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LOWER CRETACEOUS STRATIGRAPHY AND TECTONICS OF THE SOUTH-SOUTHEASTERN NORWEGIAN OFFSHORE[1]

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ABSTRACT

Hesjedal, A. & G. P. Hamar 1983 Lower Cretaceous stratigraphy and tectonics of the south-southeastern Norwegian offshore. In: J. P. H. Kaasschieter & T. J. A. Reijers (eds.): Petroleum geology of the southeastern North Sea and the adjacent onshore areas (The Hague, 1982) – Geol. Mijnbouw 62: 135-144.

The Early Cretaceous sedimentary sequence is subdivided into seven formations in the southern Norwegian Offshore. It is dominated by marine fine-grained argillaceous sediments with varying calcareous content. The Sola Formation is found to be relatively rich in organic carbon and is, therefore, expected to have a good source rock potential. A small number of sandstone accumulations is located in the vicinity of penecontemporaneously reactivated highs. The northern part of Fiskebank Sub-Basin was inverted during the Cenomanian. This correlates with renewed strike-slip movements along the Fjerritslev Fault and at other places at the edge of the Fennoscandian Shield. The 'Late Kimmerian Unconformity' is discussed.

INTRODUCTION

During the last ten years much of the geological exploration in the North Sea focussed on Jurassic sediments. These deposits contain good reservoir rocks which are often filled with hydrocarbons. In connection with this exploration effort considerable information about the overlying Lower Cretaceous was acquired.

The main purpose of the present study has been to analyse the available data in order to get a better understanding of the geological development during the Early Cretaceous. In addition to well data, large amounts of regional seismic data have also been used. The studied area covers the southern and southeastern part of the Norwegian offshore and includes parts of both the Danish and British offshore areas (Fig. 1). In terms of the geological setting the area covers the northern part of the Central Graben, the Norwegian-Danish Basin and the northern flanks of the Central Highs (Fig. 1).

The general tectonic development of northwestern Europe and its relation to the formation and evolution of the sedimentary basins has been covered by ZIEGLER (1978, 1981). The lithostratigraphic classification of the southern North Sea's Lower Cretaceous sediments has been published by RHYS (1974). The central and northern North Sea's lithostratigraphy was prepared by a Norwegian/British stratigraphic committee. The results were published in NPD's publications, edited by DEEGAN & SCULL (1977). The eastern part of the North Sea and the Danish onshore areas have been investigated by, for instance, LARSEN (1966), CHRISTENSEN (1974), MICHELSEN (1976) and RASMUSSEN (1978). A revised lithostratigraphy of the Lower Cretaceous has been proposed by HESJEDAL (1981), the present study being based on this new subdivision.

The Cromer Knoll Group, which in age represents most of the Early Cretaceous epoch (Late Ryazanian-Albian), consists solely of marine sediments. The Group is dominated by fine-grained, argillaceous deposits with varying contents of calcareous material, and with subsidiary sandstones derived from neighbouring ridges. According to reconstructions of the continental movements during the Early Cretaceous, the North Sea was situated at approximately 40°N. The climate was warm and relatively dry, the land areas had low relief and were characterized by intense chemical weathering.

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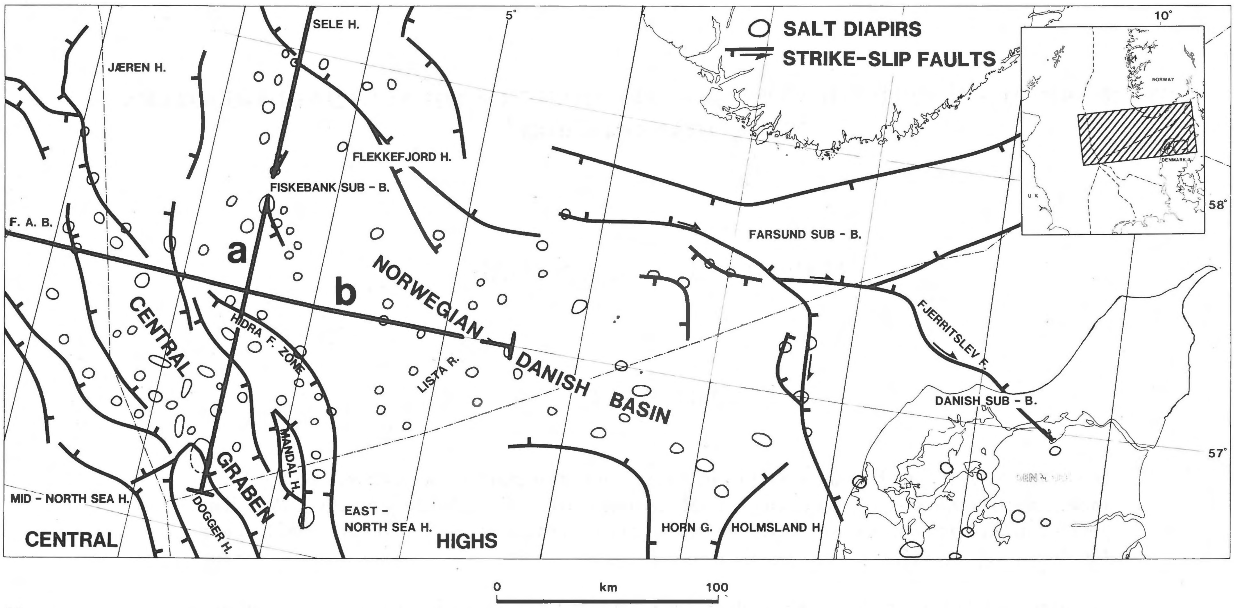

Fig. 1
Tectonic map covering the studied area. B = Basin, F = Fault, G = Graben, H = High or Horst, R = Ridge, FAB = Forth Approaches Basin. The two lines a and b indicate the positions of the cross sections shown in figures 8a and 8b.

