Boundaries: The lower and upper boundaries are defined at the base and top of the pure and soft claystone (see the log characteristics).

Distribution: The distribution may be as in the underlying formation (fig. 20). Due to the halokinetic movements the Formation may be absent locally.

Geological age: An ostracod assemblage of *Emphasia* ssp. (Michelsen 1978a) and the presence of *Ricciisporites tuberculatus* miospores indicate a Rhaetian age (Bertelsen 1978).

Depositional environment: The deposits are interpreted as being formed as the underlying sediments. A very characteristic kaoline content in the Formation seems to indicate weathering. This corresponds to the seismic information about the relatively elevated position of the drilled Formation and the probability of more sandy members along these areas.

Source rock potential: Data insufficient for an evaluation.

Reservoir potential: Poor in the claystone. May be fair to good in the sandy members.

Sealing potential: Probably poor due to the sandy sections.

3.4 Jurassic

By Jens Ole Koch, Lise Holm & Olaf Michelsen

During Early Jurassic time, deposition continued in the basinal areas occupied by Triassic sedimentation. The Danish Central Graben subsided strongly and more than 4000 m of sediments were deposited during Jurassic time (fig. 14). North of the area the thickness seems less than 2000 m and, in the Norwegian-Danish Basin, approximately 1200 m. The rythm of sedimentation corresponds closely to what is known from adjacent areas in the Northwest European sedimentary region.

During the Early Jurassic, relatively uniform marine claystone series, the Fjerritslev Formation, were deposited all over the North Sea region, including the main part of the highs. Large areas were uplifted and eroded during the Mid Cimmerian phase (fig. 23), accompanied by a general eustatic lowering of the sea level. During the Middle Jurassic period, deltaic or fluvial conditions prevailed in the main part of the North Sea, and coal-bearing sand bodies, the J-2 Unit, were deposited. During the Late Jurassic a general subsidence took place, but more restricted areas were transgressed by the sea than in the Early Jurassic. Thick marine claystone series (the J-3 and J-4 Units) were deposited in the main part of the basin. Near marginal highs, only minor sand bodies (the W-1 Unit) were laid down. The Late Jurassic is a period of main subsidence for the Central Graben. Figs. 21 and 23 show the distribution of Jurassic sediments.

Fjerritslev Formation Larsen 1966 and Michelsen 1978b

The Formation was established by Larsen (1966) and later revised and subdivided by Michelsen (1978b) into four members (F-I, F-II, F-III, and F-IV). The type well (Fjerritslev-2) is situated in northern Jylland in the northwestern part of the Danish Subbasin, in which the Formation is widely distributed.

On the basis of the assumption that the Lower Jurassic claystones present in the Central Graben and in the Danish Subbasin originally formed one coherent sediment body, which during the Mid Cimmerian tectonic episode was differentially eroded (see e.g. Michelsen 1978b, fig. 12), the name Fjerritslev Formation has also been assigned to the Lower Jurassic claystones in the Danish Central Graben.

The Fjerritslev Formation corresponds to the Dunlin Unit in the northern North Sea (Deegan & Scull 1977).

Type section: The Fjerritslev-2 well in northern Jylland from 1314 m to 2225 m b.MSL.

Reference sections: The O-1, U-1, and M-8 wells in the southern part of the Danish Central Graben (see chapter 8).

Thickness: The thickness of the Fjerritslev Formation is 155 m (O-1), 93 m (M-8), and 48 m (U-1).

In the Danish Central Graben, the Formation is rather thin in comparison to the type section. This is partly due to Mid Cimmerian erosion of the top of the Formation. The O-1 and M-8 wells are situated on domes induced by the flow of Triassic salt (or shale), but the thickness of the Fjerritslev Formation is probably unaffected by halokinesis. In the U-1 well the thickness might be slightly reduced due to Early Jurassic halokinesis in the underlying Zechstein salt pillow.

