

Magnetostratigraphy of the Tertiary Harre core, Denmark.

NIELS ABRAHAMSEN

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ABSTRACT

The Tertiary Harre Core, which is ca. 283 m long, covers a major part of the Danish Tertiary sedimentary sequence, including the Palaeocene formations (34.9 m) comprising the Kerteminde Marl (12.4 m), the grey slightly to non-calcareous clay (14.6 m), and the Holmehus Formation (7.9 m), the Ash Series, i.e. the Ølst & Fur Formations (31.1 m), the Eocene formations (13.4 m) comprising the Røsnæs Clay Formation (4.9 m), the Lillebælt Clay Formation (8.5 m), and the Oligocene formations (167 m) comprising the Viborg Formation (58 m), the Branden Formation (52 m), and the Vejle Fjord Formation (57 m).

A total of 330 palaeomagnetic specimens were collected and investigated magnetically. The NRM (natural remanent magnetization) intensity varies up to about 3 orders of magnitude (between 0.2 and 200 mA/m), the NRM intensity being essentially a function of mineralogy. Especially the Røsnæs Clay Formation and the Viborg Formation show high NRM intensities. The NRM intensity may thus be diagnostically useful in stratigraphical correlations.

The geomagnetic polarity record is less clearly depicted, as some of the sediments are likely to have been partly remagnetized by viscous magnetic effects after the deposition and early diagenetic processes. The VRM (viscous remanent magnetization) has therefore smeared out the original steep inclination values, which are only partly restorable by the alternating field demagnetization technique.

Although somewhat uncertain, a preliminary correlation with the global geomagnetic polarity scale is tentatively presented for the part of the Danish Tertiary which is present in the Harre core.

N. Abrahamsen, Geophysical Laboratory, Department of Earth Sciences, Aarhus University, Finlandsgade 6-8, DK-8200 Århus N, Denmark.

INTRODUCTION

In recent years the magnetostratigraphic technique has become a useful stratigraphical tool in studies of sedimentary sequences because of the global validity of the geomagnetic polarity scale.

The purpose of the present contribution is to present in greater detail than hitherto (Abrahamsen, 1988), and to tentatively interpret, the magnetic polarity results from the Harre sedimentary core, this core being the first major Tertiary sequence which has been magnetically investigated in Denmark, and to discuss the magnetostratigraphical implications.

The Harre borehole, situated in Salling in North Jutland, (see Introduction, this issue, Fig. 1), is special by giving a cored section with nearly 100% recovery of parts of the Tertiary sequence in Denmark, notably the Oligocene Viborg, Branden, and Vejle Fjord Formations, making up 167 m of the total 283 m cored. For full stratigraphical and lithological descriptions the reader is referred to Friis & Nielsen (1980) and Nielsen, Friis & Korsbech (1994, this volume).

In contrast to most of the Mesozoic polarity scale with rather long average polarity epochs, the Tertiary polarity sequence is characterized by polarity epochs

of somewhat shorter durations, the average polarity duration being around 0.3 Ma for the younger Tertiary (< 45 Ma) and ~ 0.9 Ma for the older part (45 to 75 Ma), respectively (Cox, 1969).

As the transition zone from one polarity to the opposite one, on a geological timescale, is very short, typically between 2,000 and 10,000 years in cases investigated in details, recognition of specific polarity epochs or events in a lithological sequence may be regarded as rather sharp chronostratigraphical markers, although the absolute age of the Tertiary polarity scale is only accurate to within a few per cent (e.g. Abrahamsen *et al.*, 1984).

Hitherto, the only magnetostratigraphic data published from the Danish Tertiary originate from the volcanic ashlayers in glacially dislocated coastal cliffs in N. Jutland with folded and block faulted ash series of Lower Eocene age. The ash series, comprising about 200 thin ash layers in some 20 m of diatomaceous clays, show a reversal sequence of 3 normal and 3 reversed polarity zones (Sharma, 1969).

More recently, Selandian (Ali *et al.*, 1994) and Paleogene and Neogene Tertiary sequences exposed in the Limfjord area and at Gram in Jutland have been magnetically investigated (Beyer, 1987a & b; Beyer *et al.*, 1988), but are not yet published in detail.