EARLY CRETACEOUS TECTONIC AND STRATIGRAPHIC DEVELOPMENT

A major phase of uplift and erosion, the Late Kimmerian phase, took place across northwestern Europe during Volgian to Ryazanian times, resulting in widespread regression and isolation of sedimentary basins (RAWSON & RILEY, in press). The regression, which culminated in Middle Ryazanian, also affected the North Sea area. The rift system experienced differential subsidence and block faulting, and positive elements were uplifted causing local fringing sands to develop. However, only very small areas were exposed to subaerial erosion and an unconformity can only be observed on structural highs. This leads to the observation that the effect of the Late Kimmerian phase is not as important within this part of the North Sea as believed earlier. In the Norwegian-Danish Basin and centrally in the Central Graben no angular unconformity can be traced at this level. There is, however, a good seismic reflector marking the base of the Valhall Formation. This distinct horizon is usually not an unconformity, but represents a lithological boundary which probably is an isochron.

The sediments deposited during the regressive Early and Middle Ryazanian show varying characteristics. Within the Central Graben they consist of the typical 'hot shale' facies (Mandal Formation), indicative of anaerobic bottom water conditions. These particular conditions are probably due to restricted ocean water circulation and tectonically controlled basin isolation. The time-equivalent deposits in the Norwegian-Danish Basin are also affected by the restricted water circulation. The central and western part of the Basin are dominated by relatively dark shales (Flekkefjord Formation), deposited in a semi-anaerobic marine environment. In the eastern part the sediments become more silty and even sandy (Frederikshavn Formation), and represent a more proximal facies of the nearshore sedimentary system prograding from the east towards the west (Fig. 2a).

In spite of the eustatic fall in sea level the distribution of the Ryazanian sediments shows a larger extension than the one of the underlying series. This typical onlapping trend indicates that the basin subsidence was more important than the fall in sea level. During Ryazanian times this net subsidence resulted in open communication between the Central Graben and the Norwegian-Danish Basin (Fig. 2a). From late Ryazanian and to the end of Barremian the whole area was subjected to a series of transgressions interrupted by minor regressions. The Late Ryazanian transgression had a remarkable effect on the sedimentary environment. The rising sea level and the following increase in water circulation caused an abrupt termination of the prevailing anaerobic conditions. This sudden change in the depositional environment is reflected in the sedimentary sequence as a lithological boundary. The contrast is not only evident in the Central Graben, but can also be seen in the Norwegian-Danish Basin. Because of the abrupt nature of this event, the resulting lithological boundary must be regarded as isochronous. This means that the base of the Valhall Formation is an isochron where there has been continuous sedimentation from Ryazanian into Valanginian. On the structural highs, however, the onlapping resulting from the Lower Cretaceous transgressions marks increasing hiatuses towards the top of the highs. Some of these highs were not fully covered until the end of Early Cretaceous.

The Early Cretaceous is generally dominated by differential subsidence, and three main depocentres developed during

