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DEPOSITIONAL CONDITIONS DURING CHALK SEDIMENTATION IN THE EKOFISK AREA NORWEGIAN NORTH SEA[1]

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ABSTRACT

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A study of Late Cretaceous-Early Paleocene deposits in the Ekofisk area is based on a large amount of data available in the Norwegian Petroleum Directorate. The quality of this material was furthered by additional detailed micropalaeontological, sedimentological, structural and diagenetic studies. Several prominent units of allochthonous chalk deposits have been recognized. Based on micropalaeontological and sedimentological data, it is now possible to define these units properly. It has been attempted to map these allochthonous units as well as their source areas in order to gain a better understanding of the depositional environments during Chalk deposition in the Central Graben.

INTRODUCTION AND REGIONAL SETTING

The Ekofisk area (Fig. 1) is situated in the Central Trough, a major northwest-southeast trending graben system of Permian to Cretaceous age, bounded by the Ringkøbing-Fyn High, the Mid North Sea High and the Vestland Arch. This Graben started its development during Late Permian to Triassic times. Thick Upper Permian evaporites were deposited in the Norwegian-Danish Basin and Central Trough; salt movements started in the Late Triassic. Several phases of Kimmerian tectonic activity affected the area during the Jurassic. An Early Jurassic transgression was followed by a period of uplift in the early Middle Jurassic.

Taphrogenic movements in the Central Trough reached a maximum during the Late Jurassic to Early Cretaceous, and salt movements continued throughout the Late Mesozoic and Early Tertiary.

Mid-Cretaceous rifting movements have been recognized in the North Sea region and in many instances Upper Cretaceous chalk rests unconformably on Lower Cretaceous. Chalk deposition which is related to a continuing rise in sea level characterized the Late Cretaceous, a period essentially of tectonic quiescence. In more northern areas the chalk grades

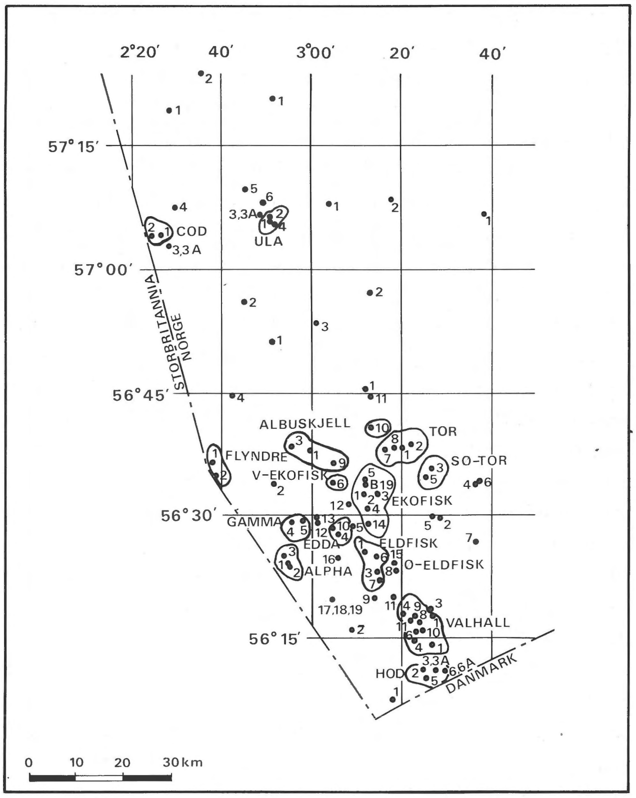

Fig. 1
Location map

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into a shaly facies, reflecting both boreal influences and greater clastic input. In the Central Trough the effects of the early Laramide movements were relatively minor, but a number of possibly local disconformities and regressive/transgressive events can be recognized. The Laramide movements started during the Senonian, climaxed in the Late Maastrichtian and finished at the end of the Paleocene. These tectonic phases caused the inversion of the Graben floor and uplift of the Graben margins. Subsequent erosion removed much of the chalk from some uplifted areas and this detritus was incorporated in the chalk deposits, which accumulated in the structurally deeper parts of the Graben. Chalk deposition persisted into the Early Paleocene as a continuation of the Late Cretaceous sedimentological and tectonic circumstances. Therefore, the Danian can be seen as predominantly a chalky facies present throughout the North Sea area, although in more northerly settings clastic influences are present.