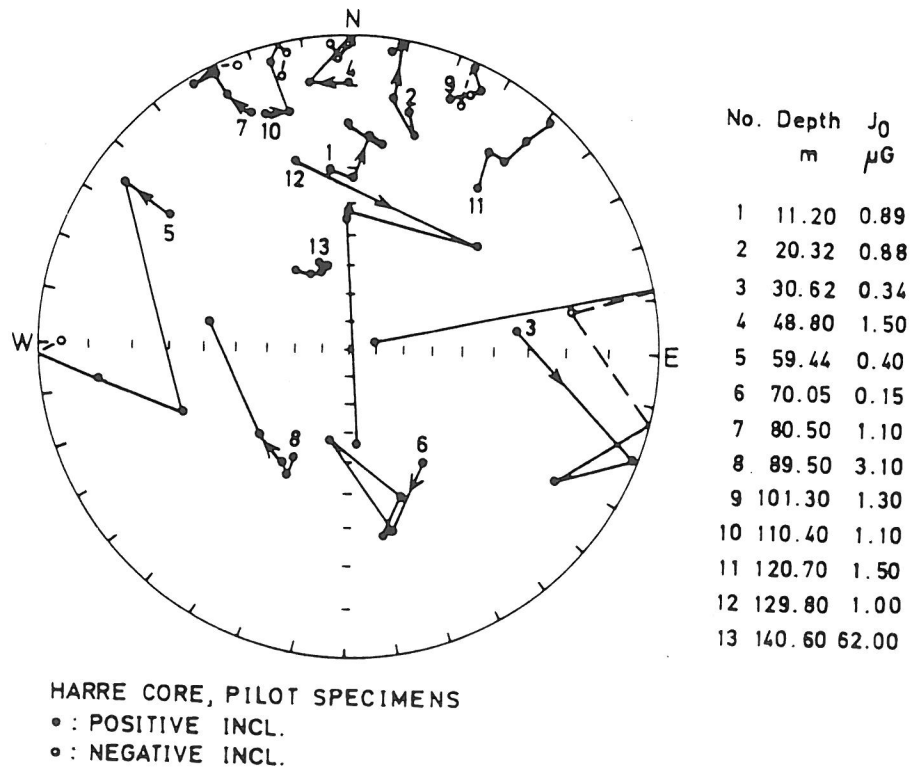


Fig. 1a: A.F. demagnetizations of 13 pilot specimens (stereographic projection). A majority of specimens show a fairly good directional stability (declinations are arbitrary because of lack of absolute orientation of the core segments).

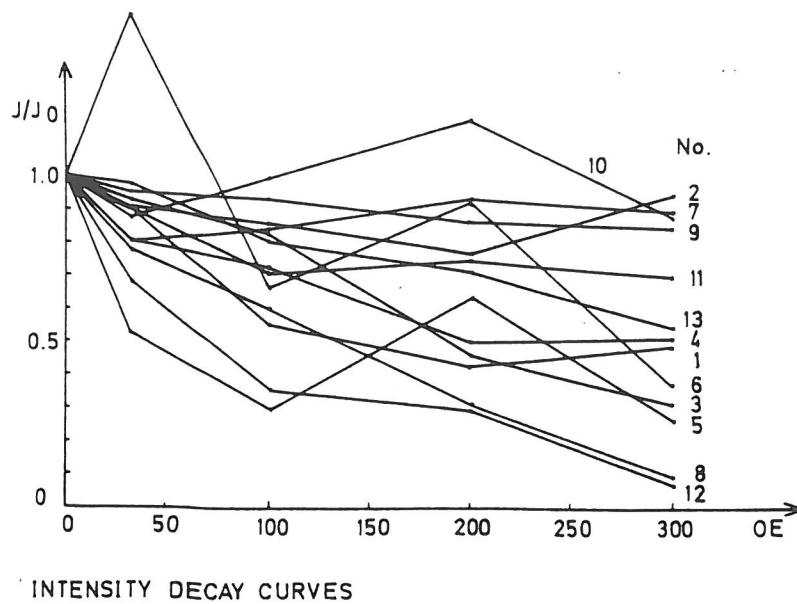


Fig. 1b: Intensity decay curves for the 13 pilot specimens. Median destructive fields vary between 30 and >300 Oe. (x .1 mT)

MAGNETIC METHODS

The palaeomagnetic specimens of the Harre core were collected shortly after the boring to secure optimum conservation of the magnetic properties. The specimens were sampled in 1 inch x 1 inch cylindrical polystyrene beakers, which were pressed into (supposed) undisturbed parts of the core, orthogonal to the core axis.

As only the vertical orientation of the core was known, only the inclination and intensity could be determined. To obtain at least a local, relative control of the magnetic vector, however, 3 specimens with the same azimuthal orientation were sampled from each core section (the section usually being 1.5 m long).

This routine was followed between 9 meter below surface (m.b.s.) and 189 m.b.s., i.e. including the Early Eocene Røsnæs Clay Formation, resulting in 333 specimens. Below 189 m.b.s. the sediment was too stiff for this sampling technique, and only 15 specimens were further sporadically sampled from the Ølst- and Fur Formations and 9 specimens from the Holmehus Formation. Subsampling by means of a diamond drill in these parts of the core was tried, but the fissility of the finely laminated clays made this sampling technique unfeasible. From the Danian limestone no palaeomagnetic specimens were sampled.

A total of 13 pilot specimens were arbitrarily selected (every 10 m) down through the top 140 m of the core, and stepwise A.F. demagnetized in alternating peak fields (A.F.) of 33, 100, 200, and 300 Oe. ($\times 0.1$ mT). After this initial study, the NRM (Natural Remanent Magnetization) was measured on the remaining specimens by means of a low-noise spinner magnetometer (Digico Ltd.; Molyneux, 1971); the specimens were then A.F. demagnetized in 3 orthogonal directions in a peak field of 100 Oe and remeasured on the Spinner magnetometer. Finally, the specimens were demagnetized in 200 Oe during thumbing and remeasured on a 3-axial SQUID magnetometer.

THE PILOT STUDY

In Fig. 1 the magnetic data from the pilot specimens are compiled, recalling that the declinations are arbitrary. The directional stability is variable and so is the coercivity, the m.d.f. (median destructive field) vary-

ing between 30 and >300 Oe.

In most cases there are more than one magnetic component. Only one pilot specimen (140.60 m.b.s.), however, shows an NRM inclination close to the present days' axial dipole inclination of the site, $I_0 = 71^\circ$. This indicates that, although viscous, remanent components are indeed present, the recent viscous overprints have not entirely destroyed older components. Three pilot specimens with NRM intensity below 0.5 mA/m (20.65, 59.44, and 70.05 m.b.s.) all show a poor directional stability, and in two cases (59.44 and 129.80 m.b.s.) the coercivities are very low. Comparing the NRM intensity J_0 (Fig. 2) with J_{100} (Fig. 3) and J_{200} (not shown) for the whole core, the above conclusions appear to hold in general, the m.d.f. typically being slightly more than 100 Oe.

MAGNETIC INTENSITY

The NRM intensity J_0 (Fig. 2) varies between 0.1 and 200 mA/m and is often a sensitive indicator of lithological variations, the intensities being dominated mainly by the magnetic content in the clay fraction.

