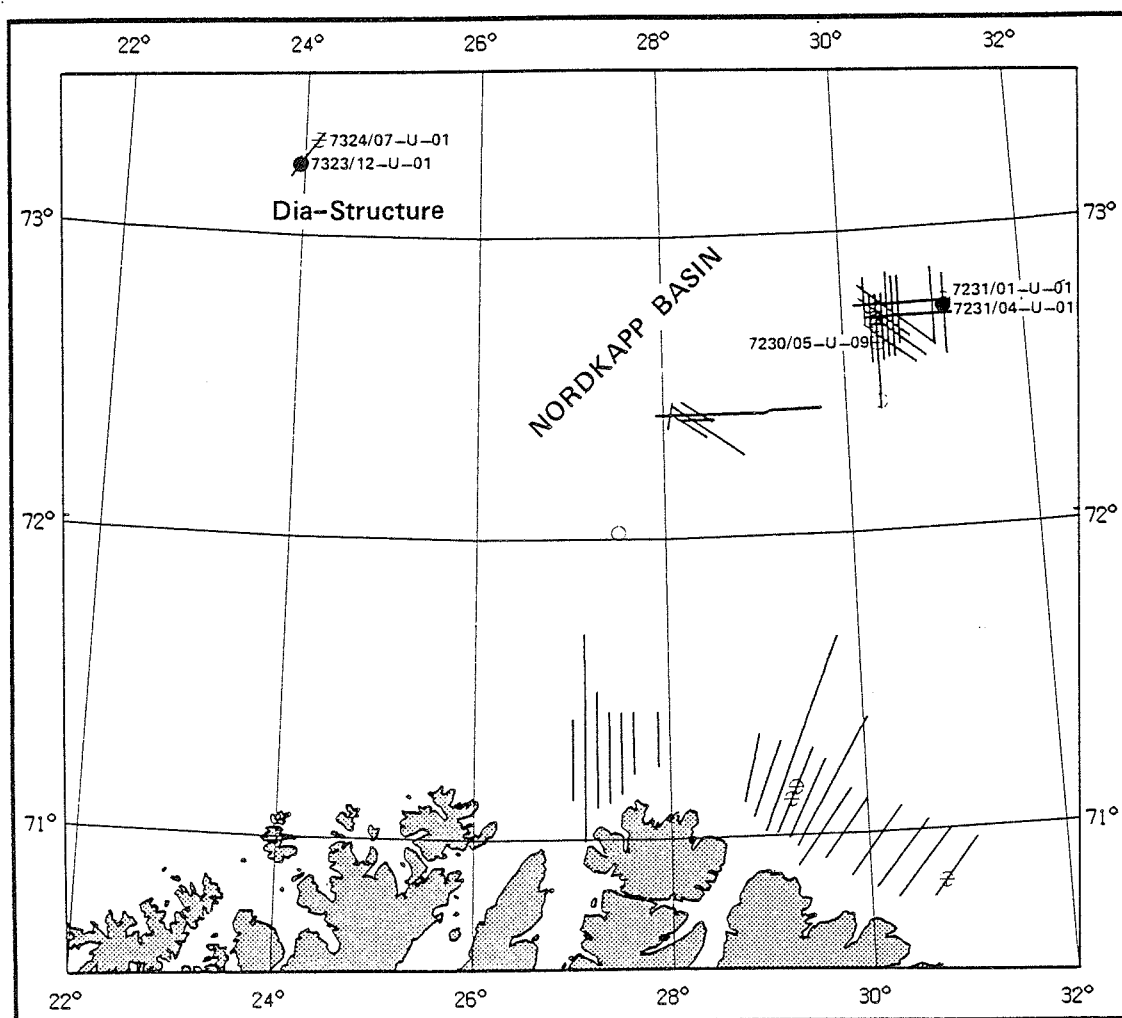


Figure 1 Map showing the locations of the drill sites in the Nordkapp Basin and at the Dia-Structure. Other cores obtained by IKU in 1987 are also indicated. (From Aarhus et al. 1987). Locations for the present study are marked by black dots.

Geological setting

The geological information is summarized from Aarhus et al. (1987) and is based on three cores drilled through dipping layers on the flanks of salt-structures in the Nordkapp Basin and two cores drilled at the Dia-Structure. The stratigraphy of the two cores selected for isotopic dating is shown in Figure 2. These cores are briefly described below. The glauconies will be described in a separate section.

Core 7231/04-U-01 represents the upper part of the sedimentary wedge that was recorded on the seismic profiles in the Nordkapp Basin. The length of the core is 59.7 m. The lithology is fairly uniform, consisting of silty and sandy mudstone. It has been subdivided into a lower unit (A) of dark grey silty to sandy claystone and an upper unit (B) with dark to very dark claystone with some silt and glaucony bearing layers. The boundary between the two units is marked by an erosional contact at the 62.7 m level and is correlated with a seismic reflector. Bioturbation is most abundant in the upper part of the core (unit B). The glaucony is concentrated in silty to very fine-grained sandy layers at 51 to 56 m.

The mineralogical variation (from XRD) is summarized in Figure 2. The main constituents are mixed layer clay, illite clay, chlorite, quartz, K-feldspar and plagioclase, with quartz and feldspars restricted to the sand and silt grains.

Palynomorphs and foraminifera within the core indicate a more or less continuous Lower Cretaceous succession of Aptian to Middle Albian age (Aarhus et al. 1987).

Core 7323/12-U-01 penetrates the youngest sequence boundary that was seismically recorded at the Dia-Structure. The 60.6 m long core consists of calcareous claystones, glauconitic limestones and greenstones in the lower part overlain by limestones and calcareous claystones (Figure 2). Glaucony is particularly abundant within limestone layers throughout the lower part, below the 102 m level. The sequence has been subdivided into two units (A and B) at the 102.3 m level, coinciding with a strong seismic reflector. The boundary layer is also marked by the occurrence of pebbles of phosphorite and glaucony up to 5 mm in diameter, above the glauconite rich successions. The sediments have been subjected to strong bioturbation as well as strong reworking and oxidation of the organic material present.

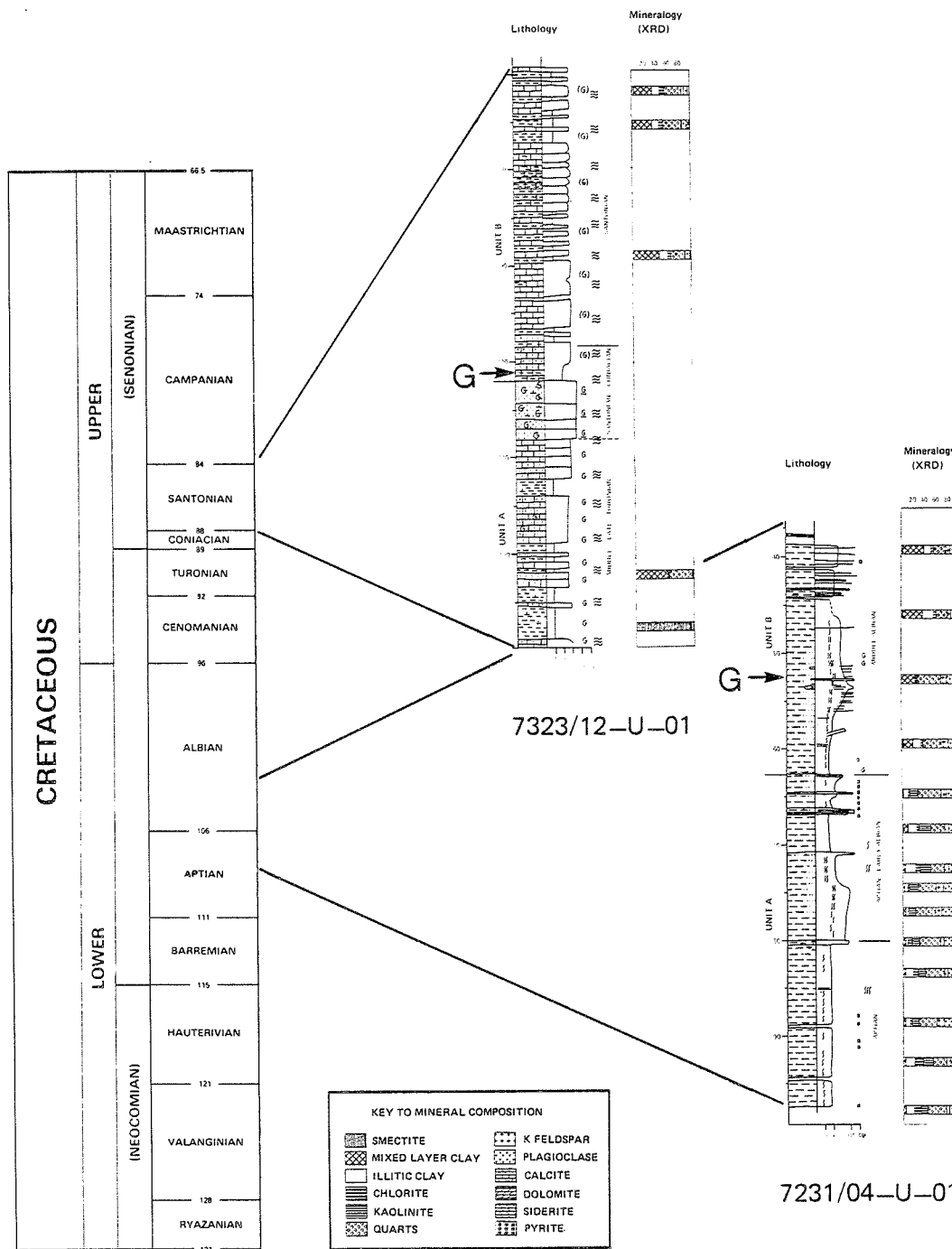


Figure 2 Stratigraphy (from Aarhus et al. 1987). The locations of the sampled glauconies are indicated by G→.

Mineralogy and petrography are described from thin-section studies and XRD analyses (Aarhus et al. 1987; pp 154-161). XRD whole-rock analyses of the claystone layers show the presence of quartz, K-feldspar, plagioclase, calcite, mica, chlorite, kaolinite, smectite, siderite and pyrite. The carbonates are mainly packstones. The lower unit is characterized by a higher clastic content (up to 5%) and larger grainsize (fine-grained sand size) than in the upper unit (silt size). *Inoceramus* fragments and glauconitic pellets are both important constituents of the uppermost packstones/greensands.

Palynomorphs, foraminifera and nannofossils indicate a more or less continuous lower Upper Cretaceous sequence from Middle Turonian to Santonian (Figure 2).

Glaucconies

7231/04-U-01. Glauccony have been collected from the dark silty claystone at the 52.3 and 52.6 m levels in unit B (Figure 2). The 100-200 μm glaucony grains appear green and homogeneous. SEM backscatter images (Figure 3) show spheroidal to ovoidal, rounded to subangular shapes. Expansion fractures may appear in the outer parts. Several grains seem to have a porous surface at high magnification.

Chemical analyses of the glauconies are presented in Table 1. The sample numbers refer to different separate fractions (see Table 2 for explanations). Fe_2O_3 vary between 16.2 and 22.3 wt.% and K_2O vary between 4.2 and 7.2 wt%. Both oxides have lowest values in N15.