Chalk depositon was interrupted in the late Danian by a phase of rifting and crustal warping, accompanied by uplift of the Graben margins and subsidence of the Graben floor. Erosion of the chalk took place on a number of uplifted structural blocks and gravity slides/slumps took place down from the fault block margins, resulting in the formation of mélange deposits.

The taphrogenic phase of the North Sea development, which was initiated during the Triassic, came to an end during the Paleocene, and was followed by a post-rifting phase of regional intracratonic subsidence. During the deposition of Upper Cretaceous-Danian sediments, the Eldfisk-Valhall-Hod area was a structural high, whereas the Albuskjell-Ekofisk-Tor area to the north was a depocentre, characterized by gravity deposits (debris flows, mud flows, slump deposits and turbidites). This setting is expressed in the Eldfisk, Valhall and Hod Fields by a prominent hiatus separating the Hod and Tor Formations, the upper part of the Hod Formation being condensed or absent.

Similarly, in the Eldfisk Field the Tor and Ekofisk formations are separated by a hiatus, the upper part of the Tor Formation and the lower part of the Ekofisk Formation being absent. On the Valhall and Hod structures the Tor Formation is strongly condensed and the Ekofisk Formation is thin (Hod Field) or absent (Valhall Field). The Eldfisk, Valhall and Hod structures are bounded to the west by a NNW-SSE trending regional fault. To the west of this fault the combined thickness of the Hod, Tor and Ekofisk formations is approximately 800 m, while this thickness is 350-400 m on the Eldfisk structure and 150-220 m on the Valhall structure. To the east of the High the total thickness of the three formations is the same as to the west, around 800 m. Thus, it is shown that such regional fault systems and tectonic elements of the Central Trough had a strong effect on the sedimentation pattern during Late Cretaceous-Danian times. Superimposed on these regional patterns local modifications due to salt and shale diapirism are observed as well (HARDMAN & EYNON, 1977).

STRATIGRAPHY

During a period of about 40 Ma (Cenomanian-Danian), chalks were deposited in the epicontinental sea covering the present-day North Sea region and adjacent onshore areas. In the Ekofisk area four sedimentary cycles can be distinguished. The first cycle includes the Rødby and the Hidra formations (the lithostratigraphic nomenclature is based on the joint work of the UK/Norwegian lithostratigraphic committees (DEEGAN & SCULL, 1977)). The second one started with the Plenus Marl Formation and ends at the top of the Lower Hod Member (HARDMAN & EYNON, 1977) The third cycle comprises the rest of the Hod Formation (Middle and Upper Hod members) and the Tor Formation. The fourth includes the Ekofisk Formation. The Lower Hod Member, representing the end of the second cycle, correlates with the Herring Formation, whereas the argillaceous interval at the base of the third cycle (Middle Hod Member) correlates with the Flounder Formation further west in the Central Trough. Within each of these major cycles, minor cyclic developments are observed.

The chalks of the Chalk Group are pelagic sediments, largely composed of the skeletons of the Coccolithophorida. The rest of the carbonates, up to 50% of the total carbonate fractions, is skeletal calcite originating from a broad spectrum of animal and plant groups, by far the most important being planktonic and benthonic Foraminiferida and calcipheres. The non-carbonate constituents play a minor role, although some levels (Lower Hod Member, Middle Hod Member and basal Ekofisk Formation) contain up to 60% insolubles, mostly clays, both detrital and authigenic. Furthermore, biogenic non-carbonate material is also preserved in the chalk, most notably dinoflagellate cysts. Remains or indications of former presence of other organisms with organic skeletons are common to abundant at some levels, the most important being radiolarians and siliceous sponges. Until recently the prevailing view was that all chalks accumulated slowly and quietly, as well known from studies of Recent nannofossil ooze deposition in which most of the sediment reaches the bottom in the form of fecal pellets of planktonic animals that feed on coccolithophorids. These pellets may have desintegrated during their descent as well as on the sea bed or may have been destroyed during subsequent compaction and by burrowing. Other planktonic contributions to the sediment such as foraminifera and radiolarians either reached the sea bed in pellets or settled individually. The remaining grains were produced by desintegration of the skeletons of benthic fauna.