The intensity of the few specimens (225-228 m.b.s.) from the Holmehus Formation and around 205 m.b.s. from the Fur Formation varies between 0.2 and 10 mA/m, while the Røsnæs Clay Formation (around 186 - 190.9 m.b.s.) shows intensities between 7 and 54 mA/m. The Lillebælt Clay Formation (177.5 - 186 m.b.s.) again shows low intensities between 0.1 and 2 mA/m.

Magnetically the Røsnæs Clay thus differs significantly from the other Paleogene sediments in the core.

Most of the Early Oligocene (Rupelian) Viborg Formation typically shows intensities between 10 and 100 mA/m (between 169 and 132 m.b.s.). The base of the formation between 177.5 and 169 m.b.s., however, shows a gradual increase in intensity, and above 132 m.b.s. a very sharp decrease is seen, which must indicate a lithological or geochemical change. Comparing with the lithology (Friis & Nielsen, 1980 and Nielsen *et al.*, 1994, this volume) it appears that the low intensity correlates with the presence of pyrite. When pyrite is present, the magnetic intensity is low, probably because only little Ferric iron has been left from initial detrital magnetites or diagenetically formed maghemites.

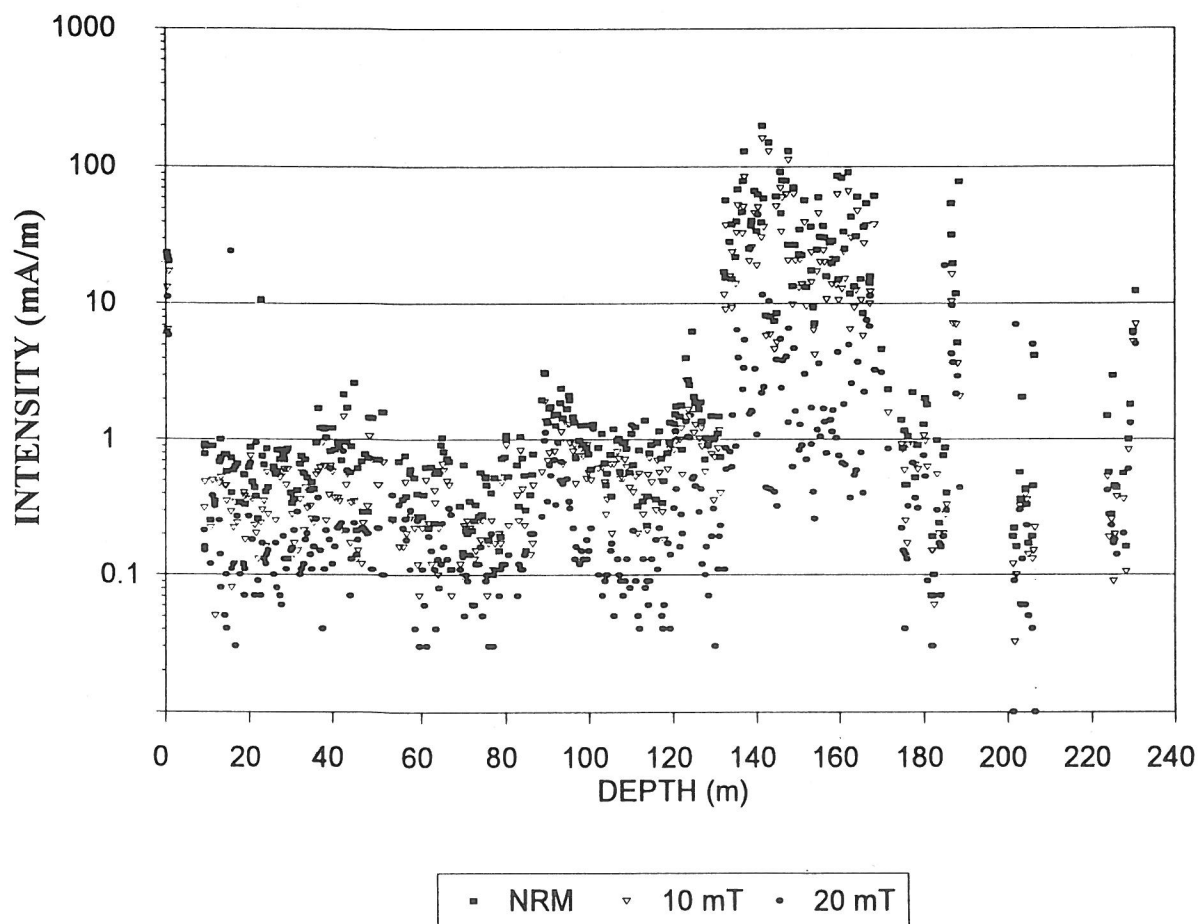


Fig. 2: Remanent magnetic intensity of the Harre Core.

The intensities of the Late Oligocene Branden Formation (119.5 to 67.5 m.b.s.) and Vejle Fjord Formation (67.5 - 9.7 m.b.s.) show low intensity values, typically between 0.2 and 2 mA/M. A certain cyclicity is seen with peak values at 87 and ca. 37 m.b.s., and a drop is found around 87 m.b.s..