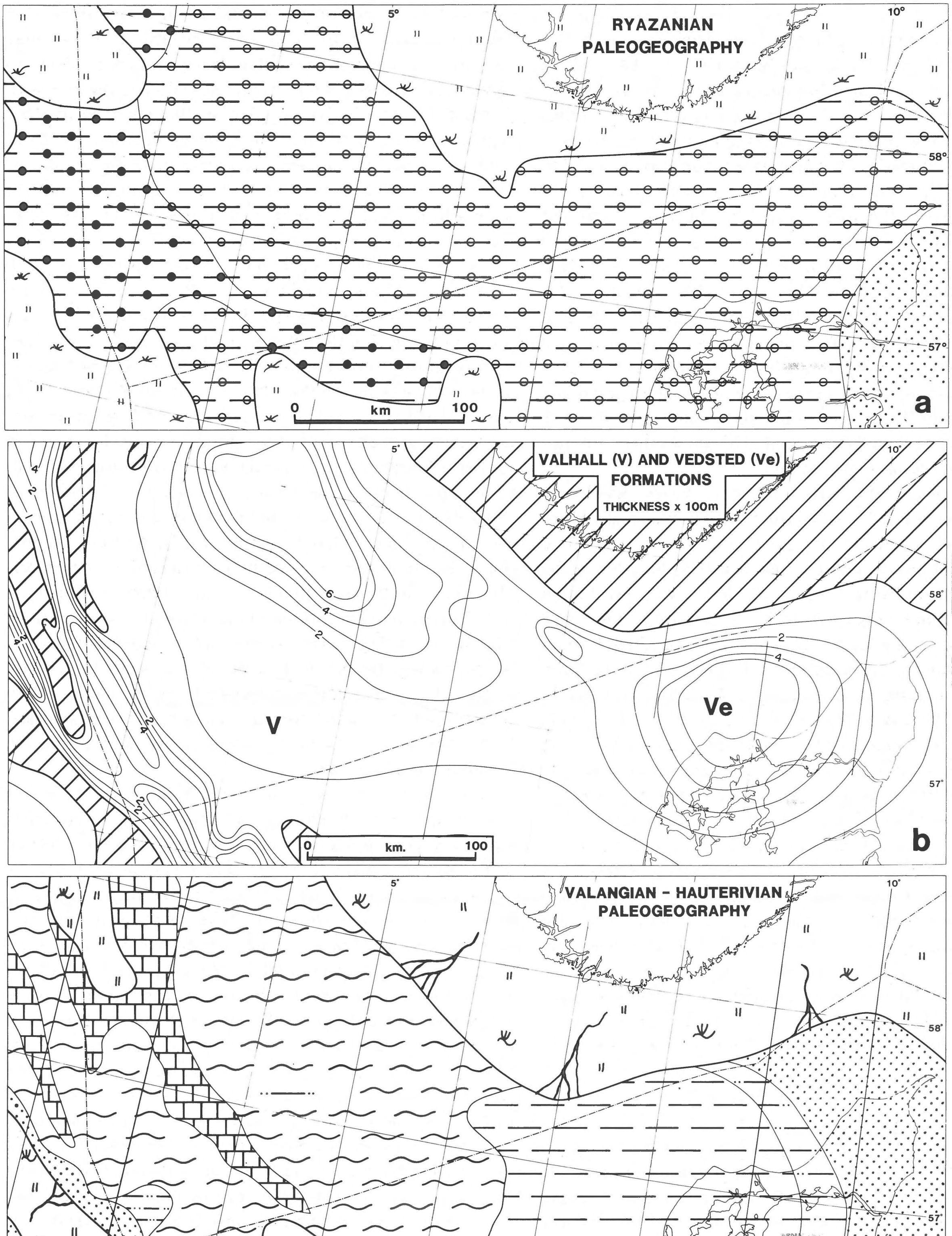

Fig. 2
Isopach and palaeogeographic maps. For legend see figure 4.

deposition of the Valhall Formation. They are located in the Central Graben in the Flekkefjord-Sele High area and in the eastern part of the Danish Sub-Basin (Fig. 1). The Valhall Formation has a large distribution area and is covering most of the study area (Fig. 2b). It generally consists of calcareous shales with a low content of terrestrial material. In the easternmost parts it grades into the more proximal, shaly and silty facies of the Vedsted Formation (Fig. 2c) while in the southwestern corner of the area it is replaced by a local sand unit called the Devils Hole Formation (Fig. 3a). This sand development is a result of local tectonic movements in the Forth Approaches Basin and has a limited lateral extent. It is deposited as relatively narrow fringes of shallow marine sand in the vicinity of the structural highs. Basinward the sand grades into the generally transgressive argillaceous sediments of the Valhall Formation. However, in the western part of the Fiskebank Sub-Basin some silty and sandy units of early Hauterivian age have been found. This may reflect a minor regression in the area at that time.

Simultaneously, another sedimentary facies developed. This facies is confined to submarine, topographic highs which received very small amounts of clastic material. In these starved conditions condensed shallow marine limestones, the Utvik Formation, were developed. The present distribution of this Formation (Fig. 3b) clearly demonstrates the subsidence pattern of the highs. At some places the Utvik Formation is very thin and represents only the lower part of the Early Cretaceous, grading upwards into the Valhall Formation. In other areas the Utvik Formation constitutes all of the time period from Valanginian to early Aptian. In these areas the Valhall Formation is absent but it has a lateral equivalent in more basinal positions (Fig. 4). This means that from agedatings of the Utvik Formation we can distinguish between the positive areas that subsided early and those areas that continued being positive features through most of the Early Cretaceous. In the last mentioned areas the Utvik Formation does not consist of continuously deposited limestones, but rather is composed of a number of condensed sedimentary units, separated by hiatuses. On some highs the transition from the Utvik Formation to the Valhall Formation occurs in the middle Hauterivian. This coincides with an increase in calcareous content of the Valhall Formation in the Norwegian-Danish Basin, and may reflect a major regional transgression during mid-Hauterivian times.

In spite of possible minor regressions during the late Hauterivian and Barremian (RAWSON & RILEY, in press), no extensive lithological changes can be observed in the study area (Fig. 3c). The content of calcareous material in the Valhall Formation gradually increases upwards, probably reflecting the overall transgressive nature of deposition in this period. This situation culminates in the early Aptian with the deposition of very calcareous shales or marls which are distributed over large areas, especially in the Norwegian-Danish Basin (Fig. 4). In some areas these carbonate-rich sediments directly overlie the previously mentioned limestones of the Utvik Formation, and are here incorporated in this Formation for the sake of simplicity. This fact may indicate that even if the sedimentary sequences show no lithological evidence of important regressions in the time span from late Hauterivian to early Aptian, there may be hiatuses, especially in elevated areas, that represent non-deposition. Later on, these areas experienced renewed onlap of calcareous deposits. This onlap also affected previously emergent areas which resulted in Barremian-Early Aptian carbonates directly overlying pre-Cretaceous rocks.

The Mid-Aptian orogenic phase (Austrian phase), which heralded sea floor spreading in the Bay of Biscay, widely affected northwestern Europe. In the North Sea the effect is not so dramatic, but the subsequent drop in sea level together with 'adjusting' movements along the North Sea rifts caused an overall shift in lithology throughout the North Sea. In basinal areas this regression resulted in a change from very calcareous, greyish coloured claystones to non-calcareous and darker coloured ones containing more terrigenous material. Contemporaneously, agglutinating benthonic foraminifera replaced the calcareous nannoplankton and benthonic microfauna in the claystones (JOHNSON, 1975). Another interesting observation is that the organic carbon content is considerably higher in this new lithological unit which is named the Sola Formation. The Formation is distributed over most of the study area (Fig. 5a) and is especially well developed in the deeper parts of the basins. It is probably deposited in a partly restricted inland ocean with reduced oxygen supply in the deeper zones. The water circulation may have been hampered by the drop in sea level and by tectonic movements during the Austrian orogenic phase.