However, PERCH-NIELSEN ET AL. (1979), WATTS ET AL. (1980), KENNEDY (1980) and HARDMAN & KENNEDY (1980) demonstrated strong evidence for resedimentation being common during Chalk deposition. The range of deposits recognised in resedimented chalks in the Ekofisk area include slumps, debris and mud flow deposits, turbidites and thick laminated chalk successions.

SEDIMENTARY DESCRIPTION OF THE HOD, TOR AND EKOFISK FORMATIONS

Hod Formation

The type well of the Hod Formation is 1/3-1, in which the thickness of the Formation is 515 m. HARDMAN & EYNON (1977) divided the Formation into three members: the Upper, Middle and Lower Hod Members, respectively.

Lower Hod Member – On the GR-Sonic logs the Lower Hod Member is characterized by a lower part with relatively high log readings indicative for argillaceous carbonates and an upper part with low log readings, probably purer carbonates.

The basal Hod Member in well 2/8-8 in the Valhall Field consists of a greenish gray and patchy oil-stained carbonate. The section is an alternation of laminated, argillaceous lime mudstone and laminated grainstone. The grains are of silt-sand size. Glauconite is common in the greenish sediment. Above this level, the sediments consist of more or less laminated, argillaceous carbonates and bioturbated, oil stained limy deposits. Burrows, such as of *Chrondrites* and *Planolites,* become more common towards the upper part of the unit. Alternations of clay-poor and argillaceous carbonates mark the upper part of the Lower Hod Member as well as the transition into the Middle Hod Member. These alternations include both bioturbated and laminated material. Laminations as well as evidence for resedimentation may have been destroyed by bioturbation. Turbidites occur at several levels. The age of the Lower Hod Member is Turonian.

Middle Hod Member – The base of the Middle Hod Member is defined by a marked increase of the GR-Sonic log readings. The unit is characterized by a serrate sonic log pattern, indicative for an interbedded carbonate-marl lithology. The top of the Middle Hod Member is marked by a decrease in GR-Sonic log readings. This Member consists of rhythmically bedded chalks and marls or clay-rich chalks. The chalk layers are generally 30-70 cm thick and strongly bioturbated. Some beds may have been deposited as turbidites, but burrowing has destroyed the evidence. Marly and clay-rich chalks are generally 7-20 cm thick. Trace fossils as *Planolites* and *Chondrites* occur throughout as well as scarce *Zoophycos*. *Thalassinoides* is common to abundant in the bedded chalks in the western area (Block 1/9). The age of the Middle Hod Member is Turonian-Santonian.

Upper Hod Member – According to log evidence the Upper Hod Member contains less clay than the underlying units. It retains the alternations as observed in the units below, but the clay content decreases upwards. Burrows of *Planolites* are often filled with clay-rich material and coarser carbonate grains. Graded beds suggest resedimentation by turbidites. The age of the Upper Hod Member is Santonian-Early Campanian.

The Hod-Tor Formation boundary – This boundary has been cored in a few wells, where it often appears as gradational. In the Eldfisk Field the boundary is erosional and a reworked Tor Formation is laid down in debris flow sediments on top of the Hod Formation. On the Valhall structure the boundary is marked by a submarine hardground. In the Albuskjell Field and in the Block 1/9 a condensed sequence of Coniacian to Early Campanian age is indicative for tectonic movements at this time.