7323/12-U-01. Glauccony is abundant in this core, forming a major part of the calcareous sediments in unit A where they may constitute 20-60 % of the sample. Unfortunately, the sample used for isotopic work was for time reasons selected and isotopically analysed at a very early stage in the project, before the core had been examined petrographically, from a level slightly above the most glaucony-rich levels at 100.8 m (unit B).

Glaucconies from this core have different appearances, including rounded grains, irregular masses, replacements of *Inoceramus* fragments, fillings of foraminifera chambers, borings of shell fragments and inclusions in phosphoritic grains (Aarhus et al. 1987).

Table 1 Electron-microprobe analyses of representative glaucony grains from the core-levels selected for isotopic analyses. Iron is given as Fe_2O_3 .

Glaucanite oxide %											
Sample	Point	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	Sum
7323/12-U1 D1	1	52.99	6.10	0.05	23.21	0.07	3.86	0.00	0.00	7.04	93.32
7323/12-U1 D1	2	51.85	6.13	0.02	22.01	0.06	3.86	0.00	0.00	7.82	91.75
7323/12-U1 D2	2	53.41	9.85	0.10	18.33	0.02	3.54	0.00	0.06	6.09	91.40
7323/12-U1 D2	3	54.14	8.51	0.09	20.00	0.00	3.62	0.00	0.10	6.39	92.85
7323/12-U1 D3	2	54.01	7.00	0.06	20.81	0.01	3.67	0.01	0.08	7.07	92.72
7323/12-U1 D3	4	53.60	6.24	0.05	22.47	0.00	3.42	0.00	0.00	6.96	92.74
7231/04-U1 N5	1.1	50.82	9.36	0.10	19.78	0.09	2.92	0.06	0.00	6.83	89.96
7231/04-U1 N5	3.1	51.99	8.40	0.10	20.93	0.01	2.79	0.00	0.11	7.20	91.53
7231/04-U1 N5	4.1	52.00	11.37	0.06	16.25	0.03	2.94	0.13	0.25	4.70	87.73
7231/04-U1 N3	1.1	49.80	8.77	0.06	21.03	0.04	2.62	0.00	0.04	6.28	88.64
7231/04-U1 N3	2.1	52.21	9.66	0.12	20.31	0.05	2.63	0.00	0.09	5.62	90.69
7231/04-U1 N3	3.1	51.45	9.10	0.18	20.53	0.00	2.50	0.00	0.09	5.21	89.06
7231/04-U1 N2	2.1	51.39	7.73	0.04	22.30	0.10	2.68	0.00	0.02	6.45	90.71
7231/04-U1 N2	3.1	50.85	9.50	0.08	19.78	0.01	2.48	0.00	0.13	4.96	87.79
7231/04-U1 N2	5.1	52.43	9.48	0.08	21.11	0.04	2.56	0.18	0.07	5.33	91.28
7231/04-U1 N2	6.1	51.46	7.94	0.08	21.68	0.05	2.54	0.00	0.12	5.91	89.78
7231/04-U1 N15	1.1	53.59	12.60	0.09	16.45	0.04	3.03	0.30	0.21	4.61	90.92
7231/04-U1 N15	1.2	53.03	12.41	0.10	16.34	0.02	3.09	0.22	0.18	4.47	89.86
7231/04-U1 N15	3.1	52.45	11.88	0.10	17.31	0.00	2.69	0.16	0.22	4.32	89.13
7231/04-U1 N15	4.1	53.23	11.96	0.10	16.73	0.05	2.82	0.35	0.13	4.33	89.70

The fractions selected for dating are granular, massive rounded grains of 100–250 μm size, often with expansion fractures in the outer parts leading to a lobate shape (Figure 4). At low magnification they appear to be homogeneous. However, SEM backscatter and X-ray images at high magnification show the presence of frequent inclusions in many of the grains (Figure 4 b,c,d). EDS analyses show the presence of quartz, phosphate (apatite, monazite), K-feldspar, sulphide (pyrite?) and ilmenite.

Chemical analyses of three different fractions show a Fe_2O_3 variation between 18.2 and 23.2 wt % and K_2O between 6.1 and 7.8 wt %. These values are fairly similar to those given in Aarhus et al. (1987) from the same core, which also include glauconies from unit A.

Glaucy formation

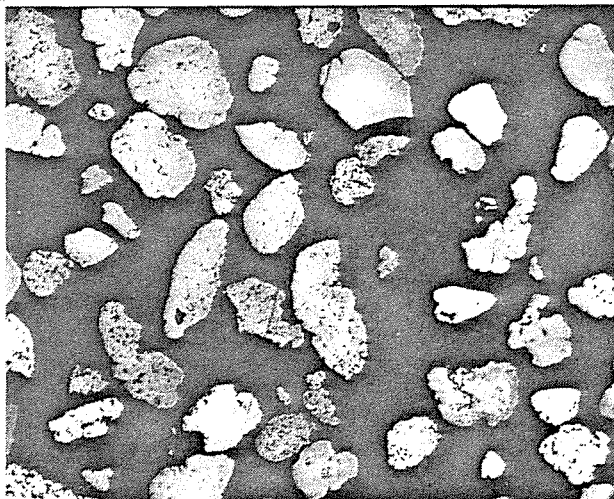
Glaucies form by growth within pore spaces of an original substrate combined with a process of continuous chemical replacement of the solid part of the original substrate ('glaucitization'). The original substrate can be of various kind; such as different clastic mineral grains, fossil fragments, sediments or authigenic material, etc.. The process of glaucitization has been divided into different stages according to the degree of replacement of the original substrate, and the textural and chemical evolution towards maturity (cf. Odin & Matter 1981). Evolved glaucies are characterized by complete replacement of the original substrate, by green colour, homogeneous appearance and by mineral-chemical compositions that approaches glaucite (*sensu strictu*). The evolved glaucies are characterized by high values of Fe_2O_3 and K_2O compared to the more immature glaucy stages.

The present analyses show that the glaucies are fairly evolved with slightly lower K_2O and Fe_2O_3 values than those of completely evolved glaucy. The colour and habitus also support that the grains are fairly mature to mature, resembling stage 3 and 4 in the evolution scheme of Odin & Matter (1981, Figure 12). The analyses also indicate a tendency of slightly higher K_2O and Fe_2O_3 values for glaucy from core 7323/12-U-01 than for those in 7231/04-U-01 (Table 1).

Analytical procedure - sample preparation

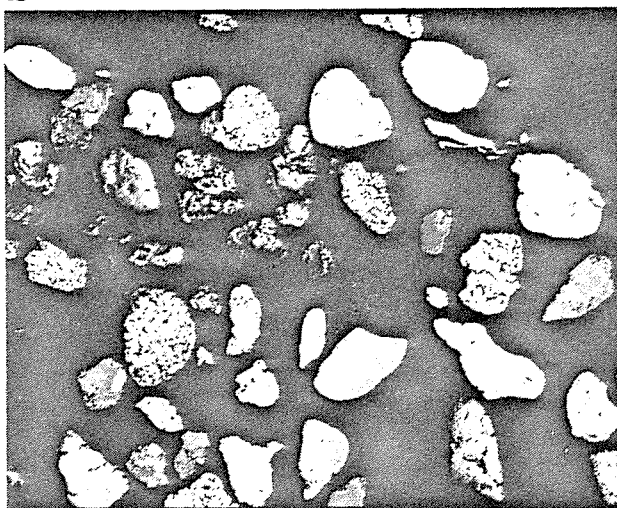
The preparation of the samples was undertaken according to the method described by Odin & Matter (1981) and Smalley et al. (1987). The samples (loosely cemented) were carefully crushed in a mortar and disintegrated in distilled water by using an ultrasonic dispergator. To remove the finest clay particles from the disintegrated material, ultrasonic dispergation in distilled water was carried out several times until the water phase appeared clean. The material was then dried at 40°C and sieved. Based on examination of the sieved fractions under the microscope, the 63 - 125 μ fraction was chosen for further purification.

a



100μ

b



100μ

Figure 3 Core 7231/04-U-01
Backscattered electron images showing the unpurified glaucony-fractions from a) "sample" 15 (52.60 m, 0.40A) and b) "sample" 2 (52.27 m, 0.35A) after the magnetic separation. Only the coarser, apparently homogeneous grains (under the stereomicroscope) were selected for isotopic analyses.

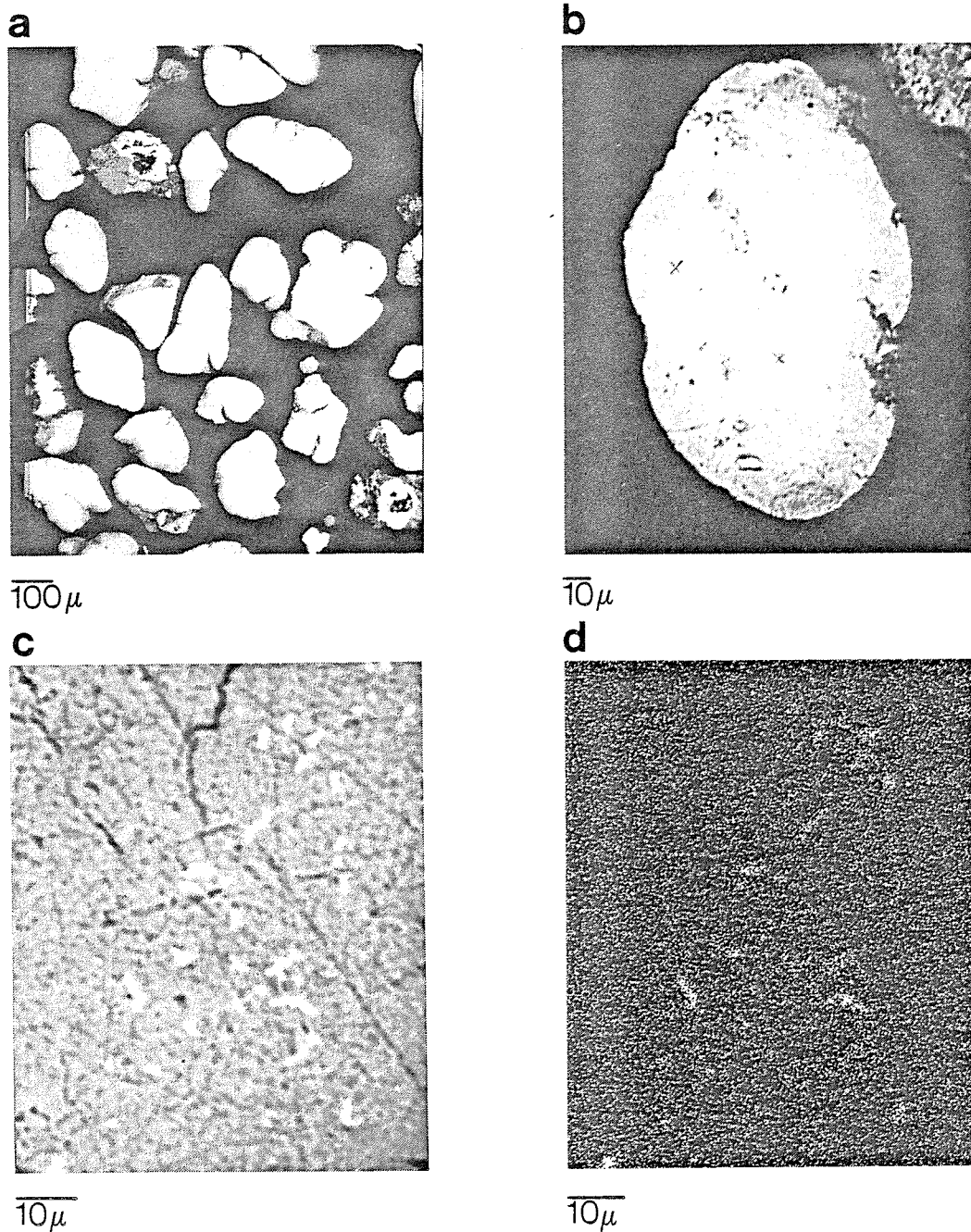


Figure 4 Core 7323/12-U-01

- a) Backscattered electron image of a 0.35A magnetic fraction of glaucony from the 100.82 m level, before purification.
- b) Close up backscattered electron image of a single glaucony grain from the 0.40A magnetic fraction from the 100.82 m level. Note the occurrence of K-feldspar inclusions.
- c) Close-up backscattered electron image of the central grain in a), showing the appearance of sulphide-inclusions.
- d) X-ray image showing the distribution of sulphur in the same section as c).