Along with the facies change in the basin areas, the higher areas were exposed to erosion, and wedge shaped sand bodies (the Kopervik Formation) were deposited along the flanks of some structural highs (Fig. 5b). The sand was probably deposited in a relatively low energy, shallow marine environment. Thinly bedded sands and silts incorporated in otherwise homogeneous clays observed in more basinal positions at the same level, may indicate that submarine gravity flows have been active too. The two last mentioned formations are time equivalent and grade laterally into each other. They both represent a sedimentary response to the Austrian orogenic phase. Further north sand deposition very similar to the Kopervik Formation was developed along the western coast of Norway (the Florø Formation, figure 3a). The southern extent of this Formation has not yet been established because of limited well control. Sands and silts of Aptian/Albian age that may represent distal parts of this Formation are, however, encountered in the area around the Sele High (Fig. 5c). This may indicate that the distribution of the Florø Formation should be extended southward along the Norwegian coast. In addition to these observations previous investigations have proved a simultaneous clastic depositional episode in the Danish-Polish Trough (MICHELSEN, 1978) and volcanic activity in Scania (PRINZLAU & LARSEN, 1972). This could indicate that

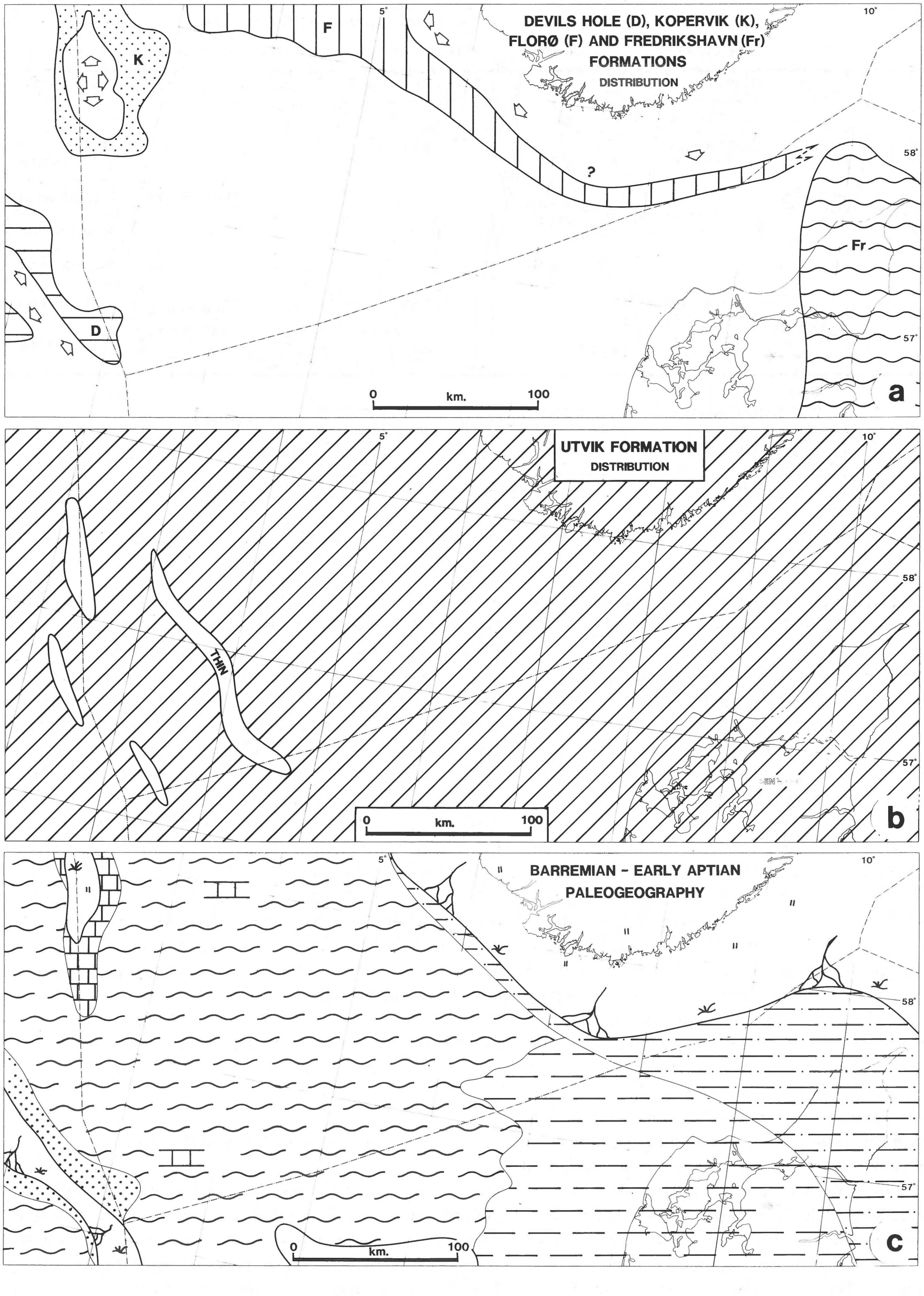

Fig. 3
Distribution- and palaeogeographic maps. For legend see figure 4.