Figure 2 shows the thickness of the Hod Formation. There is a marked thinning to the northeast and east as well as over the Hod-Valhall-Eldfisk Ridge, where strong indications of synsedimentary movements occur. The deepest part of the basin is situated to the west coinciding with the area with the thickest Hidra Formation.

The Tor Formation

The type well of the Tor Formation is 1/3-1, where the Formation reaches 473 m. The lower part of the Formation is generally a homogeneous bioturbated chalk, with a low clay content. *Chondrites, Planolites* are the most common trace fossils. Upwards, bioturbated chalk follows, in expanded sequences, in decimeter to meter thick alternations of bioturbated and laminated chalk. The laminated units have been interpreted as deposited fall-outs from mud clouds in suspension. Turbidites are especially developed in upper part of the Formation. In the Albuskjell Field, WATTS ET AL. (1980) describe the top 110 m of the Tor Formation as predominantly redeposited sediments, with slumps, debris flows, bottom traction deposits and turbidites. According to KENNEDY (1980) the top 100 m of the Tor Formation in the Tor Field consists of debris flows of various types with turbidites and conglomerates, all of which have been involved in later slumping. In the Ekofisk Field a few preserved cores from the Tor Formation show the presence of debris flows and mud flow deposits. These are interpreted as blanket deposits which can be traced on log evidence from well to well in the area between the Albuskjell Field and the Tor Field. In the Valhall and Hod Fields the Tor Formation is developed in a condensed sequence, the highest 10 m being characterized by *Thalassinoides* on a series of omission/erosion surface that are marked as levels of early diagenetic cementation. The age of the Tor Formation is Late Campanian to Late Maastrichtian.

Figure 3 shows the thickness of the Tor Formation. The Formation is thin to absent to the northeast and east as well as over the Hod-Valhall-Eldfisk Ridge. The depocentre has now moved towards the NE in which the Albuskjell, Ekofisk and Tor Fields are situated.

The Tor - Ekofisk Formation boundary – In the Hod Field this boundary is developed as a submarine hardground. In Block 1/9 it varies from a submarine hardground to an erosional surface overlain by a complex resedimented turbiditic conglomerate. In other places the boundary is marked by some