THE HARRE CORE POLARITY RECORD

To investigate in greater detail the polarity of the individual formations of the Harre core, the inclinations are redrawn to the right in Figs. 5 to 10 with a blown-up depth scale. The values for NRM, 100 Oe and 200

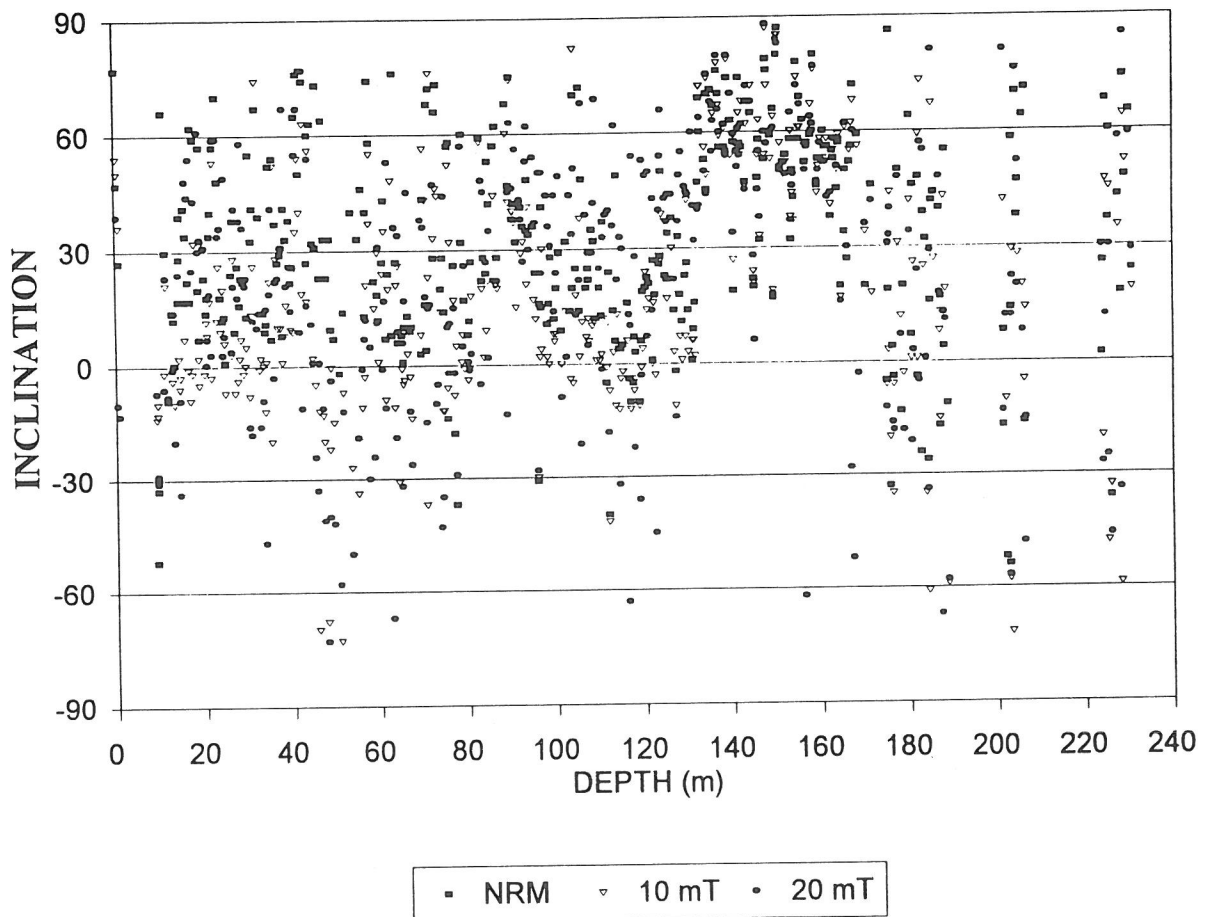


Fig. 3: Inclination of the Harre Core. Values shown are for the NRM and after A.F. demagnetization in 10 and 20 mT, respectively.

O_e (x 0.1 mT) are given with different signatures, and the latter values are connected by a solid line.

To the left is shown a polarity interpretation in black (N = normal) and white (R = reverse polarity). It

should be stressed, however, that this interpretation is not unambiguous because of the magnetic as well as the lithological, mineralogical, geochemical and rheological properties of the sediments involved.

The following criteria may be set up as a guidance to

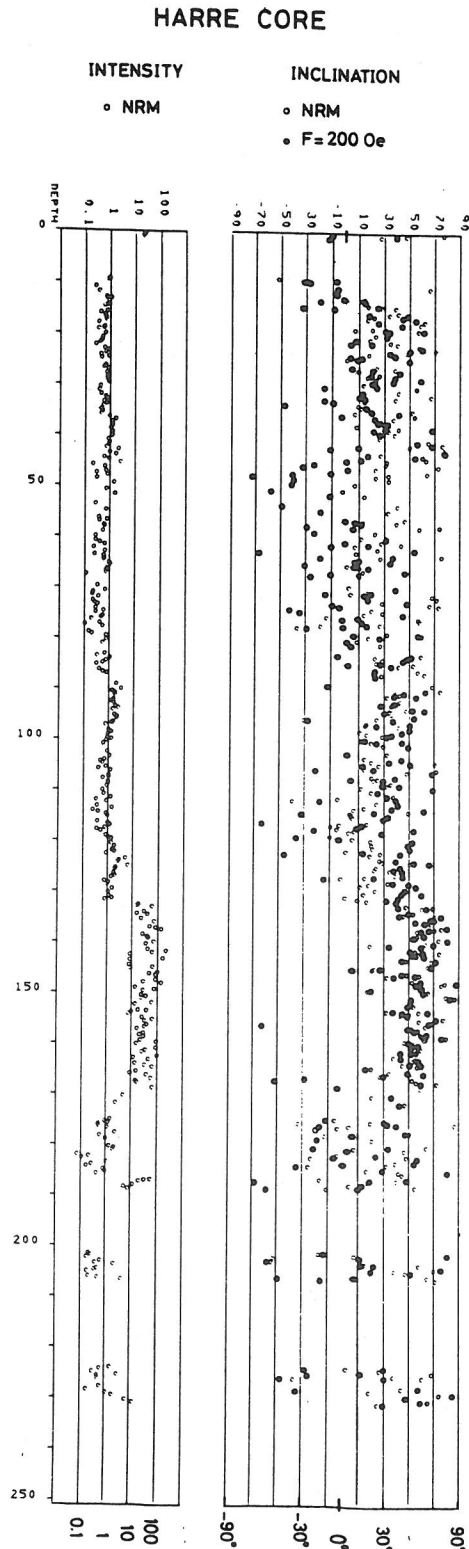


Fig. 4: Inclination of the Harre Core after partial A.F. demagnetization in 20 mT (200 Oe, solid dots), as well as NRM intensity and inclination (open symbols).

judge the fidelity of the record:

- 1) Reversed polarities are more reliable than normal ones (because of the viscous magnetic effect from the normal geomagnetic field prevailing during the last 700 000 years).
- 2) A.F. cleaned values of inclination are more reliable than less cleaned or uncleaned ones (because of the removal of soft viscous components secondarily induced).
- 3) Several consecutive data points with the same sign are more reliable than individually flipping ones.
- 4) The higher the intensity, the more reliable the result (because of improved signal to noise ratio).