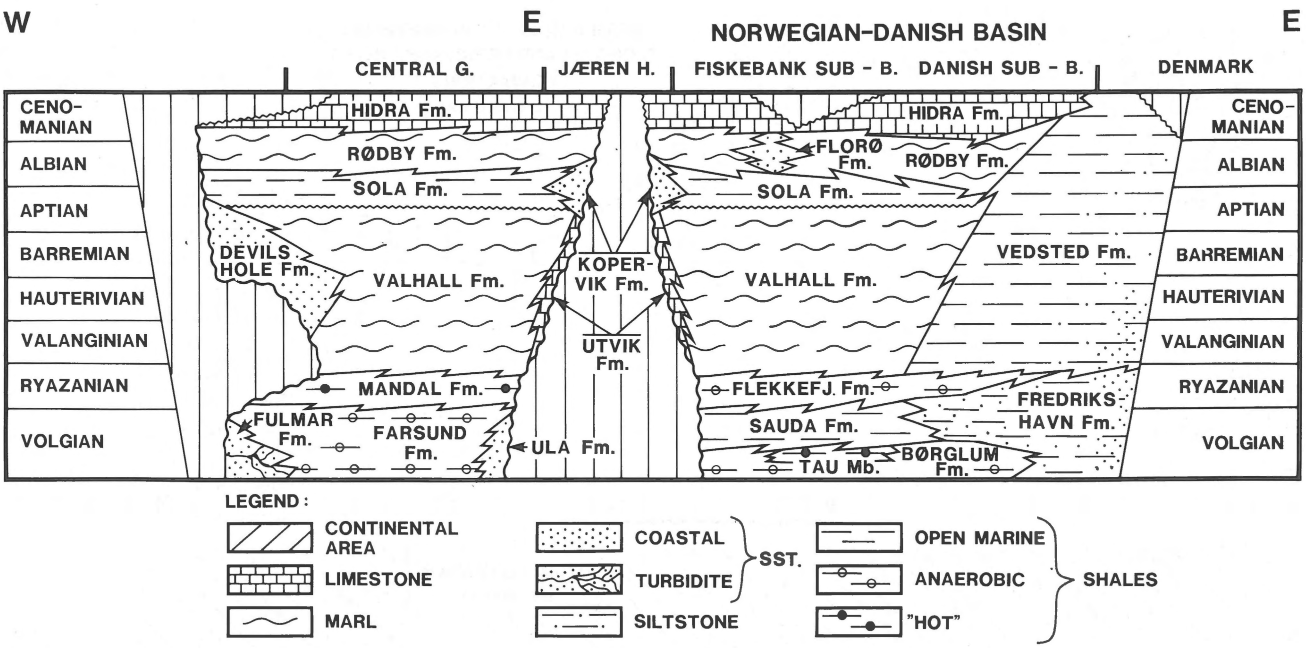

Fig. 4
Lithostratigraphic correlation chart, Lower Cretaceous. The symbols used in this figure are also used on the palaeogeographic maps (Figs. 2, 3 and 5).

the Fennoscandian Border zone was reactivated during the Austrian orogenic phase and perhaps was affected by strike slip movements.

The relatively shortlived mid-Aptian regression was once again replaced by a transgressive period. The Sola Formation, in the course of early to middle Albian, gradually passed into a new calcareous fine-grained unit, the Rødby Formation. This Formation is distributed all over the North Sea (Fig. 6) and onlaps pre-Jurassic rocks along the basin margins, for instance onto the Ringkøbing-Fyn High. The calcareous claystones and marls are often reddish in colour and are deposited in an inner to outer shelf environment with reduced clastic input.

The carbonate content continued to increase towards the end of Albian. At the same time a large increase in planktonic foraminifera can be observed (JOHNSON, 1975), as the supply of terrigenous material gradually decreased. In the southern part of the North Sea (to approx. 60°N) the terrigenous supply is so much reduced that from the transition into the Cenomanian and onwards, pure carbonates were deposited (Chalk Group), figure 4. A similar evolution can also be observed in onshore areas in Northwestern Europe (Fig. 7).

Along the Norwegian western coast structural movements and erosion of the positive elements continued through Albian times, but the erosion products were generally not transported far from the coastline, except for the turbiditic sands round the Sele High. This particular area was inverted during Albian-Cenomanian times and consequently one of the previous depocentres became an area of erosion or non-deposition (Fig. 8). The movements may be a result of large scale lateral faulting along the continuation of the Fjerritslev Fault (Fig. 1). The inversion can be correlated with simultaneous movements around the Fennoscandian Shield and coincides with the onset of the Alpine orogeny. Tectonic results of strike slip movements, such as inversions, en-echelon faulting and alternating synclines and anticlines along the major faults, have been traced from the Polish basins through to the southern North Sea and possibly all the way along the Norwegian coast to the Kola Peninsula (HAMAR ET AL., 1982; HAMAR, 1982; HESJEDAL, 1981; POZARYSKI & BROCHWICS-LEWINSKI, 1978; SIEDLECKA, 1975). Tangential forces in connection with the Alpine orogeny may have acted on the Fennoscandian Shield through the Carpathian fold belt and consequently given rise to this kind of movements (Fig. 9).

Structural and stratigraphic cross-sections across the Central Graben indicate that Early Cretaceous hiatuses are no longer localized on the tops of the structural highs, but occur somewhat further down on the basin slopes (Fig. 8b). This is due to movements which have led to a gradual migration of the basin edges in a landward direction, and thereby to an extension of the basin areas themselves. These movements can be dated as post Aptian.

EXPLORATION CONSIDERATIONS

Geochemical analyses show that Early Cretaceous sediments generally have a relatively high content of organic material. The Sola Formation is especially a promising unit for the generation of hydrocarbons. Together with the underlying Upper Jurassic shales it is considered to be of very good source rock potential.