Table 2. Explanation of sample reference nos. Glauconite separates used for isotopic analyses.

Location 7231/04-U-01

Sample no.	Sample depth (meters)	Magnetic fraction (current strength)
2	52.27	0.350 A
3	52.27	0.375 A
4	52.27	0.400 A
5	52.27	0.425 A
11	52.27	0.450 A
14	52.60	0.375 A
15	52.60	0.400 A
16	52.60	0.425 A

Location 7323/12-U-01

5	100.87	0.350 A
13	100.83	0.350 A
14	100.83	0.375 A
15	100.83	0.400 A
16	100.83	0.450 A
19	100.85	0.350 A
23	slab below 100.8; carbonate fossil	

Magnetic separation was carried out on a Frantz isodynamic separator using current intervals of 0.025A between 0.30 and 0.45A. The separate fractions used for dating with explanation of the reference numbers are given in Table 2.

The fractions selected for dating were further purified by hand picking under a binocular lens. Finally, each fraction was cleaned by use of HCl, NH₄Ac and distilled water.

Ten to fifty milligrams of purified material were used for isotope analyses. The analyses were carried out at the National Laboratory for Geological Mass Spectrometry at Mineralogisk-Geologisk Museum, University of Oslo (late 1987, early 1988) by Toril Enger (wet chemistry) and Bjørn Sundvoll (mass spectrometry). Ppm Rb and Sr were determined by isotope dilution. Ages have been calculated according to the method of York (1969) using a computer program written by Lars Kullerud (1988). Errors are given as expanded σ values.

Table 3 Isotopic data

No	ppmRb	ppmSr	$^{87}\text{Rb}/^{86}\text{Sr}$	SE	$^{87}\text{Sr}/^{86}\text{Sr}$	SE
7231/04-U-01						
2)	263.7	27.42	27.932	0.279	0.744590	0.000030
3)	259.1	36.51	13.290	0.133	0.724870	0.000030
4)	244.4	53.69	13.192	0.132	0.724860	0.000030
5)	196.6	58.55	9.726	0.097	0.722660	0.000030
11)	218.1	68.80	9.181	0.092	0.720030	0.000030
14)	232.7	78.57	8.578	0.086	0.720120	0.000030
15)	193.0	71.83	7.785	0.079	0.720650	0.000030
16)	223.1	79.91	8.085	0.081	0.718850	0.000030
7323/12-U-01						
5)	3.39	2.95	3.433	0.034	1.054858	0.000030
13)	2.46	2.94	2.496	0.025	1.058339	0.000030
14)	5.70	3.90	4.341	0.043	0.964537	0.000030
15)	40.09	6.44	18.285	0.183	0.864528	0.000030
16)	49.66	8.08	17.944	0.179	0.796780	0.000030
19)	27.27	3.15	25.803	0.258	1.031655	0.000030
23)	0.01	1359.9	0.0000	0.000	0.707367	0.000030

Table 4

Model ages, relative to inferred sea-water composition
($^{87}\text{Sr}/^{86}\text{Sr} = 0.707367 \pm 0.000030$).

a) 7323/12-U-01

Glauc. frac.	Model ages Ma	Error (1 σ)
5	6790	64
13	9265	87
14	4053	39
15	602	6.0
16	350	3.5
19	880	8.7

b) 7231/04-U-01

2	93.8	0.9
3	92.7	1.0
4	93.3	1.0
5	110.6	1.1
11	97.0	1.0
14	104.6	1.1
15	120.1	1.3
16	100.0	1.1

Results

Rb and Sr analyses and $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios are presented for glauconies and one carbonate in Table 3. Glauconies from core 7231/04-U-01 have Rb and Sr contents similar to common published glaucony compositions. By contrast, glaucony analyses from core 7323/12-U-01 show anomalously low values for both Rb and Sr. Glauconies from the latter core also show an unsystematic scatter for the $^{87}\text{Rb}/^{86}\text{Sr}$ - $^{87}\text{Sr}/^{86}\text{Sr}$ values in the isotope plot (Figure 5).

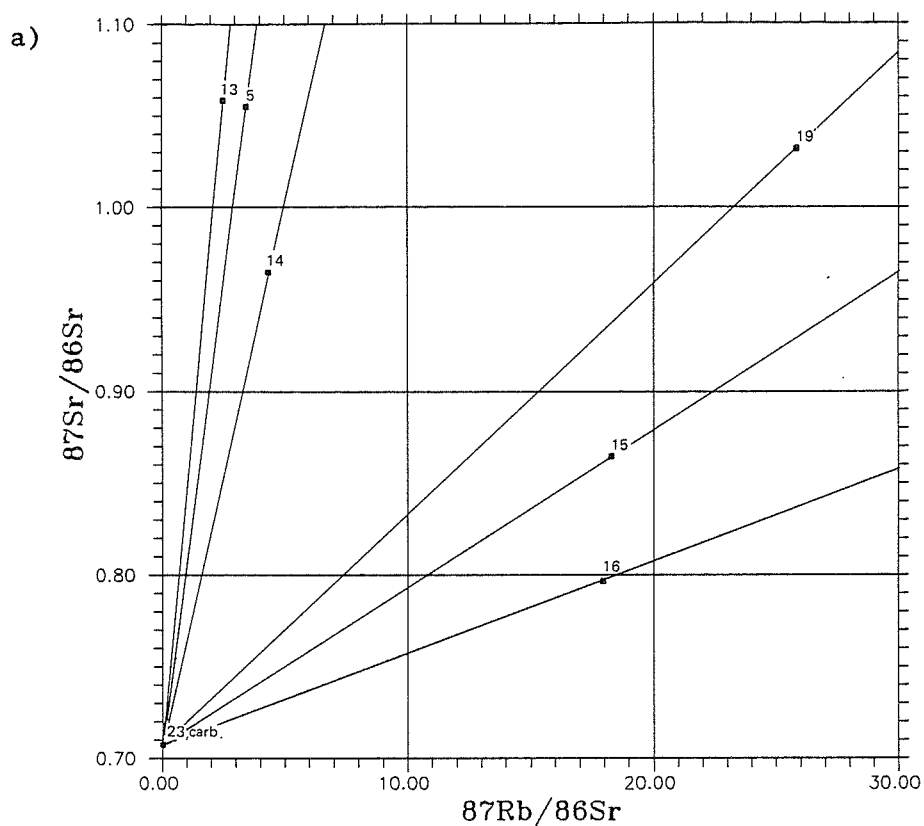
The carbonate (*Inoceramus* fragment) from core 7323/12-U-01 has a Sr isotopic composition of 0.707367 ± 0.000030 . This value is similar to the $^{87}\text{Sr}/^{86}\text{Sr}$ plateau at ca. 90 - 100 Ma on the sea-water composition curve (Burke et al. 1982) and also very close to the values shown of the Santonian to Coniacian (ca. 0.70730 - 0.70735). Biostratigraphical dating from this part of the core indicates a Santonian to Coniacian deposition age. With the somewhat poor resolution of the curve of Burke et al. (1982 figure 1) it may be concluded that the isotopic composition for the carbonate is representative for the sea-water composition at the time of deposition. This ratio may therefore be used to calculate model ages for the glauconies. Model ages can be used to examine the possibility of equilibration between glauconies and sea-water. This is particularly useful in the present case due to the irregular scattering of the points in the isotope plots (Figures 5, 6).

Model ages:

7323/12-U-01: The combination of carbonate with any of the glaucony samples from this core would lead to meaningless high "ages" in all cases (Table 4a) due to the anomalously high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and low $^{87}\text{Rb}/^{86}\text{Sr}$ ratios. This illustrates that none of these glaucony compositions represent equilibrium with sea-water at the time of glaucony-formation. The disequilibria will be discussed in a later section.

7231/04-U-01: The same carbonate composition is used for model-age considerations for this core, since it's composition is representative for the sea-water at the time of deposition (Burke et al. 1982). Model ages for the 8 different glauconies relative to sea-water carbonate vary from about 93 Ma to 120 Ma, 7 of the fractions with values between 93 and 104 Ma. Fractions 11, 14 and 16 give model ages within the Albian (Table 4b).

7323/12-U-01



7231/04-U-01

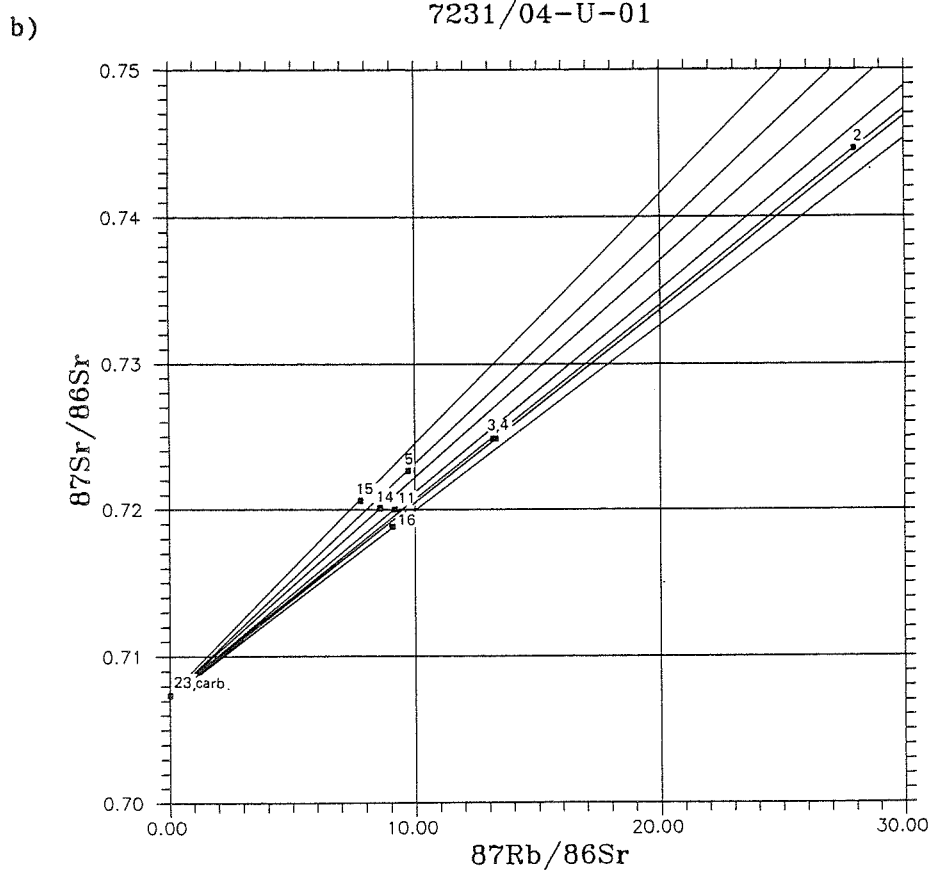


Figure 5 Isotope diagram for glauconies from a) 7323/12-U-01 and b) 7231/04-U-01. Note the irregular scattering of the points in a). Carbonate (23) is shown for comparison.