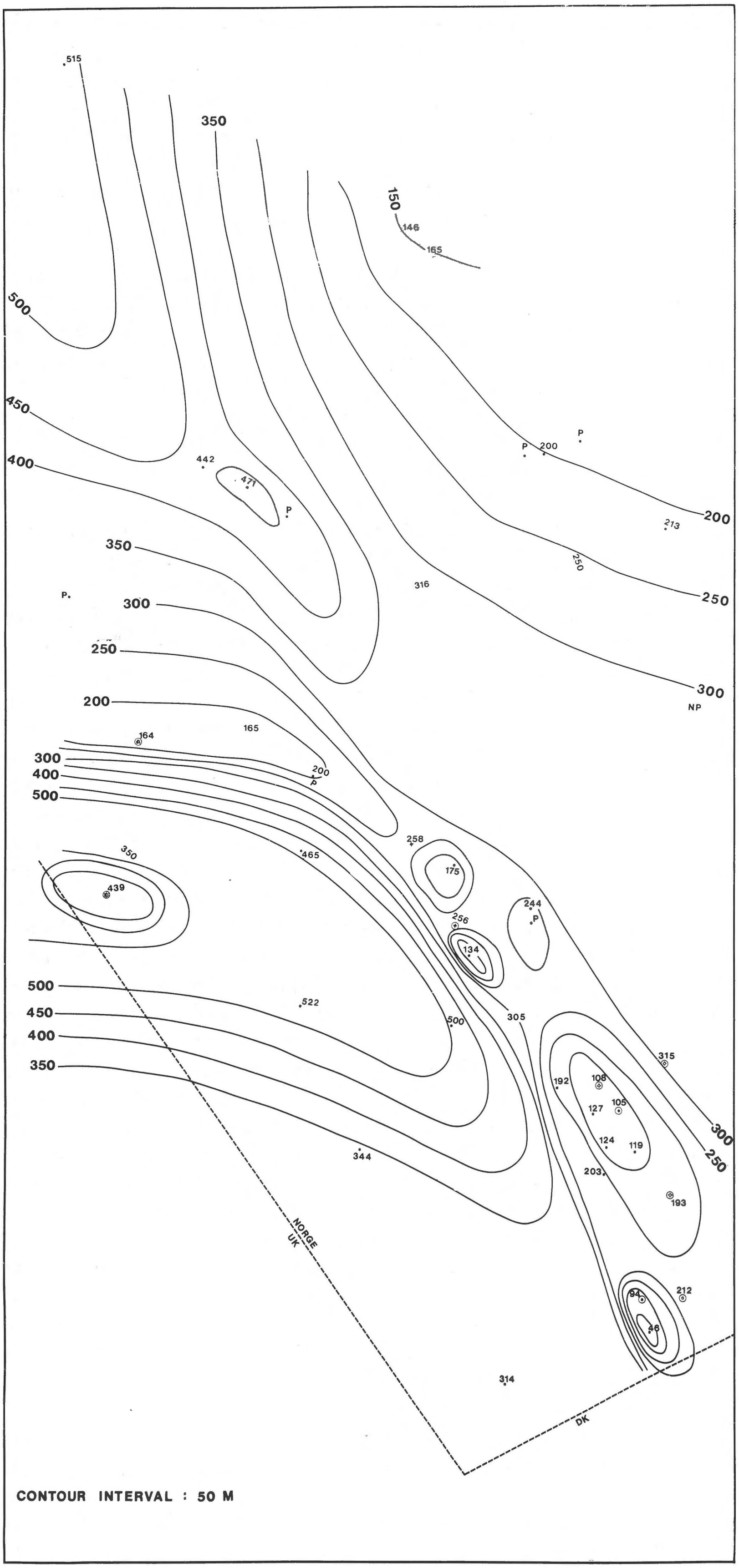

Fig. 2
Isopach map Hod Formation (scale 1:240 000)