The Early Cretaceous epoch was characterized by very

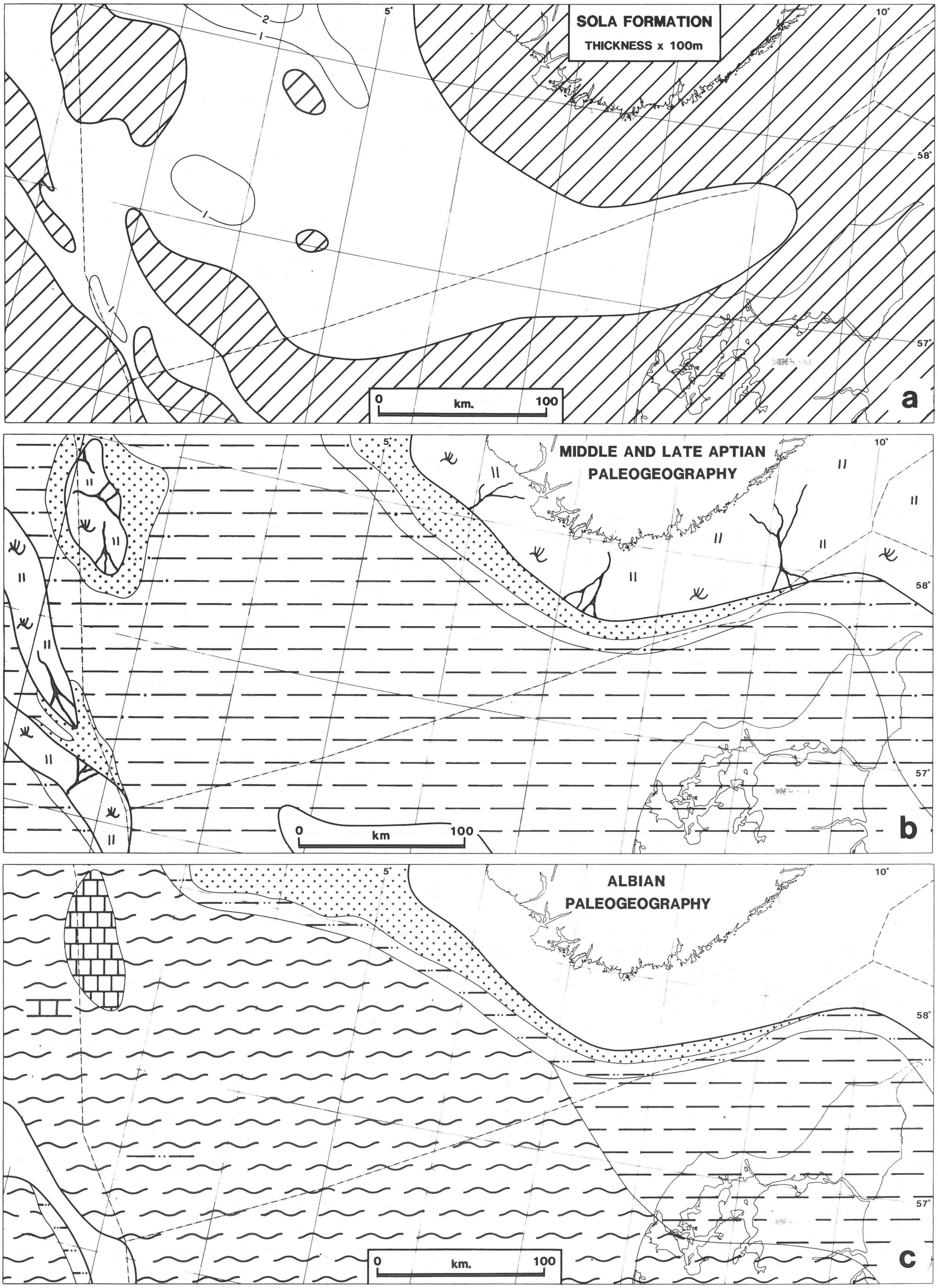

Fig. 5
Isopach and palaeogeographic maps. For legend see figure 4.

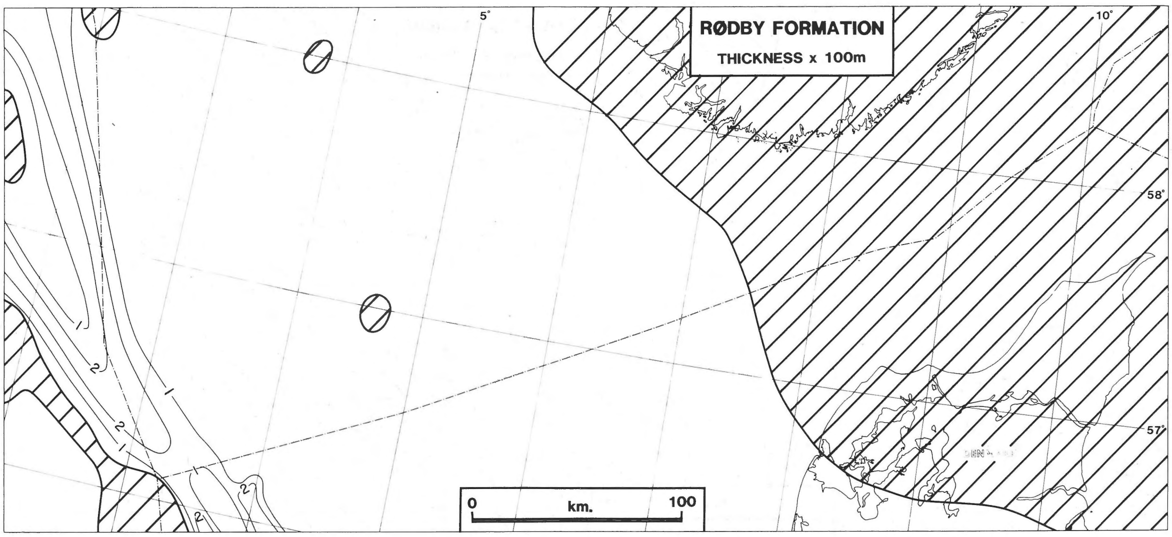

Fig. 6
Isopach map. Rødby Formation.