These three glaucony-fractions therefore have Sr-isotopic compositions that could have been close to equilibrium with the sea-water composition at the inferred time of formation from the fossil datings (Middle Albian; Figure 2, Albian = 96-106 Ma; using Haq et al. 1987). Excluding fraction 15 with the most immature chemistry (Table 1) and the oldest model age (Table 4b), the isotopic data can be used to support the paleontological dating of this part of the core. However, the quality of the data is not good enough for a more precise age determination or detailed division into substages.

Isochron method: Internal isochrons may be defined if the different magnetic fractions of glauconite from a single sample all equilibrated isotopically with the same fluid (sea-water or a post depositional pore fluid), providing sufficient variation in the glaucony compositions.

Table 5

"Age" calculations (expanded σ) by the isochron-method for different combinations of points from 7231/04-U-01.

a)	Points included:	2, 3, 4, 5, 11, 14, 15, 16
	Age	87.5 ± 9.4 Ma
	MSWD	77.9
	Intercept	0.709505 ± 0.001348
b)	Points included:	2, 3, 4, 5, 11
	Age	89.3 ± 10.5 Ma
	MSWD	64.3
	Intercept	0.708878 ± 0.001786
c)	Points included:	2, 3, 4, 11, 14, 16
	Age	88.2 ± 4.2 Ma
	MSWD	14.1
	Intercept	0.708757 ± 0.000645
d)	Points included:	2, 3, 4, 5, 11, 14, 15, 16 + carbonate from 23 (7323/12-U-01)
	Age:	101.8 ± 3.9 Ma
	MSWD	86.0
	Intercept	0.707416 ± 0.000274

a) The combination of the eight glaucony fractions from the samples from 7231/04-U-01 indicates a date of 87.5 ± 9.4 Ma with a $^{87}\text{Sr}/^{86}\text{Sr}$ intercept of 0.709505 ± 0.001348 (Figure 6, Table 5). The large uncertainty and the high value of the MSWD (78) illustrate the lack of complete equilibrium between the different fractions.

- b) Exclusion of the fractions from the lower level of the sampled part of the core (14, 15 16, see Table 2) give nearly the same age (89.3 Ma) and does not lead to a smaller error (Table 5).
- c) Exclusion of the two points above the line (5 and 15) would also lead to a similar age (88.3 Ma) with a smaller error (4.2 Ma) and a lower MSWD (14; Table 5). Exclusion of point 15 may be verified due to the relatively immature chemical composition (Table 1), while fraction 5 is compositionally indistinguishable from the other fractions. In general, all these regressions have high MSWD values and should not be considered as isochrons, but rather as errorchrons (cf. Brooks et al. 1972).
- d) By including the carbonate into the regression a larger compositional spread is defined, leading to an older date of 101.8 ± 3.9 Ma, but with a high MSWD-value of 86. This date is similar to the inferred sedimentary deposition age, but again a perfect isochron relation is not achieved.

Discussion of the isotopic results

The present results demonstrate the lack of equilibrium for the $^{87}\text{Sr}/^{86}\text{Sr}$ - $^{87}\text{Rb}/^{86}\text{Sr}$ isotopic systems of the glauconies from both the cores studied. The disequilibrium is most obvious at location 7323/12-U-01. Some possible mechanisms that lead to isotopic disequilibrium are:

- a) Inheritance of the isotopic compositions of the substrate that the glauconies grew on and replaced, i.e. lack of isotopic equilibration during the glaucony formation.
- b) Incomplete or partial readjustments of the isotopic systems of the glauconies by a later, post-depositional event.
- c) Selective removal or addition of Rb and Sr, by exchange with a different system leading to disturbance of the isotopic ratios.

The effect of a) is particularly important for immature glauconies where relicts of the substrate may persist within the glaucony grains. However, even when the substrate is completely vanished, there is no guarantee that the isotopes are completely reset to a glaucony - pore fluid or glaucony sea-water equilibrium. The ability to equilibrate is dependent on the degree to which all parts of the grain can exchange ions with the fluid

medium. The persistence of different types of relict minerals, or inherited isotopic ratios, within the glaucony grains can lead to large scatters in the measured isotopic ratios of the glaucony grains and thus to isotopic disequilibrium.

In the present case, both the compositions, colour, and appearance of the glauconies suggested that they are fairly mature and therefore with a good possibility for application for isotopic dating. Also, the glauconies from 7323/12-U-01 seemed to have more evolved compositions than those from the other core. The highly irregular scattering of the isotopic ratios in Figure 5 was therefore not to be expected.

Although the fractions used for dating had been purified by hand-picking, grains with relict inclusions of the substrates may not have been totally excluded. This is evidenced by the SEM back-scatter images that demonstrated the existence of both K-feldspar, apatite and monazite as inclusions within glaucony of evolved chemical compositions (cf. Figure 4b and Table 1, analyses D2-2). A contamination effect is therefore possible even in the evolved glauconies. It is possible that the isotopic compositions analysed for 7323/12-U-01 is a mixture of the relict host mineral (inclusions) and the glaucony. In that case, the isotopic disequilibrium suggested from the glaucony analyses may be artifacts due to physical contamination. However, the low Rb-contents of the separates indicates that the glaucony chemistry is also anomalous. Physical contamination can therefore not explain all the observed disequilibrium. It is therefore likely that the glauconies have been disturbed chemically.

The anomalously low Rb contents and the generally low $^{87}\text{Rb}/^{86}\text{Sr}$ and high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios recorded in 7323/12-U-01 cannot be explained by simple mixing with a relict clastic grain. Higher values for the $^{87}\text{Rb}/^{86}\text{Sr}$ ratio and the contents of Rb and/or Sr would have been expected if inherited from old feldspar, mica or apatite. The observed isotopic composition could however be explained by a combined process with selective loss of Rb (point c above) and inheritance of (or partial mixing with) a substrate with a high $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. From the abundance and type of inclusions within the glauconies the contamination effect would be most likely in the 7323/12-U-01 glauconies, in accordance with the observed degree of disequilibrium.

7231/04-U-01

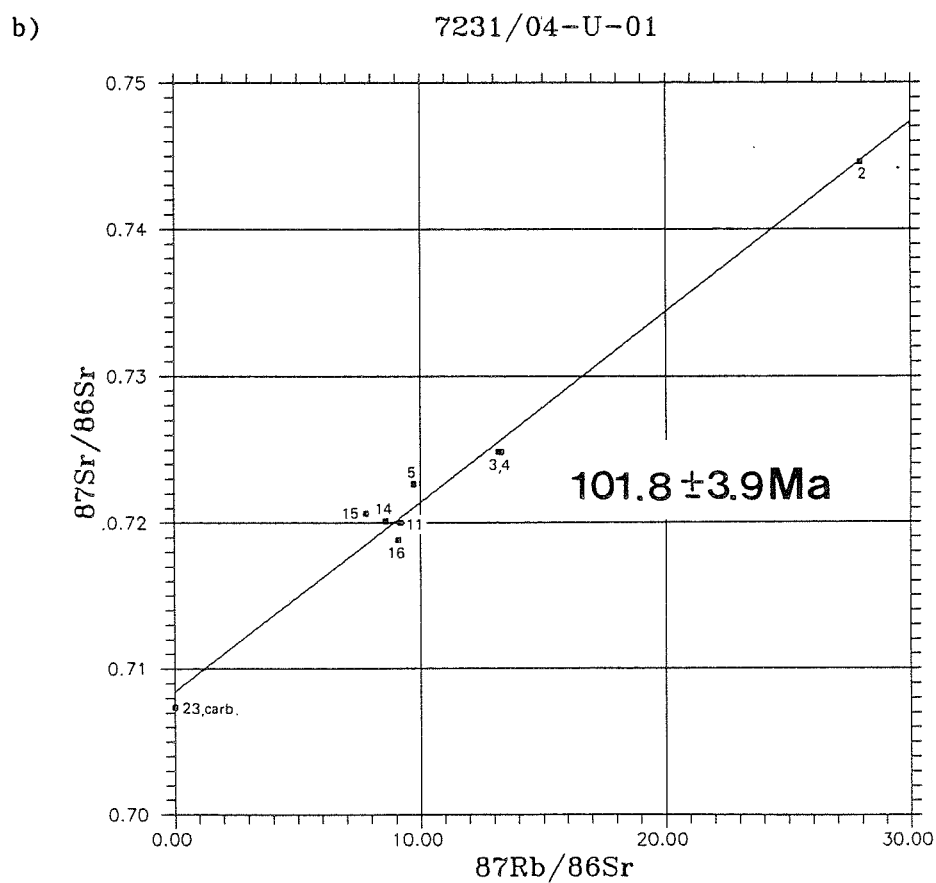
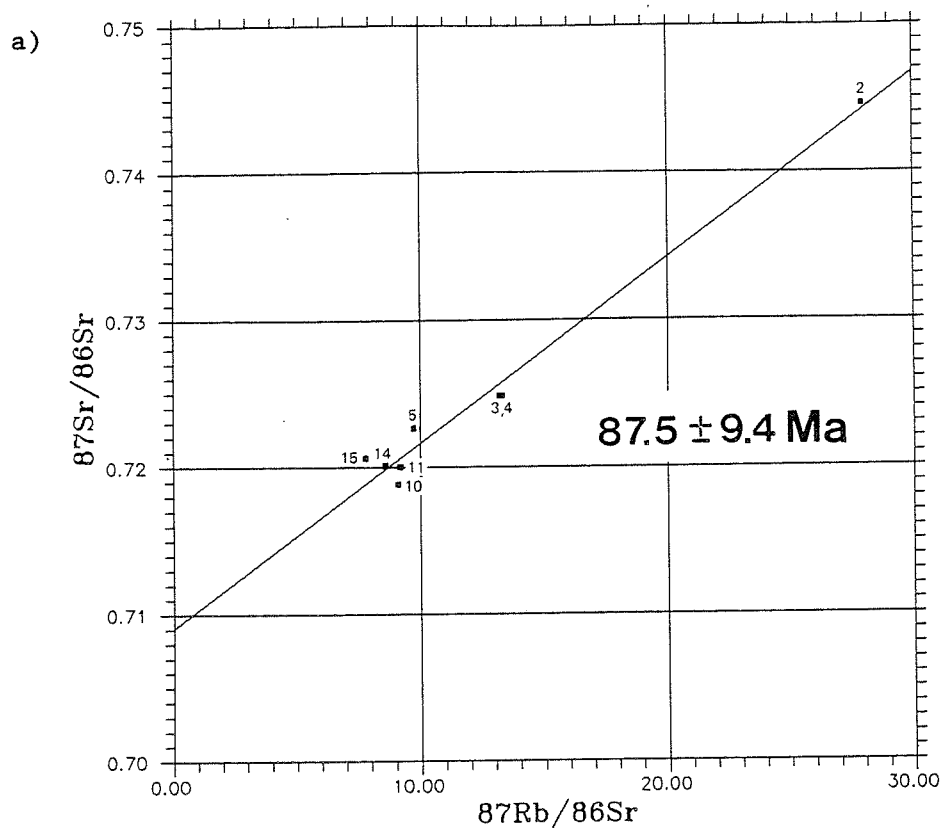


Figure 6 Isotope diagram for glauconies from 7231/04-U-01 a) with an errorchron b) with an errorchron which also includes carbonate (23; 7323/12-U-01).