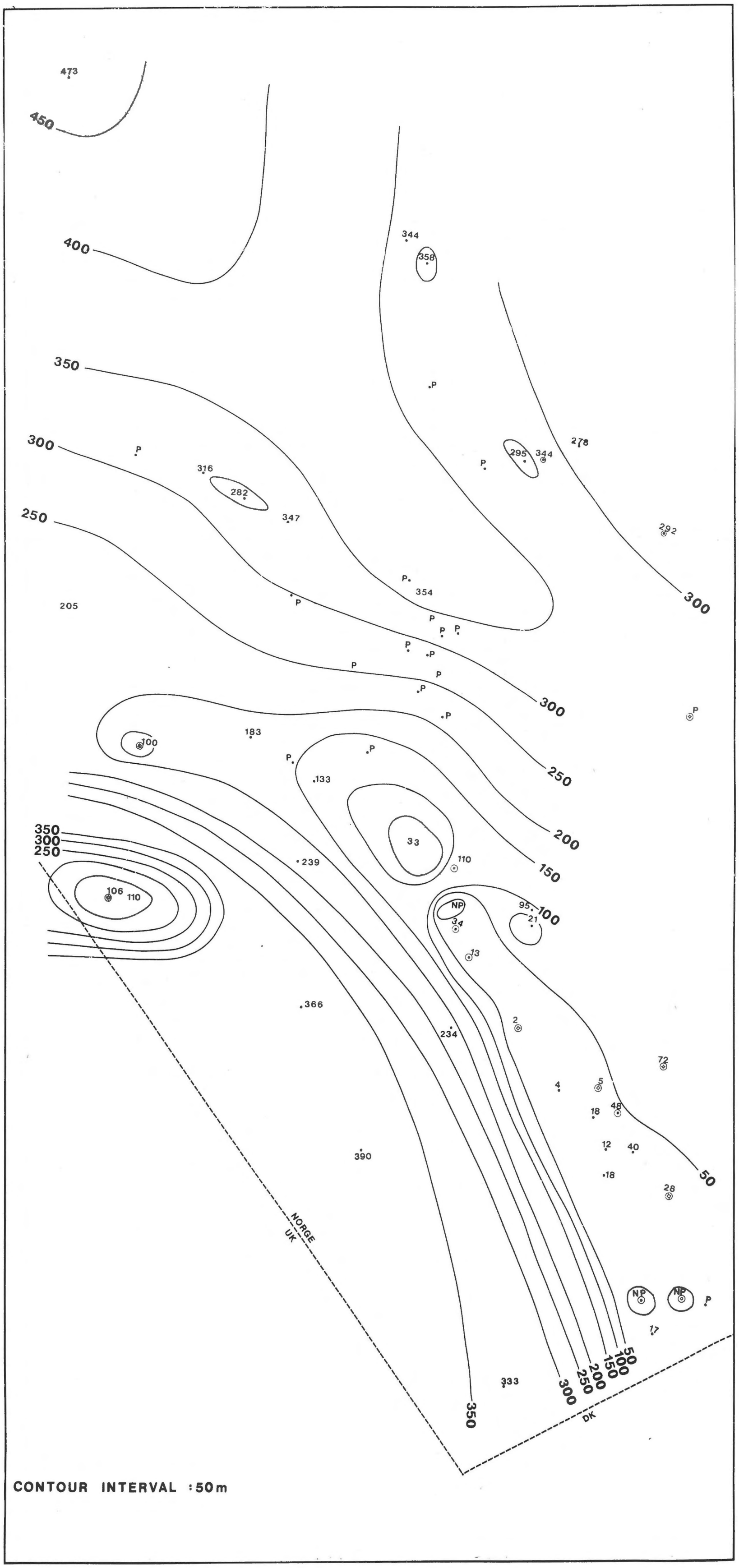

Fig. 3
Isopach map Tor Formation (scale 1:240 000)