As the geographical latitude of the site during the Tertiary was close to the present one of 56.5° N, inclination values of the primary magnetic components should be close to $+$ or -70° for the normal and reversed polarity epochs, respectively, provided there were no significant grain rotations or compaction of the sediment after the magnetization was stabilized, as a compaction would make the inclination more shallow.

What exactly should be understood by the concept PRM (primary remanent magnetization) in an originally soft sediment may be open for discussion. In the present context in the search for polarity markers which may be of some chronostratigraphical value, a relevant *ad hoc* definition may be: primary magnetizations are magnetic components which were locked in at or shortly after the deposition, where 'shortly' means shortly compared to the geological age as well as compared to the local stratigraphical scale in question.

An uncertainty of say $\pm 3\%$ of an absolute age of ca. 30 Ma is thus ± 0.9 Ma, which compares to the duration of one and three average polarity epochs of the lower and upper Tertiary, respectively. In the present context, magnetizations may thus be accepted as 'primary' as far as they were locked in the sediment in say within the order of 0.1 Ma after the time of deposition.

HARRE CORE: Holmehus Fm., U. Paleocene

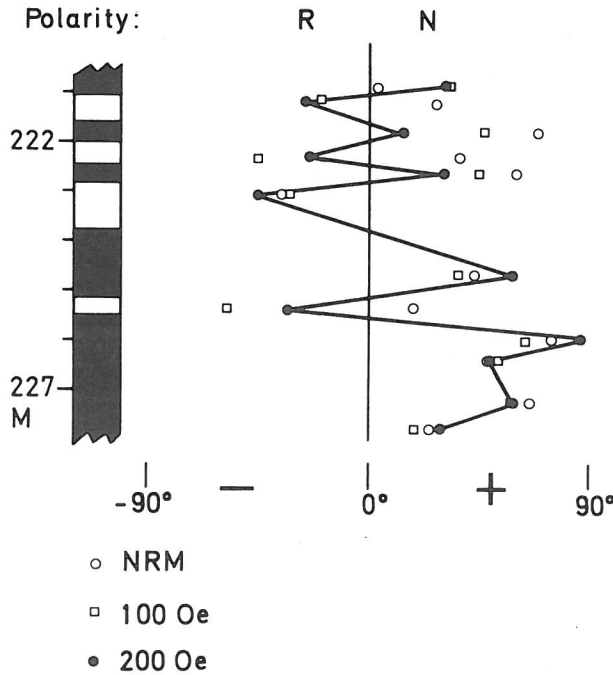


Fig. 5: Polarity of the Holmehus Fm. (Late Paleocene). Inclinations are shown for the NRM and A.F. demagnetized levels of 100 and 200 Oe, respectively. The polarity evaluation is based mainly on the 200 Oe value (solid line).

HARRE CORE: Ølst/Fur Fm., U. Paleocene/L. Eocene

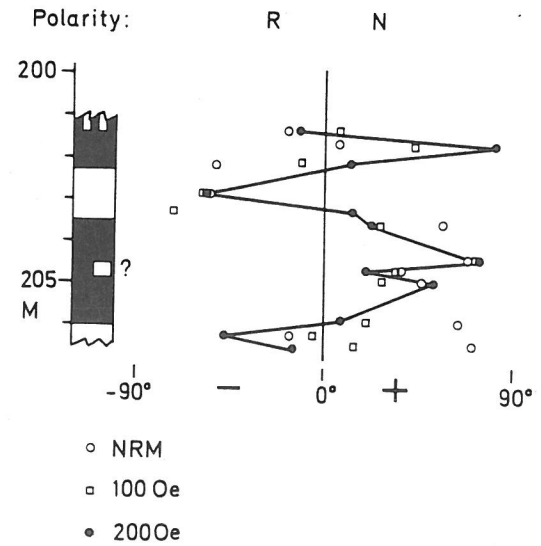


Fig. 6: Polarity of the Ølst- and Fur Fm's. (Late Paleocene/Early Eocene).

The PRM may thus be composed partly of a pure detrital remanent magnetization (DRM), partly by a post-depositional remanent magnetization (PDRM) acquired by statistical alignments of the magnetic particles during and after deposition (Shcherbakov & Shcherbakova, 1983), and partly by a chemical remanent magnetization (CRM) acquired by chemical growth of magnetic particles from the superparamagnetic to the single domain state ($> 0.05-0.1 \mu$ in case of magnetite) during various diagenetical processes.

If a significant compaction takes place (dependent on the clay percentage and mineralogy as well as the overburden) after the major part of the magnetization processes mentioned above have finished, a signifi-

cant flattening of the inclination may be expected (Abrahamsen, 1992). Also a reversal occurring shortly after the deposition may have a 'flattening' effect as may the natural demagnetizing effect of the geomagnetic field from the subsequent reversals which occurred between the time of deposition and the present time.

Especially the recent normal polarity period during the last ca. 700 000 years (the Brunhes normal polarity period) will tend to slightly steepen the NRM's of normal polarity, whereas the NRM's of reverse polarity will tend to be shallowed; however, the resulting more recent VRM (Viscous Remanent Magnetization) is likely to be soft and easy to remove by partial demagnetization.