By contrast, the Rb and Sr contents of glaucony from 7231/04-U-01 is similar to common glauconies of different ages from the literature, suggesting that point c is not an important mechanism in this case.

Mechanism b) involves a reopening of the glaucony grains for isotopic exchange after post-depositional closure. This may lead to partial or complete reequilibration of the isotopic systems on a local scale or on a larger scale depending on the degree of interaction with a fluid phase and on the fluid distribution and mobility. Complete resetting leads to a younger, post depositional age, as documented in glaucony-studies elsewhere (cf. Smalley et al. 1987). The "errorchron" in Figure 6a may indicate that such a process has occurred for the glauconies in 7231/04-U-01 leading to the younger (ca. 88 Ma) post-depositional date. The associated $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio (0.7095) is significantly higher than for Cretaceous (or Mesozoic-Cenozoic) sea-water composition (Figure 6a, Table 5). During the time interval indicated by the deposition and the 88 Ma date, the sea-water had a fairly constant $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic composition. The "errorchron" value therefore indicates that the fluid that caused the partial glaucony-reequilibration was not identical to sea-water composition. As pointed out earlier, the equilibration was not complete, leading to the irregular scattering of the points (Figure 6a).

The large uncertainties of the present data, and the poor knowledge of the detailed geological history of the area do not allow for more detailed speculations of the timing and significance of the event that led to the inferred post depositional disturbance of the isotopic systems.

Summary and conclusions

1) Glauconies from the Cretaceous sedimentary wedge within the Dia-Structure, (core 7323/12-U-01, 100.8 m level) could not be used for Rb-Sr isotopic dating although the glauconies satisfied common criteria for maturity and are chemically evolved. The Sr-isotopic compositions are all far from equilibrium with the Cretaceous sea-water composition. The irregular scattering of the Rb-Sr isotopic compositions in isotope plots, combined with the anomalously low Rb and Sr contents may have been caused by different mechanisms such as

- a) physical contamination by very minute clastic inclusions
- b) chemical inheritance of the Sr-isotopic composition of the substrate grain within the glaucony; i.e. lack of isotopic equilibration during the glaucony formation
- c) leaching of Rb (and possibly Sr) from the glaucony grains. All of these mechanisms may have contributed to the anomalous analytical results.

2) Glauconies from the Cretaceous sedimentary wedge within the Nordkapp Basin (core 7231/04-U-01, 52.3 and 52.6 m levels) have Rb-Sr isotopic compositions that are close to equilibrium with Cretaceous sea-water at the biostratigraphically determined deposition age. This is indicated by the Albian model ages for three of the glaucony fractions relative to sea-water (ca. 97-104 Ma), while four other fractions give slightly younger model ages.

A combination of all the glaucony fractions analysed from this core shows the lack of complete isotopic equilibrium, resulting in an errorchron with a date of ca. 88 Ma (± 9 Ma) with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio which is significantly higher than for Cretaceous sea-water. This suggests that the glauconies were subjected to disturbance by a fluid phase that was compositionally different from the sea-water some million years after the sediment deposition.

The present data from the Nordkapp Basin can be interpreted to support the biostratigraphical dating of the core (Aarhus et al. 1987) but they do not allow for more precise age determinations and geological modelling. In order to improve the age-determinations a more detailed procedure for treatment of the samples prior to dating is wishable. This involves 1) careful selection of the best parts of the core material based on detailed petrographic knowledge and 2) examination of the various fractions of glaucony by electron microprobe before the final selection of the fractions to be used for isotopic dating.

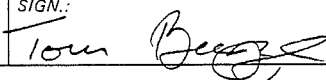
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REPORT

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REPORT TITLE: SHALLOW DRILLING ELF AQUITAINE / NORSK HYDRO / STATOIL BARENTS SEA 1987. ROCK MECHANICAL ANALYSIS. 21.3435.00//88 REPORT NO.:
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SUMMARY: Rock mechanical analyses have been carried out on five core samples in the project "Shallow drilling Barents Sea 1987" and on two samples from core 7323/12-U-01 in the present project. The analysis results of the first five samples, were reported in the main report of that project (Elvebakk et.al. 1988, Appendix A.8). The present report is a complete report containing all analysis result of the seven samples.				

KEY WORDS:	
Barents Sea	Rock mechanics
Shallow drilling	Cretaceous
Nordkapp Basin	

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ROCK MECHANICAL ANALYSIS

1. INTRODUCTION

Knowledge of rock mechanical behaviour is of importance in many aspects of petroleum exploration and production. For instance, knowing the stress (i.e. burial) history of a formation, one can better judge its potential as a source rock. Knowing the present stress field and its orientation, one can design drilling programs to avoid hole instabilities. The in-situ elastic/non-elastic behaviour plus rock strength parameters also play an important role here, as well as in stabilizing the wellbore against sanding during petroleum production.

Formation damage prevention or hydraulic fracturing/stimulation treatments are other tasks where rock mechanical input parameters from the near-wellbore region are necessary. Reservoir compaction/surface subsidence prediction requires information of mechanical behaviour of the entire structure, composed of the reservoir itself, the overburden and also the strata beneath. Rock mechanical parameters are also important for evaluation of flexuring of the crust due to, for instance, glacial isostatic depression.

Obtaining reliable rock mechanical data is not straightforward. Acoustic and density logs give elastic moduli, but the measurements are dynamic - and in general give different results from static measurements. Further, strength evaluation from logs is currently based on empirical correlations with static elastic properties - and may give erroneous results, in particular in weak formations.

In-situ stress measurements are normally performed by integrating the density log (vertical stress), by fracturing the formations or performing leakoff tests (minimum horizontal stress), and by RFT (Repeat Formation Tester) measurements in the reservoir (pore pressure). Methods based on expected trendlines for sonic or other measurements may reveal abnormally pressured zones.

Measurements on cores in the laboratory on the other side offer a possibility of direct determination of static elastic properties and strength parameters. Core alteration due to unloading, changes due to sample treatment or due to rock-fluid interactions represent uncertainties in tests besides direct experimental uncertainty, rock heterogeneity and size effects.

Laboratory experiments serve not only as a possibility of getting data for current operations. As important, in particular in this context, is to collect information and establish correlations and experience for future use. This includes:

- Establish data base of mechanical properties for key formations
- Explore elastic/non-elastic and strength behaviour vs. stress to obtain a picture of the stress-field and eventually stress history.
- Relate static and dynamic properties with rock strength for future log evaluation.

In the following, we present results and discussion of a series of experiments performed with samples from the 1987 shallow drilling program in the Barents Sea.

2. LABORATORY EXPERIMENTS

2.1 Samples

The following 54 mm diameter core plugs, see Table 1, were selected for rock mechanical testing:

Table 1: Overview of the samples.

Plug	Core	Depth [m]	Age	Lithology
D5189	7230/05-U-06	93.0	M. Triassic	Clayey siltstone
D5190	7230/05-U-05A	43.0	M. Triassic	Clayey siltstone
D5193	7230/05-U-03	64.5	U. Triassic	Sandstone
D5191	7230/05-U-03	105.4	U. Triassic	Shale
D5192	7230/05-U-03	111.1	U. Triassic	Shale
D5158	7323/12-U-01	103.5	L. Cretaceous	Greensand
DX	7323/12-U-01	128.2	L. Cretaceous	Shale

The samples, which had been stored in plastic bags with remaining formation water, were in the process of drying out when received in the laboratory. This is expected to have a large influence on the results, in particular for rocks with high clay content. We should therefore use the results more as guidelines rather than relying too much on the quantitative results.

To perform mechanical testing in the triaxial cell, 1½" diameter x 3" length samples had to be drilled out from the cores. This drilling process turned out to be very difficult, particularly in the clay rich rocks. In the cases of samples D5191 (7230/05-U-03, 111.1 m) and DX (7323/12-U-01, 128.2 m) it was not possible to obtain suitable core plugs.

2.2 Unconfined acoustic measurement

Prior to preparation for failure testing, acoustic velocities were measured with the core plugs at atmospheric conditions. Both P- and S-wave velocities were measured axially, while in the radially direction only the P-wave velocity was recorded. The measuring frequency is in the range of 250-500 kHz. The results are summarized in the Table 2. All velocities are given in km/sec.

Table 2 P- and S-wave velocities measured at atmospheric conditions.

#	Lithology	Density [g/cm ³]	v _{pz}	v _{pr}	v _{sz}	v _{pz} /v _{sz}	v _{pr} /v _{pz}
Block: 7230:							
D5189	Clayey Siltstone	2.28	2.73	3.22	1.72	1.59	1.18
D5190	Clayey Siltstone	2.11	2.19	2.62	1.63	1.34	1.20
D5193	Sandstone	1.85	1.80	1.95	1.20	1.50	1.08
D5191	Shale	2.25	2.39	3.05	1.72	1.39	1.28
D5192	Shale	2.17	2.21	2.64	1.55	1.43	1.19
Block: 7323:							
D5158	Greensand	2.01	1.99	1.68	1.55	1.28	1.35
DX	Shale	-	1.86	2.49	-	-	1.34

Sample no. DX, which was a smectite-rich shale, could not be preserved at room conditions due to severe slaking. This prevented drillout of core plugs, but acoustic measurements could still be performed by applying a compressive force to the ultrasonic transducers, sufficient to close most of the newly opened fractures. Fig. 1 shows the difference between the acoustic signal recorded with the (moist) sample in air and soaked in fresh water. Exposure to water causes a dramatic reduction in signal amplitude, i.e. a large acoustic attenuation.

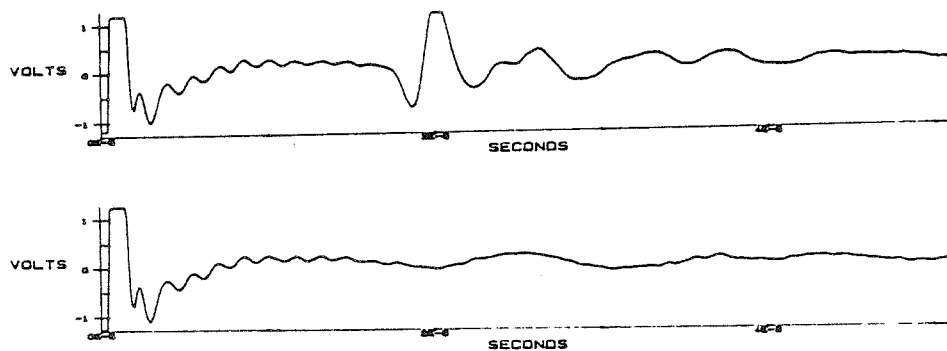


Figure 1: Acoustic P-wave signatures with shale sample DX (7323/12-U-01,128.2 m) in a dry atmosphere (above) and when exposed to water (below).