rapid sea floor spreading in the Atlantic, which on the shelf led to repeated transgressions. The temperature of the ocean waters was considerably higher than it is today, and this together with good nutrient availability resulted in abundant organic production. In the greater part of the Early Cretaceous, however, the water circulation was prevalent enough to destroy considerable parts of the organic material by oxidation and by animal scavengers. An exception to this is the Sola Formation of middle to late Aptian age which was deposited during or immediately following a regressive period in more or less restricted basins with almost anaerobic bottom water conditions. As a consequence, this Formation contains more organic rich shales than the rest of the Lower Cretaceous sediments. Average TOC-values are greater than 2% with an increasing trend towards the centres of the basins (TOC = total organic carbon). Because of the regressive depositional setting the organic content of the Formation is dominated by terrestrial material. This fact reduces the oil source rock

TETHYAN TIME SCALE	GERMANY (NIEDERSASCHISHES) BECKEN	ENGLAND WEALDEN AREA	ENGLAND EASTERN PART	DANISH SUB-BASIN	SOUTHERN NORTH SEA	FISKEBANK SUB-BASIN	BOREAL TIME SCALE
CENOMANIAN	KALK CENOMAN-MERGEL	LOWER CHALK	LOWER CHALK	LIMESTONE & MARL	CHALK GROUP	HIDRA FM.	CENOMANIAN
ALBIAN	FLAMMEN MERGEL; ALB-TONMERGEL	GAULT CLAY; U.GREEN SAND; FOLKSTONE B.	GAULT CLAY; RED CHALK; CARSTONE	RØDBY FM.	RED CHALK FM.	RØDBY FM.; FLORØ & KOPERVIK FM.	ALBIAN
APTIAN	APT-TONMERGELSTEINE; FISCH-SCHIEFER	L. GR SAND: SANDGATE B.; HYTHE B.; ATHERF. CLAY	SUTTERBY MARL; EWALDI MARL	VEDSTED FORMATION	SPEETON CLAY FORMATION	SOLA FM.	APTIAN
BARREMIAN	BARREME-TONE	WEALDEN BEDS: WEALD CLAY	SPEETON CLAY: FULLETBY B.			VALHALL FORMATION; UTVIK FM.	BARREMIAN
HAUTERIVIAN	HAUTERIVE-TONMERGEL		TEALBY B.				HAUTERIVIAN
VALANGINIAN	VALANGIN-TONSTEINE	HASTINGS BEDS	CLAXBY B.; LEZIATE B.				VALANGINIAN
BERRIASIAN	NW-GERMANWEALDEN; "SERPULIT" BEDS	PURBECKIAN BEDS	SPILSBY SANDSTONE	BØRGLUM Mb.; FREDRIKSHAVN Mb.	SPILSBY SANDSTONE FM.	FLEKKEFJORD FM.	RYAZANIAN
TITHONIAN	MUNDER-MERGEL					SAUDA FM.	VOLGIAN
U.KIMMERIDGIAN	OBER-MALM	PORTLANDSTONE	KIMM. CLAY FM.		KIMMERIDGE CLAY FM.	TAU Mb.; BØRGLUM FM.	

Fig. 7
Correlation chart, Lower Cretaceous, Northwestern Europe.