HARRE CORE: { Lillebælt Clay Fm., M. Eocene
Røsnæs Clay Fm., L. Eocene

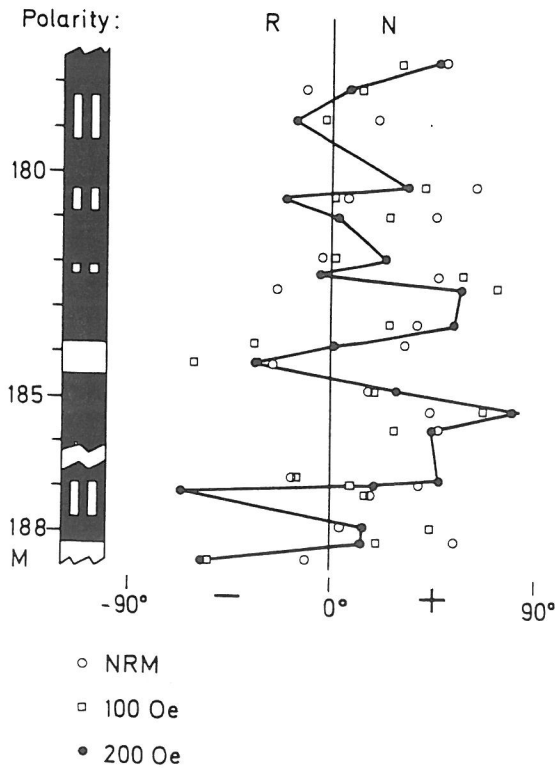


Fig. 7: Polarity of the Røsnæs Clay Fm. (Early Eocene) and Lillebælt Clay Fm. (M. Eocene).

With due respect to the considerations above, a compilation of all the magnetic information of the Harre core available is shown in Fig. 11.

For comparison the geomagnetic polarity column according to Cox (1982), which has been used as a standard during the anomaly interpretation of the Harre core, is also summarized to the right in the figure (with equidistant time-scale in Ma, and including the marine anomaly numbers), whereas the scale to the left is the depth-scale in m.b.s. of the Harre core.

The suggested marine polarity scale numbers, as given in Figs. 5 to 10, are labeled on the Harre core too, and suggested hiati are marked with 'H'.

The mean rates of deposition of the formations at the Harre locality obviously have been highly varying, as illustrated by the dashed lines embracing the Viborg and Branden Formations.

HARRE CORE: Viborg Fm., L. Oligocene (Rupelian)

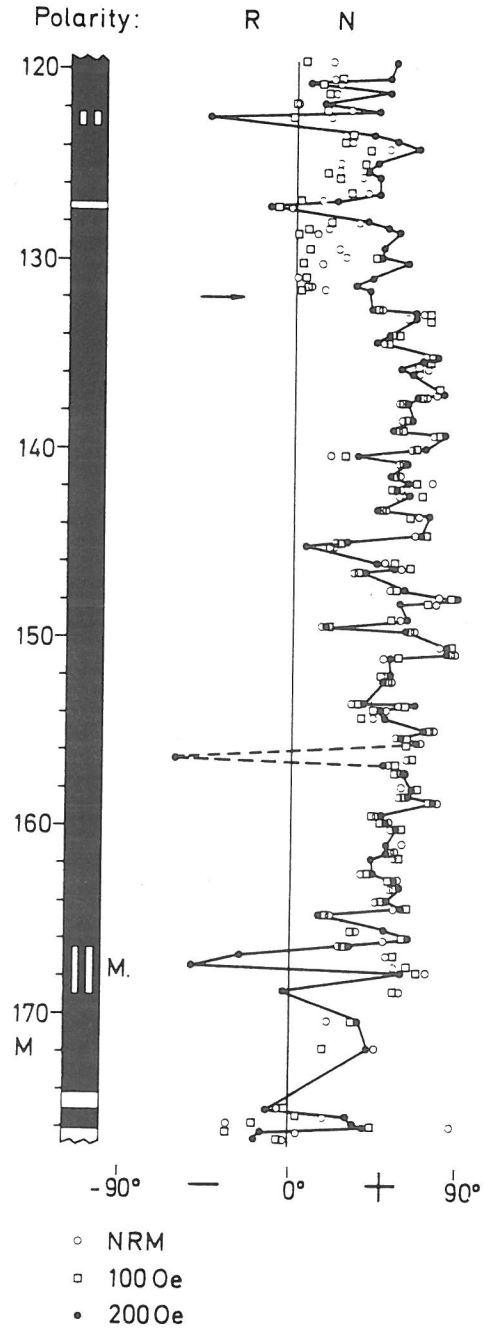
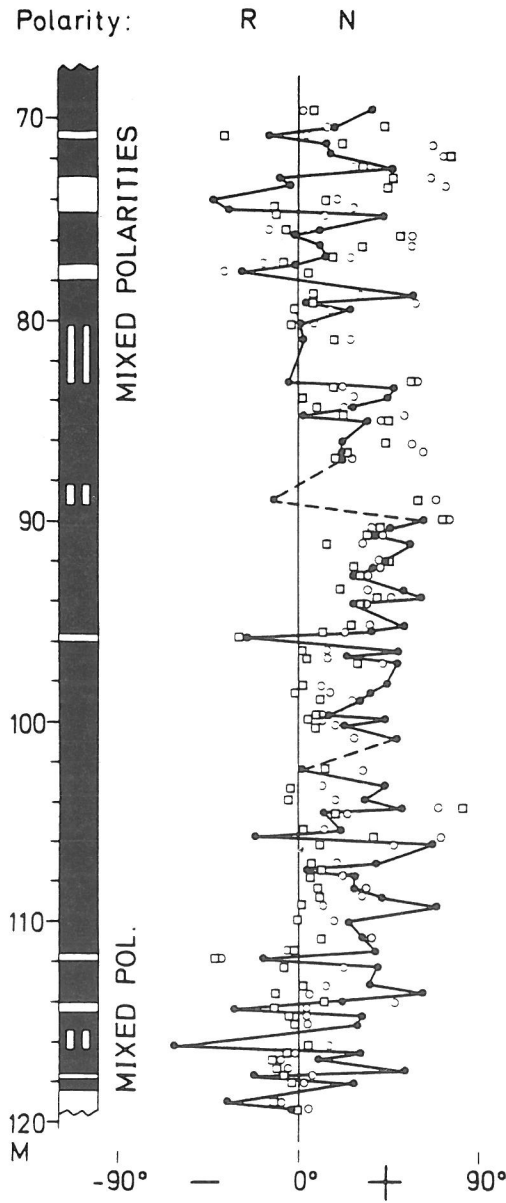