2.3 Instrumentation for rock mechanical tests

The present work has been carried out in IKU's Formation Mechanics laboratory. Figure 2 shows a sketch of the experimental set-up. The sample is confined in a plastic sleeve inside a triaxial cell. Steel pistons are pressed against its end surfaces. The load frame (Robcon OY, Finland) gives force to the lower piston which may be moved by displacement control (constant strain rate) or force control. In the present experiments, the displacement control was used. A hydraulic system is pumping oil into the cell around the plastic sleeve to give the required confining pressure. This may be regulated to follow the axial stress (hydrostatic testing) or to be maintained at a constant value during loading/unloading (triaxial testing). During the tests, axial force and confining pressure are measured together with axial and radial displacements. The latter are measured with 3 LVDT's (linear variable displacement transducers) which are placed in a horizontal plane near the middle of the sample, and with 120° angle between each other. - Broadband acoustic transducers (~ 0.1 - 1 MHz) are placed inside the steel pistons as well as in the confining oil, where they are pressed with spring forces against the wall of the sleeve (see Figure 3). This gives the possibility of measuring ultrasonic velocities in two directions

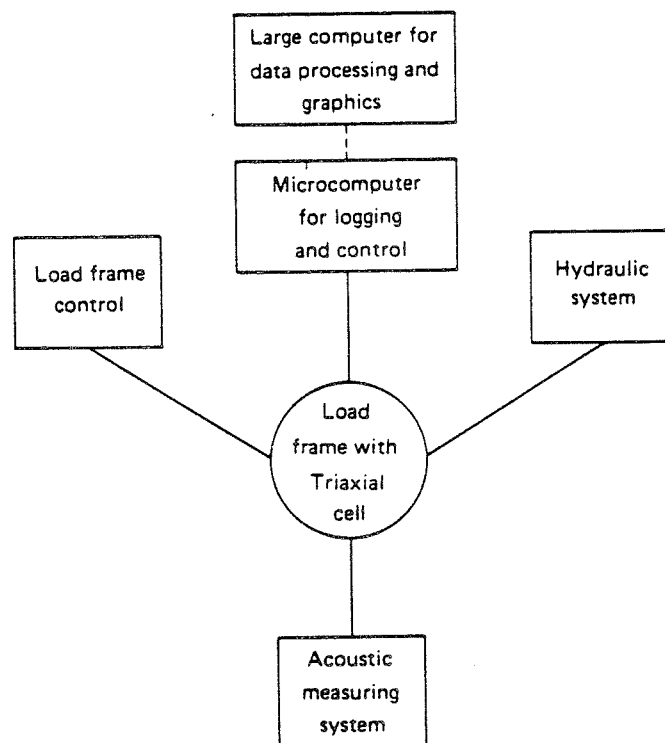


Figure 2: Sketch of the experimental set-up.

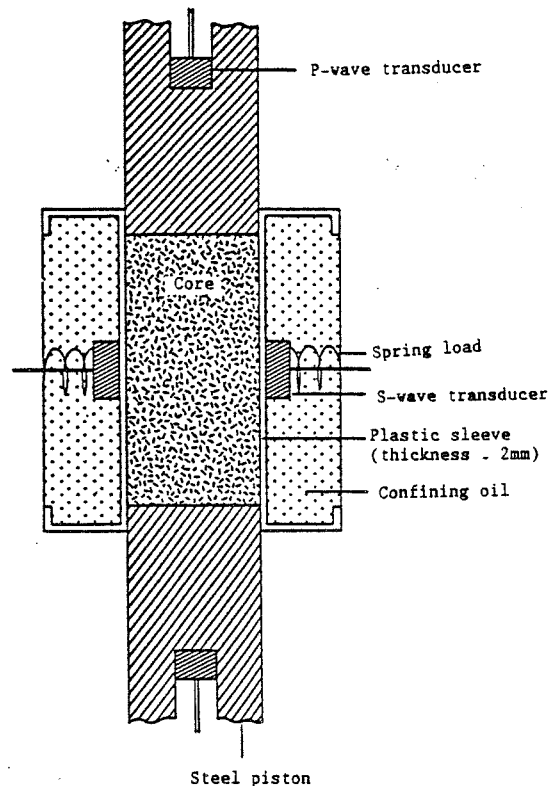


Figure 3: Inside look in the triaxial cell showing acoustic transducer configuration.

during a laboratory test. - In the present experiments, Panametrics P-wave transducers were placed inside the steel pistons in order to be able to record the vertical wave velocity. A thin layer of glue (Panametrics Shear Wave Couplant) is used to ensure a good acoustic coupling between the transducers and the pistons as well as between pistons and sample. At low pressures (< 3 MPa), the coupling may be too poor to allow reliable measurements of the axial wave velocities. Panametrics S-wave transducers were placed in the confining oil.

2.4 Uniaxial Compression Tests

A total of three uniaxial tests were performed, in one of them acoustic measurements were included. The stress path is shown in Figure 4. The E-modulus has been defined as the slope at a stress level corresponding to 50% of the ultimate strength. Table 3 gives a list of measured E-modulus, uniaxial compressive strength, shear modulus and Poisson's ratio. The

stress-strain response obtained during the tests are shown in Figure 5.a, 5.b and 5.c.

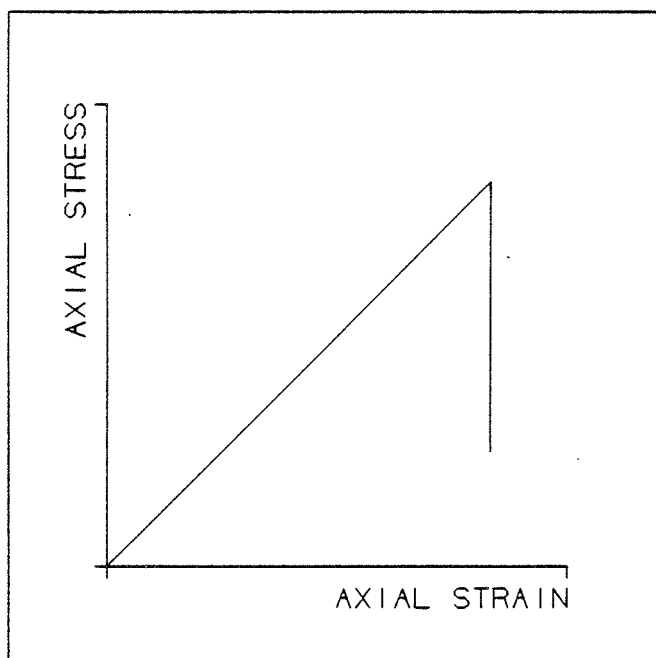


Figure 4: Stress path in uniaxial test.

In an uniaxial test without a confining oilbath, it is difficult to get a good acoustic coupling between the transducer, the rubber sleeve and the sample. The acoustic measurements in the radial direction were not reliable during this test. The P-wave velocity measured on plug 5193 (7230/05-U-03, 64.4 m) was 2930 m/s with an axial load of 11.3 MPa.

Table 3 Measured uniaxial compressive strength, E-modulus, Poisson's ratio and shear modulus for cores from Block 7230.

Plug	Uniaxial compressive strength [MPa]	E-modulus [GPa]	Poisson's ratio	Shear modulus [GPa]
D5189	30.6	2.8	0.00	1.4
D5192	25.5	2.6	-0.01	1.3
D5193	11.3	1.2	0.07	0.6

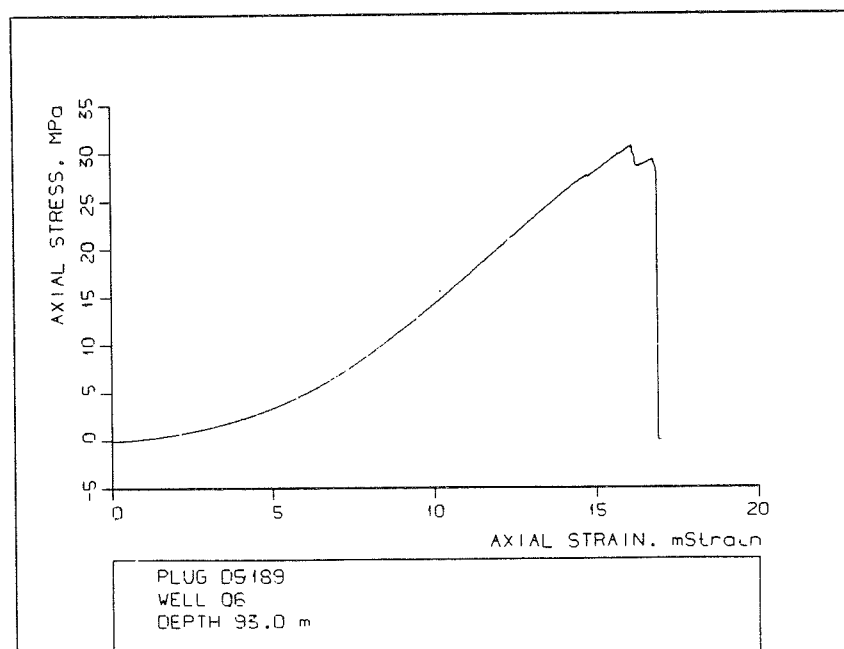


Figure 5.a: Axial stress vs. axial strain for plug D5189 (7230/05-U-06,93.0 m).

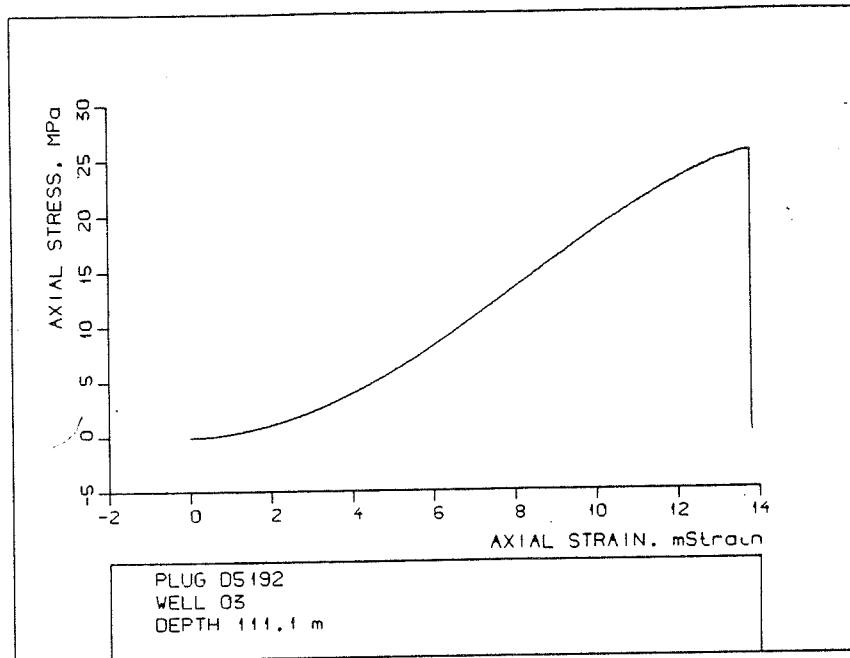


Figure 5.b: Axial stress vs. axial strain for plug D5192 (7230/05-U-03,111.1 m).