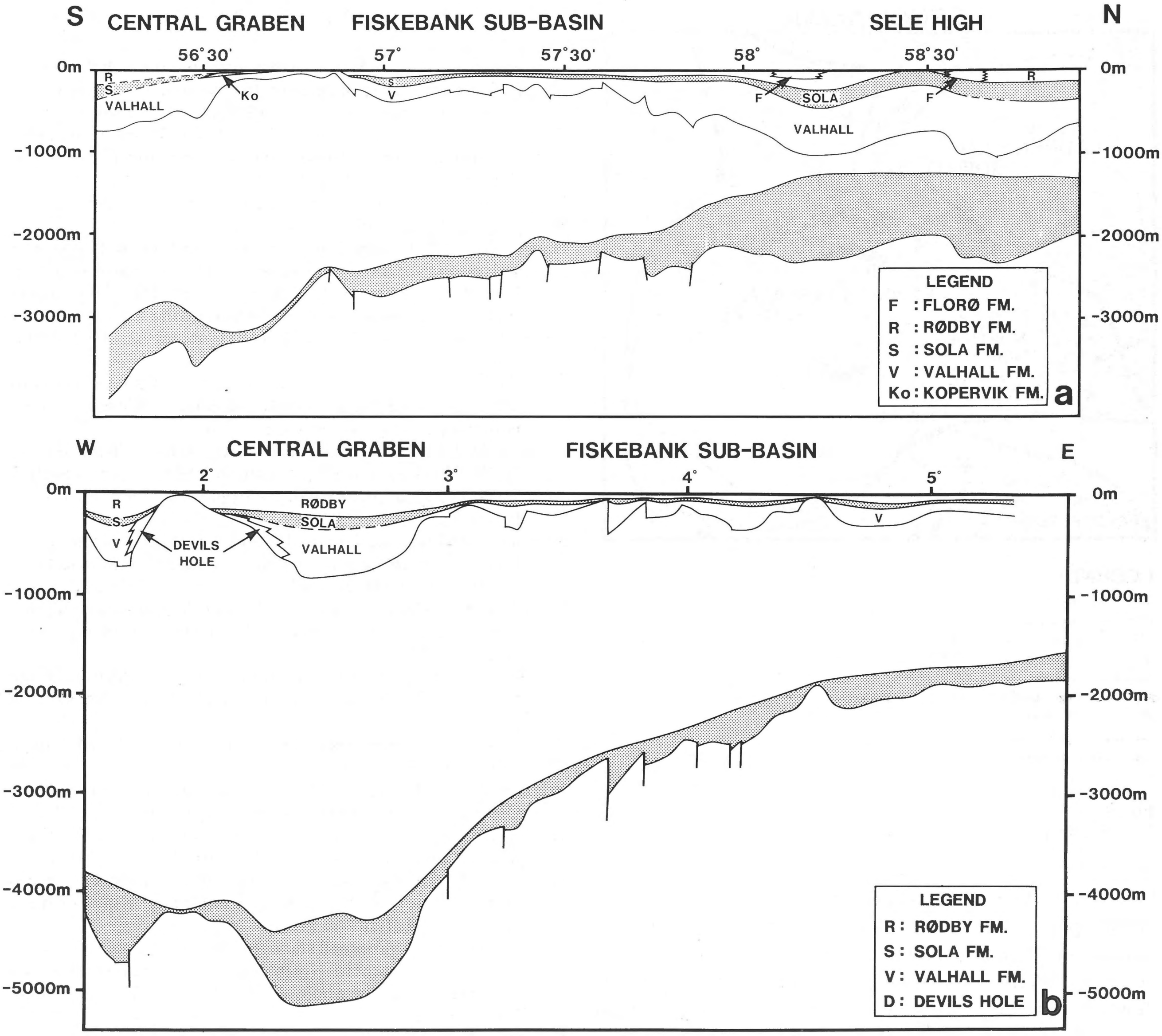

Fig. 8
Structural and stratigraphic cross-sections. The lower part of each figure is a structural cross-section showing the top and the base of the Lower Cretaceous. The upper part is a stratigraphic cross-section with the top of Lower Cretaceous as a datum. The positions for these cross-sections are shown on figure 1.

potential, but still the Sola Formation probably has a fairly good potential for the generation of gas and lesser quantities of oil.

The thickness of the Sola Formation varies from about 20 m to more than 200 m and the sediments have a considerable source rock potential. Proper maturation is, however, the main critical factor for this source rock. The oil window is reached only in the deeper parts of the Central Graben area. The gas window is probably not reached anywhere within the study area. Within the study area three separate formations of Early Cretaceous age have been recognised as potential reservoir rocks. These are: the Devils Hole-, the Kopervik- and the Florø Formations. They are all situated in ideal stratigraphic positions relative to hydrocarbon migration from potential source rocks. In addition, the thicknesses, regional distribution and reservoir properties make them an interesting target for exploration.

Hydrocarbon shows have been encountered in each of the formations, but in spite of more than hundred wells drilled in the study area, no commercial Early Cretaceous discovery has yet been made. One of the reasons for this lack of success is probably the structural location of the wells. As a rule the wells have been drilled in optimal structural positions to test Jurassic or Late Cretaceous prospects. This type of structural test is, however, not necessarily the most favourable location for the Early Cretaceous prospects. The Lower Cretaceous

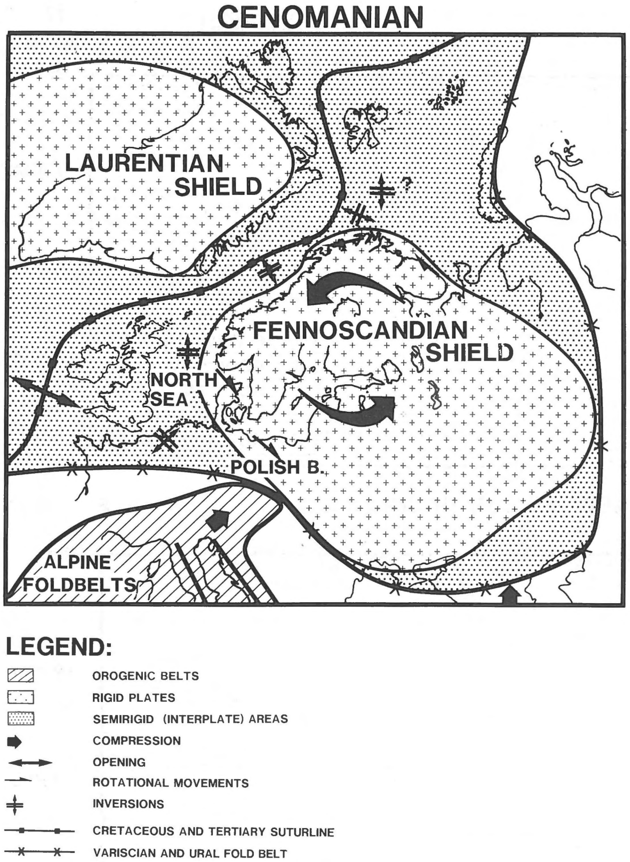

Fig. 9
Major tectonic features at the onset of the Alpine Orogeny.

reservoir rocks were deposited on a Jurassic block faulted topography and this means that the reservoir rocks may be situated in the troughs and not on the crests which have been tested by drilling. The most promising type of trap in the Lower Cretaceous may well be in the class of stratigraphic traps. This fact makes the exploration for such reservoirs a great challenge to the North Sea explorationists and more effort should be paid to this type of play.

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