Fig. 8: Polarity of the Viborg Fm. (Rupelian, Early Oligocene).

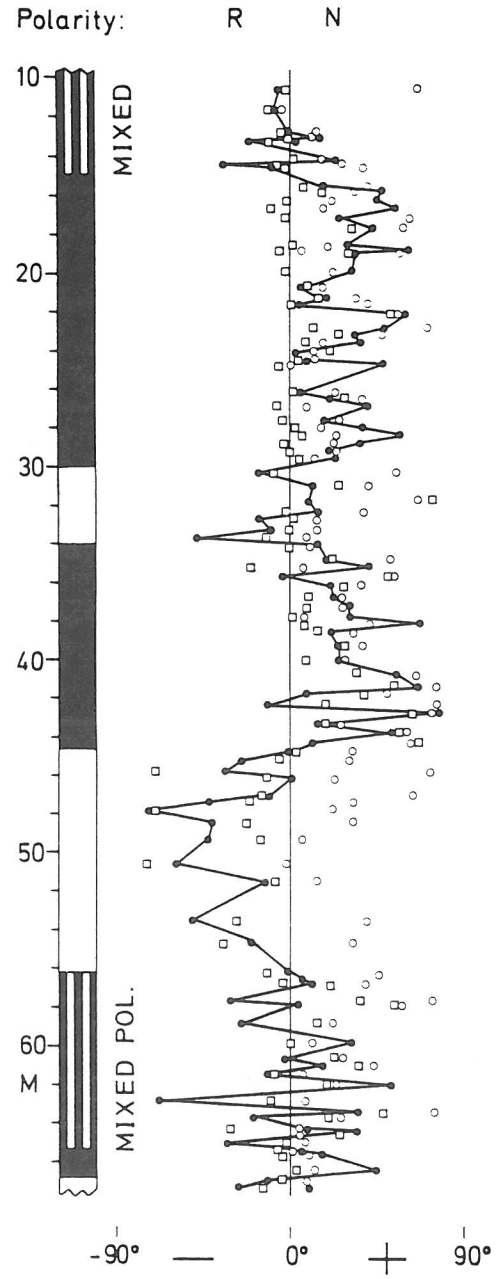
HARRE CORE: Vejle Fjord Fm., U. Oligocene

HARRE CORE: Branden Fm., U. Oligocene



- NRM
- 100 Oe
- 200 Oe

Fig. 9: Polarity of the Branden Fm. (Late Oligocene).



- NRM
- 100 Oe
- 200 Oe

Fig. 10: Polarity of the Vejle Fjord Fm. (Late Oligocene).