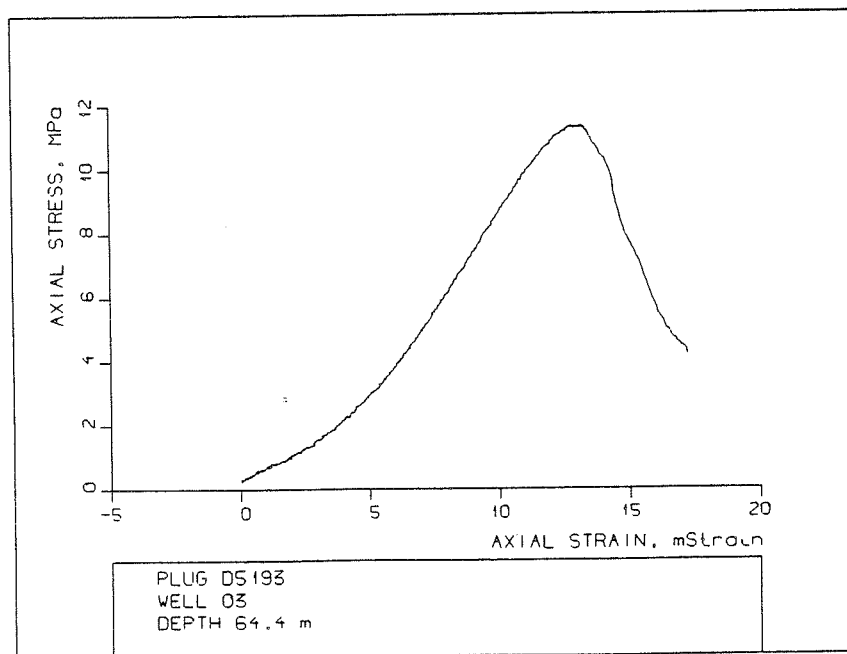


Figure 5c: Axial stress vs. axial strain for plug D5193 (7230/05-U-03,64.4 m).

2.5 Hydrostatic and Triaxial Compression Test

The stress path is shown in Figure 6. One core (plug D5190, 7230/05-U-05,43.0 m) was undertaken a triaxial test. The sample is brought hydrostatically to the confining pressure. From here the confining pressure is held constant and the axial load is increased until failure. The stress-strain response is shown in Figure 7. The readings from all three LVDT's are shown in the left part of the plot. Below we summarize, (Table 4), the measured peak strength and elastic moduli.

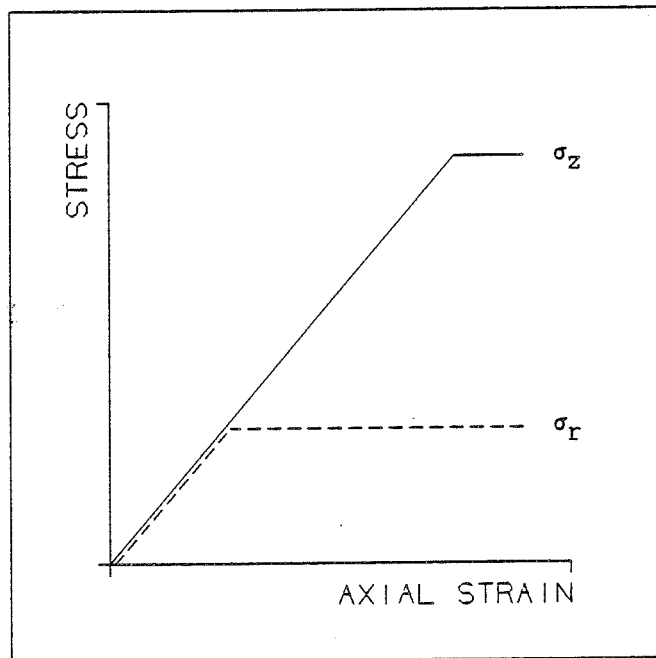


Figure 6: Stress path in triaxial test.

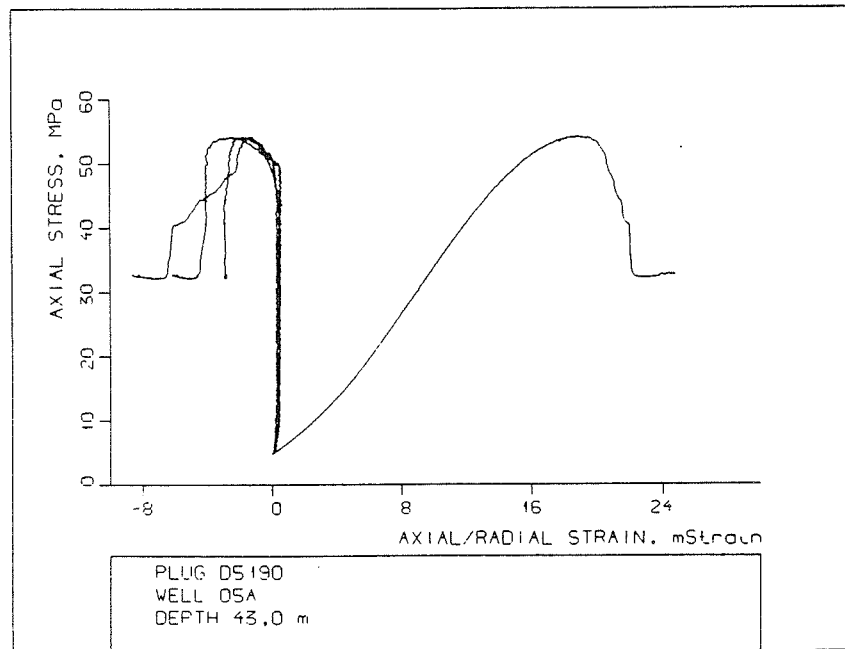


Figure 7: Stress-strain response for plug D5190 (7230/05-U-05,43.0 m) radial strains are the three curves in the left part of the plot

Table 4 Measured peak stress, E-modulus, Poisson's ratio, shear strength and shear modulus for plug D5190 (7230/05-U-05,43.0 m)

Confining Pressure [MPa]	Peak Stress [MPa]	E-modulus	Poisson's ratio	Shear Strength [MPa]	Shear modulus [GPa]
5	53.9	3.6	-0.0	24.4	1.8

During the test the radial P- and S-wave and axial P-wave velocities were measured. In Figure 8 the velocity is plotted against axial strain. Figure 8.a shows the results from the hydrostatic loading and Figure 8.b shows the results from the triaxial part. The velocity at hydrostatic conditions, 5 MPa, at failure and the maximum reading is tabulated in Table 5.

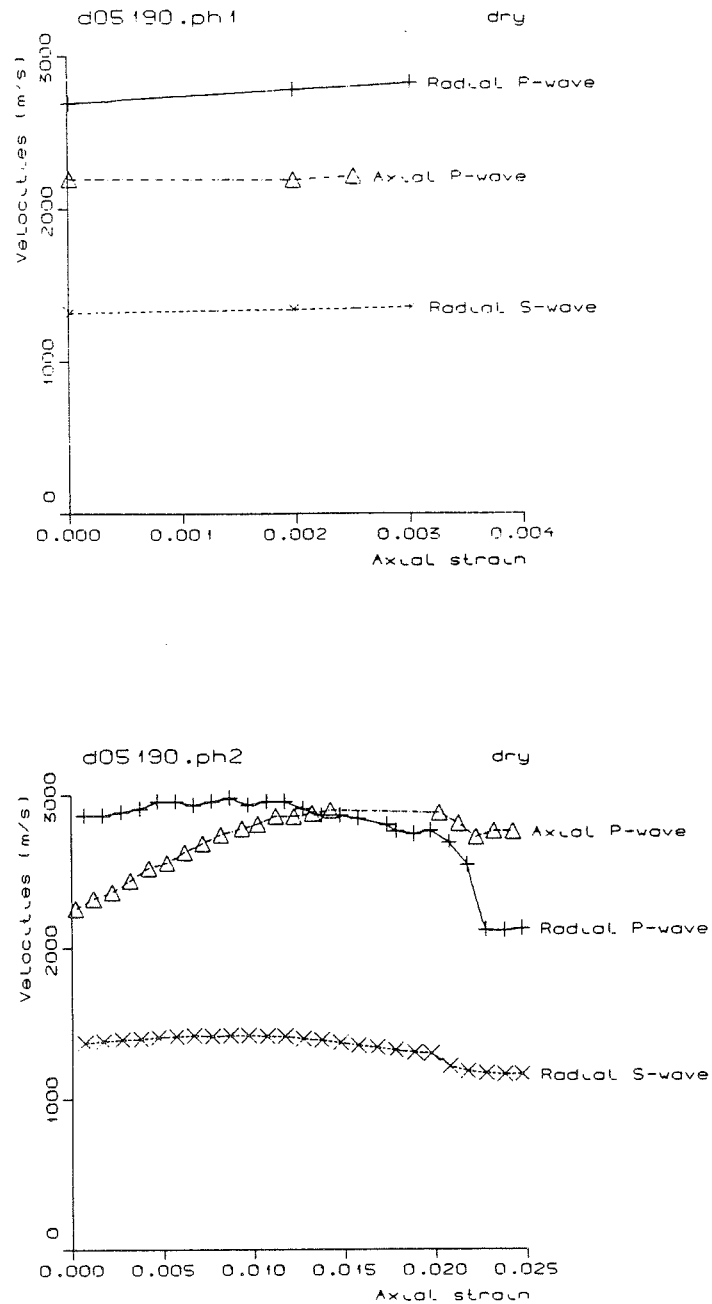


Figure 8 P- and S-wave velocity vs. axial strain, measured on plug D5190
(7230/05-U-05,43.0 m)
a) Hydrostatic loading
b) Triaxial part

Table 5 Measured velocities at hydrostatic conditions, at failure and the maximum reading (plug D1590, 7230/05-U-05,43.0 m).

	$\sigma_H = 5 \text{ MPa}$	$\sigma_Z = 53.9 \text{ MPa}$	Maximum reading
v_{pz}	2210	2870	2890
v_{pr}	2810	2740	2970
v_{sr}	1350	1310	1410

2.6 Multiple Failure Test

The loading path is shown in Figure 9. The sample is brought hydrostatically to a confining pressure, σ_{r1} . Then the axial load is increased and the sample is deformed axially until initial yielding is observed. The radial pressure is increased to the next predetermined level, σ_{r2} . From here the axial load is increased until initial yielding occurs at the new confining pressure, etc. This gives a possibility to measure the entire failure envelope using only one core plug.