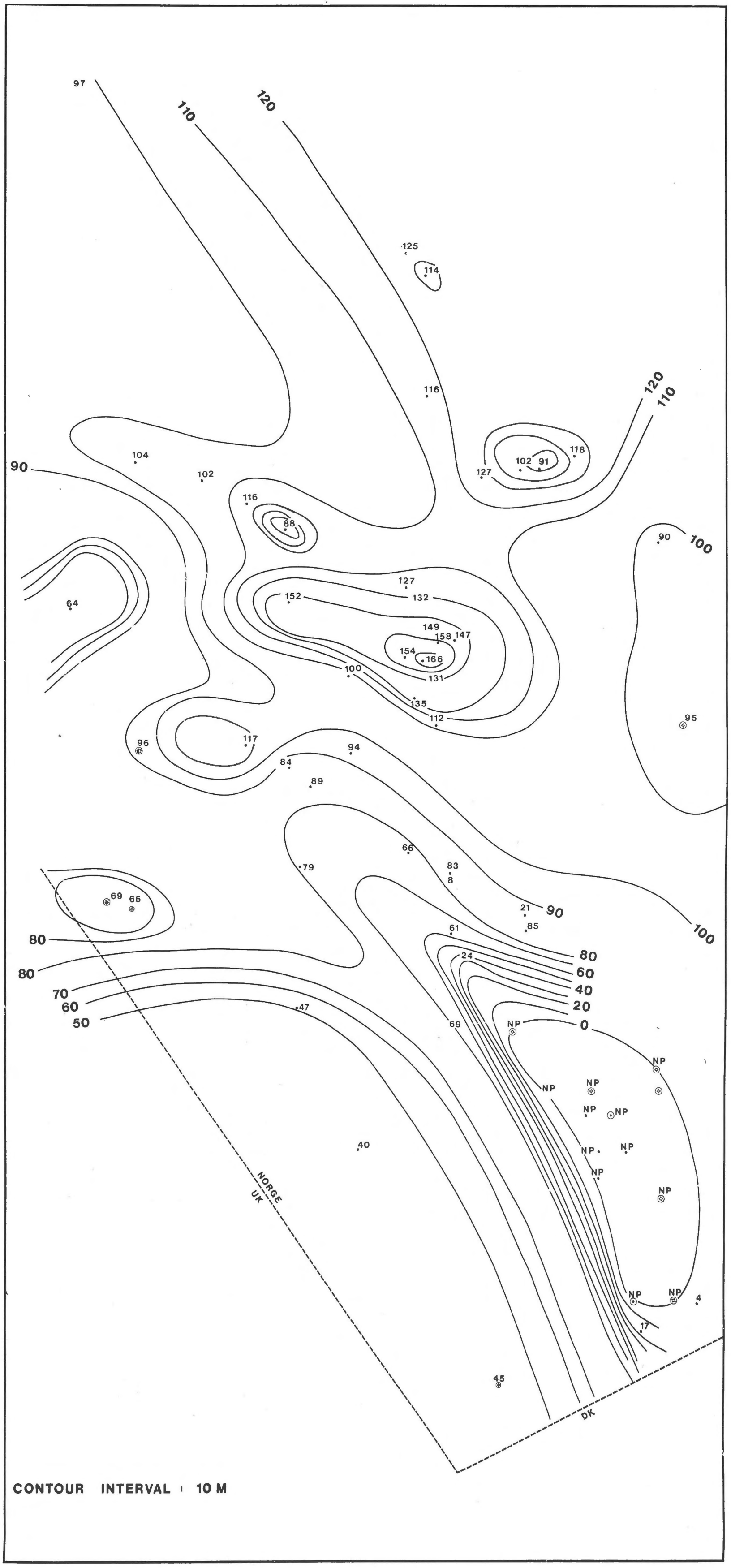

Fig. 4
Isopach map Ekofisk Formation (scale 1:240 000)

erosion, with a basal marly to shaly Ekofisk Formation having a high content of fossils indicative for a condensed sequence.

The Ekofisk Formation

The type well of the Ekofisk Formation is 2/4-5, where the thickness of the Formation measures 127 m. The lower part of the Formation, called 'the tight zone', marks a return to rhythmically bedded argillaceous limestone-marl alternations, as seen in the Middle Hod Member. The lower part of the sequence has clay contents as high as 48%, and is locally even developed as a shale. Strong burrowing activity is present, especially *Zoophycos* being common. Turbidites are present in the basal part of 'the tight zone'.

In the Ekofisk Field a redeposited Maastrichtian unit, 30-80 m thick, is incorporated in 'the tight zone'. This unit was described in detail by PERCH-NIELSEN ET AL. (1979). In the Tor Field the whole Ekofisk Formation is considered as a megaslump complex (KENNEDY, 1980). WATTS ET AL. (1980) recognized a slide deposit of Danian material in the Ekofisk Formation in the Albuskjell Field. The upper part of the Ekofisk Formation, called 'the porous zone', consists of homogeneous bioturbated chalk. These redeposited units are absent in the Block 1/9 area. Upwards and downwards it grades into rhythmically bedded chalks. Wells in the Hod Field (HARDMAN & KENNEDY, 1980) show a thin and condensed Ekofisk Formation, with levels of early diagenetic nodules, winnowed conglomerates and incipient hardgrounds.

Figure 4 shows the thickness of the Ekofisk Formation. Greatest thicknesses are found in the Albuskjell, Ekofisk, Tor area, all southwest of the Hidra fault zone, indicative for a derivation of the material from the northeast. Erosion took place during Danian times on the Hod, Valhall and Eldfisk structures as well, pointing to another possible source area. To the southwest the Formation is remarkably thinner suggesting that subsidence was less pronounced here than along the northeast flank of the Trough.

The Maureen Formation equivalent caps the Chalk Group over the whole area. In places the Ekofisk Formation - Maureen Formation boundary is a gradational transition from a chalk to a more clay-rich marl (Ekofisk Field), in other places (Hod Field) it is marked by a spectacular submarine hardground (HARDMAN & KENNEDY, 1980).

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