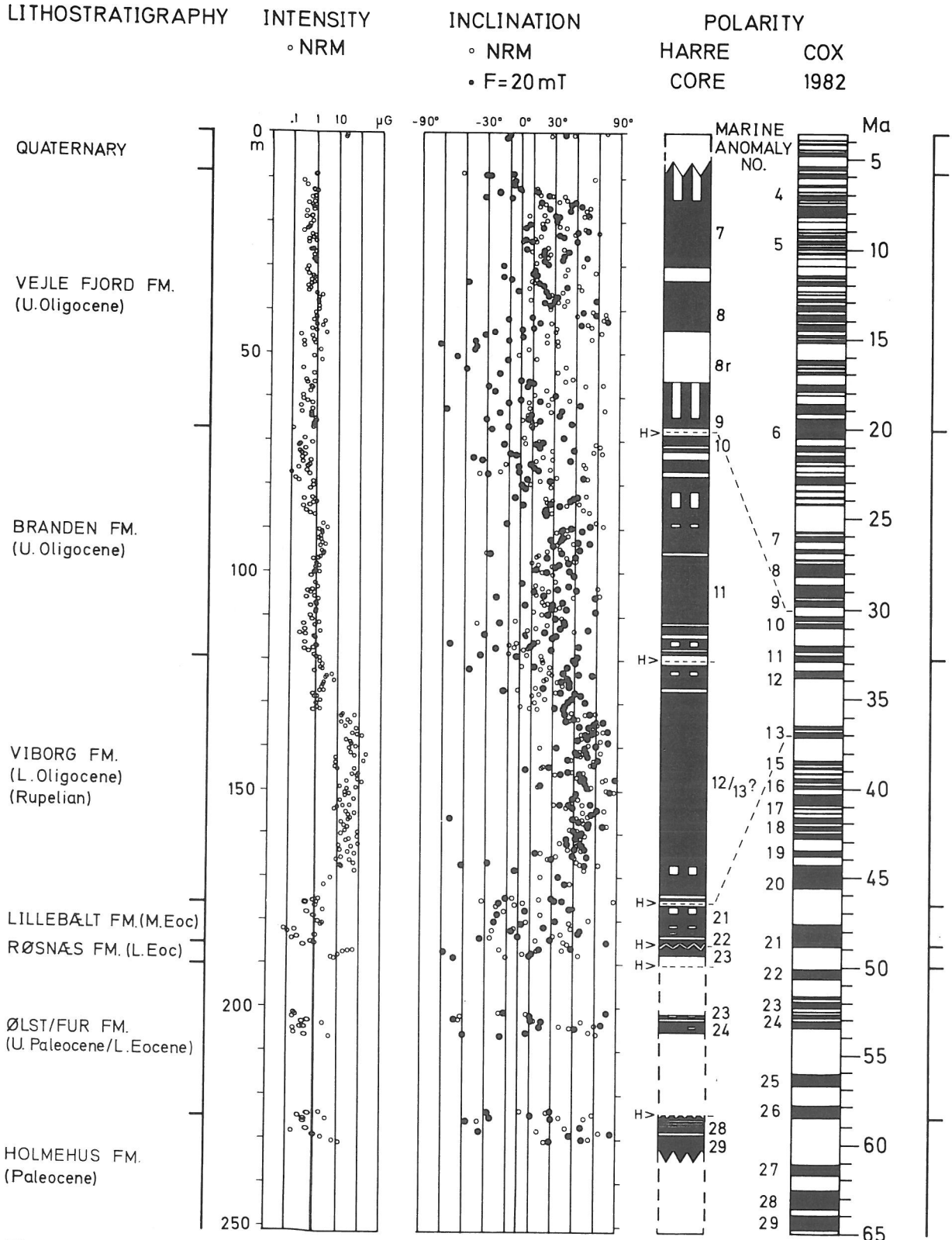


Fig. 11: Complete magnetostratigraphy of the Tertiary Harre core, as interpreted by comparisons with the global polarity scale of Cox (1982). Small numbers indicate suggested correlation with the marine magnetic anomalies, and 'H' indicate hiatus present in the sequence.

CONCLUSIONS

Although the magnetic record of the Harre core is not of high fidelity, mainly due to shallow inclination values in some parts of the record, and probably also due to partial remagnetisations, it is hoped, that this record, which is only a first step of iteration towards a complete magnetostratigraphy of the Danish Tertiary, nevertheless may be useful in relation to future magneto-stratigraphical work in the southern Scandinavian, North Sea and Baltic area.

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DANSK SAMMENDRAG

Resultaterne fra en palæomagnetisk undersøgelse af 330 sedimentprøver, udtaget fra sedimentkerner fra Harre boringen i Salling i Nordjylland beskrives. Prøverne blev udtaget i 1" cylindriske polystyren bægre, og efter en magnetisk pilotundersøgelse af 13 prøver (Fig. 1) der blev afmagnetiseret (og dernæst genmålt i et spinmagnetometer) i et vekselmagnetfelt på 33, 100, 200 og 300 Oe ($\times 0.1$ mT), blev alle prøvernes naturlige remanente magnetisering (NRM) målt; dernæst blev prøverne afmagnetiseret i et vekselfelt på 100 Oe og genmålt på et Digico Ltd. spinmagnetometer, og til slut blev prøverne afmagnetiseret i et vekselfelt på 200 Oe og genmålt på et Squid magnetometer.

Pilotundersøgelsen viser, at prøverne oftest indeholder flere magnetiske komponenter, der vidner om en kompliceret magnetisk historie. Efter dannelsen af den oprindelig detritale remanente magnetisering (DRM) vil således både diagenese, kompaktion og evt. senere remagnetisering i perioder med modsat

magnetisk polaritet kunne inducere sekundære magnetiske komponenter, der typisk bevirker en udfladning (Abrahamsen, 1992) af den målte magnetiske inklination fra de forventede værdier for Tertiæret på omkring ± 65 til 71° . I nutiden er inklinationen i Nordjylland $+71^\circ$.

NRM intensiteten varierer op til tre størrelsesordener (Fig. 2), og kan være en sensitiv indikator for lithologiske variationer, idet intensiteten især domineres af indholdet af magnetiske mineraler i ler- og siltfraktionen. I Holmehus Formationen, Fur Formationen og Lillebælt Formationen er intensiteterne generelt lave (0.1-10 mA/m), i kontrast til Røsnæs Formationen (7-54 mA/m). Hovedparten af Viborg Formationen har høje intensiteter (10-100 mA/m), med et markant fald til omkring 1 mA/m i 132 m's dybde. Der synes her at være en korrelation imellem den lave intensitet og pyritindholdet, formentlig fordi kun lidt trivalent jern er bevaret fra det oprindelige detritale indhold af magnetit eller eventuelt diagenetisk dannet maghemit. Branden Formationen og Vejle Fjord Formationen viser lave intensiteter, typisk imellem 0.2 og 2 mA/m.

I Figurerne 5-10 er de målte inklinationer gengivet i detaljeret skala med forskellige signaturer for NRM samt efter afmagnetisering i vekselfelter på henholdsvis 100 Oe og 200 Oe. Sort angiver normal polaritet (som i nutiden), mens hvidt angiver revers polaritet. Mange af prøverne viser inklinationer med numerisk lavere værdier end de forventede værdier omkring $\pm 70^\circ$ (jfr. ovenfor). I Fig. 11 er alle de magnetiske målinger sammenstillet, og ved sammenligning med den geomagnetiske polaritetsskala (Cox, 1982), er de enkelte magnetiske polariteter i Harreboringen søgt tolket ved angivelse af nummeret for den tilsvarende marinmagnetiske anomali.

Det skal til slut understreges, at den her viste magnetiske fortolkning kun er første skridt imod en generel magnetostratigrafisk opbinding på de globale magnetochroner af den danske tertiære lagserie. En del af korrelationerne er usikre og indbyder til mere detaljerede undersøgelser, især baseret på indsamling fra daglokaliteter, for at kunne blive endeligt afklaret.

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