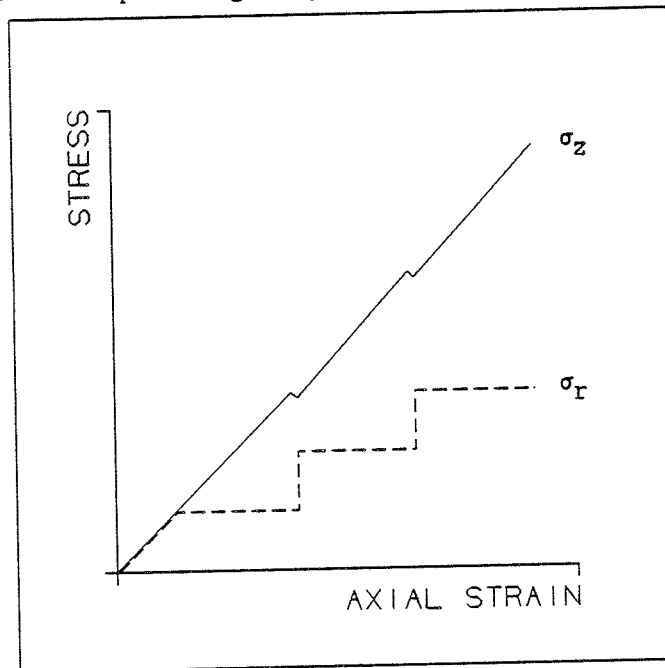


Figure 9: Stress path in multiple failure test, plug D5158 (7323/12-U-01,103.5 m).
 σ_z : Axial stress
 σ_r : Confining pressure

One multiple failure state test with acoustic measurement has been carried out on plug D5158 (7323/12-U-01,103.5 m). The stress-strain plot is shown in Figure 10. Table 6 summarizes the results.

Table 6 Results from the multiple failure test on plug D5158 (7323/12-U-01,103.5 m).

Plug	Confining Pressure [MPa]	Peak Stress [MPa]	Shear Strength [MPa]
D5158	5	50.2	22.6
	10	63.1	26.5
	15	71.9	28.4

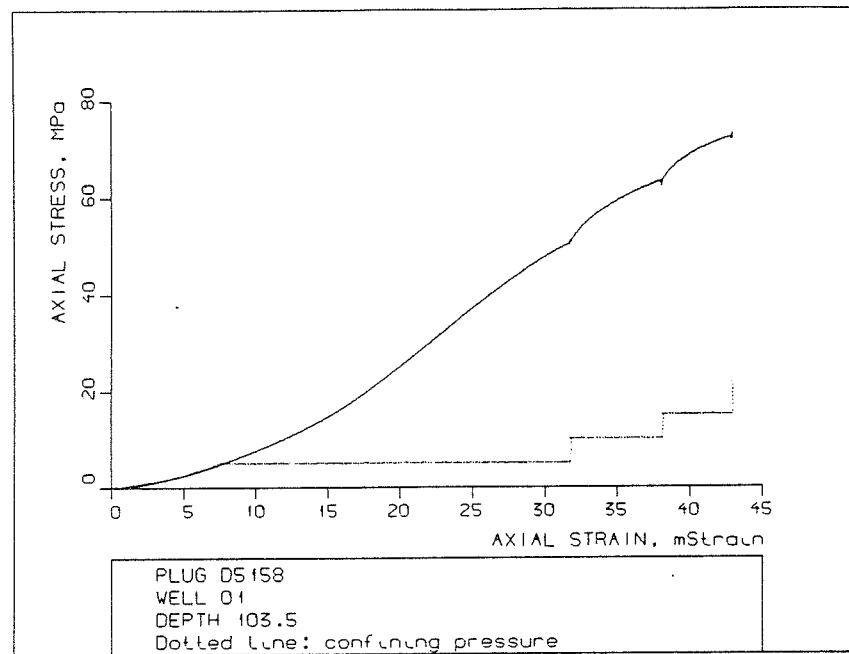


Figure 10: Stress-strain response from the multiple failure test, plug 5158 (7323/12-U-01, 103.5 m).

During this test the radial P- and S-wave and axial P-wave velocity were measured. In Figure 11 the velocity is plotted against axial strain. The readings at the peak stress levels are tabulated in Table 7.

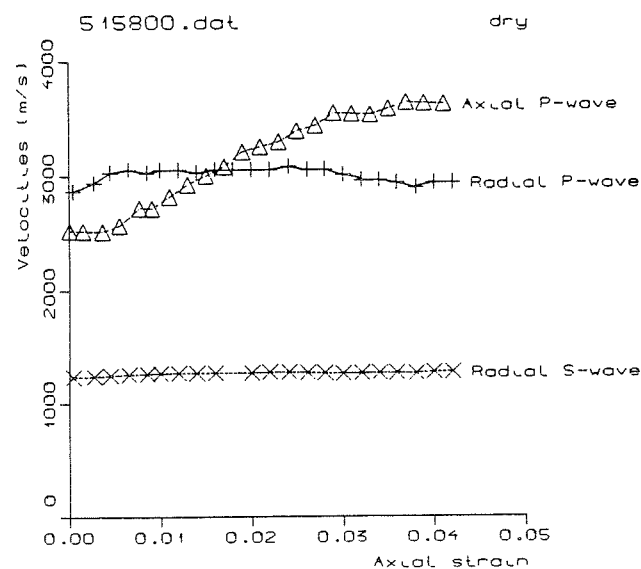


Figure 11: P- and S-wave velocity vs. axial strain measured on plug D5158 during the multiple failure test.

Table 7 Velocities measured at peak stress levels, plug D5158 (7323/12-U-01,103.5 m).

	$\sigma_H = 5 \text{ MPa}$	$\sigma_Z = 50.2 \text{ MPa}$	$\sigma_Z = 63.1 \text{ Mpa}$	$\sigma_Z = 71.9 \text{ Mpa}$
v_{pz}	2710	3530	3630	3620
v_{pr}	3050	3010	2890	2940
v_{sr}	1260	1270	1270	1280

3. DISCUSSION

The amount of data collected during this study is not sufficient to draw any firm conclusions regarding mechanical behaviour and stress history. We feel, however, that it represents a starting point, and as such, it is of value to inspect closer the data recorded and the information that can be extracted.

3.1 Acoustic measurements

The acoustic measurements performed at unconfined conditions (Section 2.2), show a significant acoustic anisotropy, which is largest in the shales and in the greensand. This is expected, since these rocks are strongly bedded by flat clay minerals oriented parallel to each other. The sound velocity is as expected higher in the direction parallel to the bedding than perpendicular to it.

Also in the sandstone there is a significant anisotropy. In previous work (Holt et. al., 1987), we have proposed that acoustic anisotropy can be related also to cracks opened during unloading. This is particularly valid in sandstones, and can be used to aid evaluation of in-situ stress directions, and hopefully, at a later stage, also magnitudes. Sedimentological studies including thin sections, show a massive sandstone without any lithological microlamination. We may therefore conclude that the measured anisotropy of the sandstone is due to stress release.

It is, anyway, important to be aware of the acoustic anisotropy when analysing logs and seismic data, since logs will read mainly the vertical and seismics the horizontal velocity. Not taking the anisotropy into account may lead to erroneous depth estimates (Banik, 1984).

During loading, the sound velocities change. In the case of uniaxial compression, the P-wave velocity in the sandstone sample was found to increase from 1850 to 2930 m/s when σ_z increased from 0 to 11.3 MPa. This shows the potential of using the acoustic log as a stress indicator. In the triaxial test with sample D5190 (clayey siltstone at 43 m in core 7230/05-U-05), one can see not only a velocity increase during loading, but also the development of a strong acoustic anisotropy due to the anisotropic loading of the rock. Beyond failure this causes the vertical velocity to exceed the horizontal. This effect has been discussed in more detail elsewhere (Holt

and Fjær, 1987), and is related to the development of an oriented microcrack pattern prior to rock failure. This is yet another documentation that acoustic velocity anisotropy can be used to monitor stress field anisotropy. The main, fundamental problem lies in distinguishing between lithological and stress-induced anisotropy.

A particularly interesting observation is the dramatic increase in acoustic attenuation when exposing a smectite rich, fractured shale (sample DX 7323/12-U-01, 128.2 m) to water. This effect, although not investigated in detail, is likely to be caused by chemical reaction, and indicates a potential for acoustic log detection of swelling clay zones.

3.2 Rock mechanical measurements

Dynamic elastic moduli for the unconfined situation can be derived from the acoustic data in Section 2.2. The dynamic Young's modulus, defined as:

$$E_{\text{dyn}} = \rho v_{\text{sz}}^2 \cdot \frac{3v_{\text{pz}}^2 - 4v_{\text{sz}}^2}{v_{\text{pz}}^2 - v_{\text{s}}^2} \quad (\text{x.1})$$

can be tabulated as follows (Table 8):

Table 8 Dynamic Young's modulus.

Sample	Core	Depth [m]		Unconfined E_{dyn} [GPa]
D5189	7230/05-U-06	93.0	Clayey Siltstone	16.0
D5190	7230/05-U-05	43.0	Clayey Siltstone	9.9
D5193	7230/05-U-03	64.5	Sandstone	5.9
D5191	7230/05-U-03	105.4	Shale	12.8
D5192	7230/05-U-03	111.1	Shale	10.6
D5158	7323/12 -U-01	103.5	Greensand	7.0

During failure tests, E_{dyn} increases slightly, in accordance with the increase in sound velocities. It is therefore clear that E_{dyn} exceeds its statically measured counterpart by a factor of at least 4-6 in the uniaxial tests, regardless of lithology.

The uniaxial strength (σ_c) increases with the static E-modulus:

$$\sigma_c \text{ [MPa]} \sim 10 E_{\text{stat}} \text{ [GPa]}$$

The factor 10 must not be taken to lithology, since the relation is based on just 3 experiments, but the relation is not off scale from what has been found from rock testing elsewhere (Holt et. al., 1987; and references cited therein). Notice, however, the correction that needs to be made due to the static-dynamic disagreement when logs are to be interpreted for strength parameters. More data is required to establish reliable conversion schemes between E_{stat} , E_{dyn} and σ_c .

It is seen from all the tests performed that the stress-strain curves are nonlinear. The rock stiffness increases with increased loading. This is due to closing of preexisting microcracks in the samples. If we believe that all the microcracks were opened during unloading while coring, the transition between nonlinear and linear behaviour can be used as a guideline (together with acoustic measurements) to establish previous stress levels experienced by the rock. Again, the amount of data here is too scarce to allow such an investigation.

Finally, in the case where the failure envelope was explored (sample D5158, 7323/12-U-01, 103.5 m), the peak stress clearly increase with confining pressure. The increase is, however, lower at the higher confining pressure, meaning that the failure criterion is not linear. This is commonly observed in sedimentary rocks, although the linear Mohr-Coulomb failure criterion is often used in practical calculations.

4. CONCLUDING REMARKS

A mechanical property analysis has been carried out with selected samples of sandstone, siltstone, shale and greensand from the shallow drilling program in the Barents Sea. The rocks were not properly preserved prior to testing, and the amount of data obtained is modest. We have, however, found:

- i) Static are exceeded by dynamic elastic moduli by a factor of at least 4-6 regardless of formation.
- ii) Correlations between static and dynamic modulus and peak strength can be found. These findings (i and ii) have importance for future mechanical property logging.
- iii) Acoustic velocities, velocity anisotropy and elastic nonlinear behaviour may be tracked back to the in-situ stress state.

Acoustic anisotropy is also due to lithological bedding. This is important for correlations between seismic and log readings.

- iv) Acoustic attenuation may be a sensor of smectitic, swelling shales.
- v) The failure criterion is - as expected - seen to be nonlinear.

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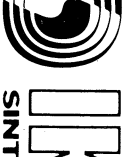
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Shallow Drilling

Elf Aquitaine/Morsk Hydro/ Statoil

Additional studies

Barents Sea 1987



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