Lithology: The Fjerritslev Formation consists mainly

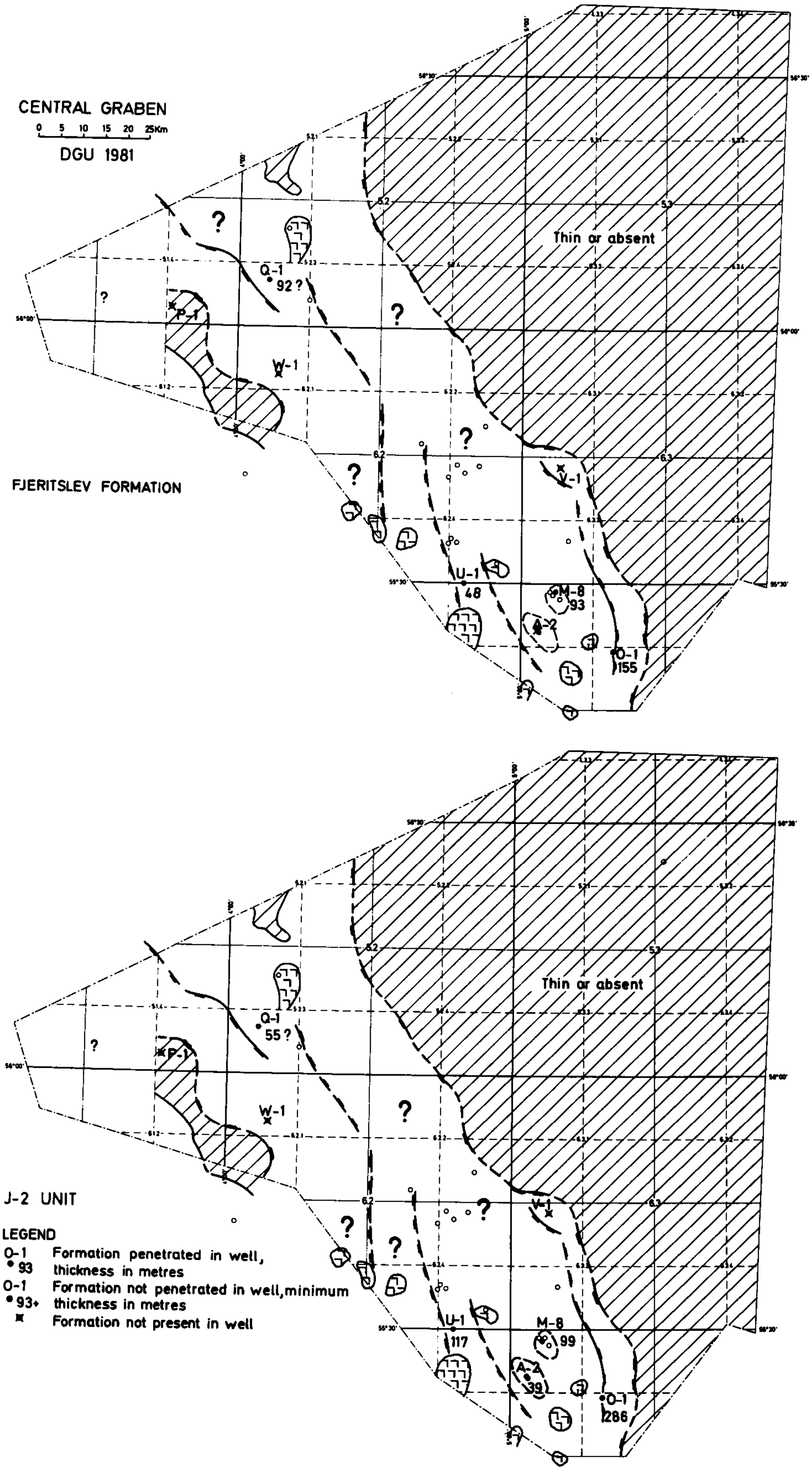
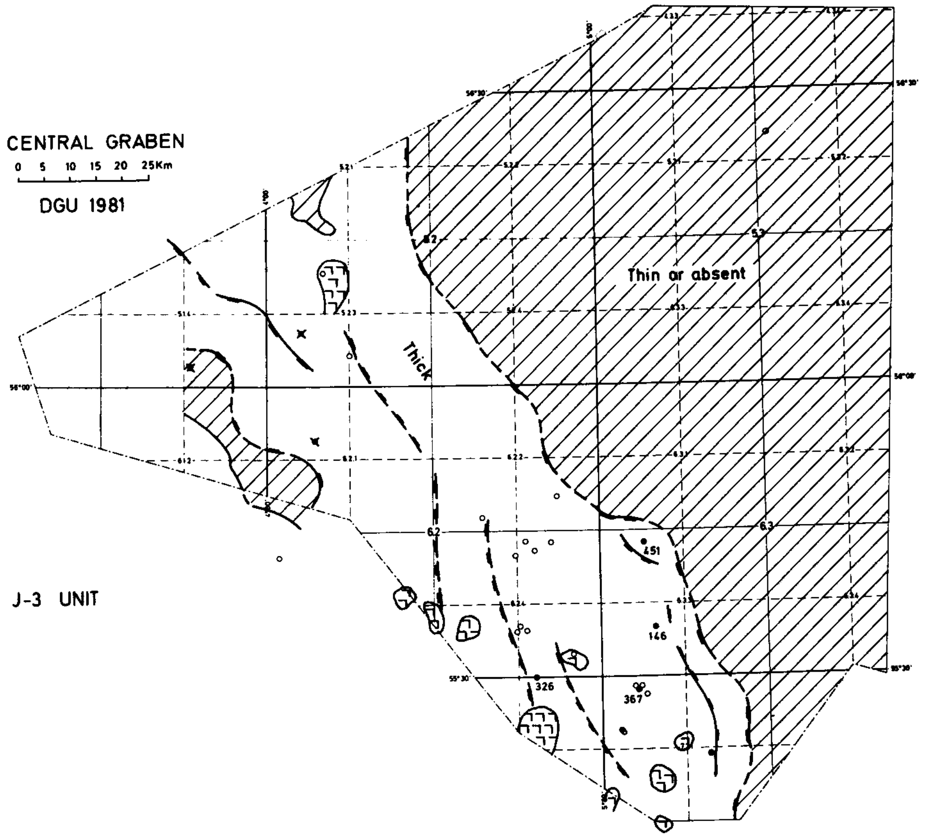


Fig. 21: Distribution and thickness of a) the Fjerritslev Formation and b) the J-2 Unit.



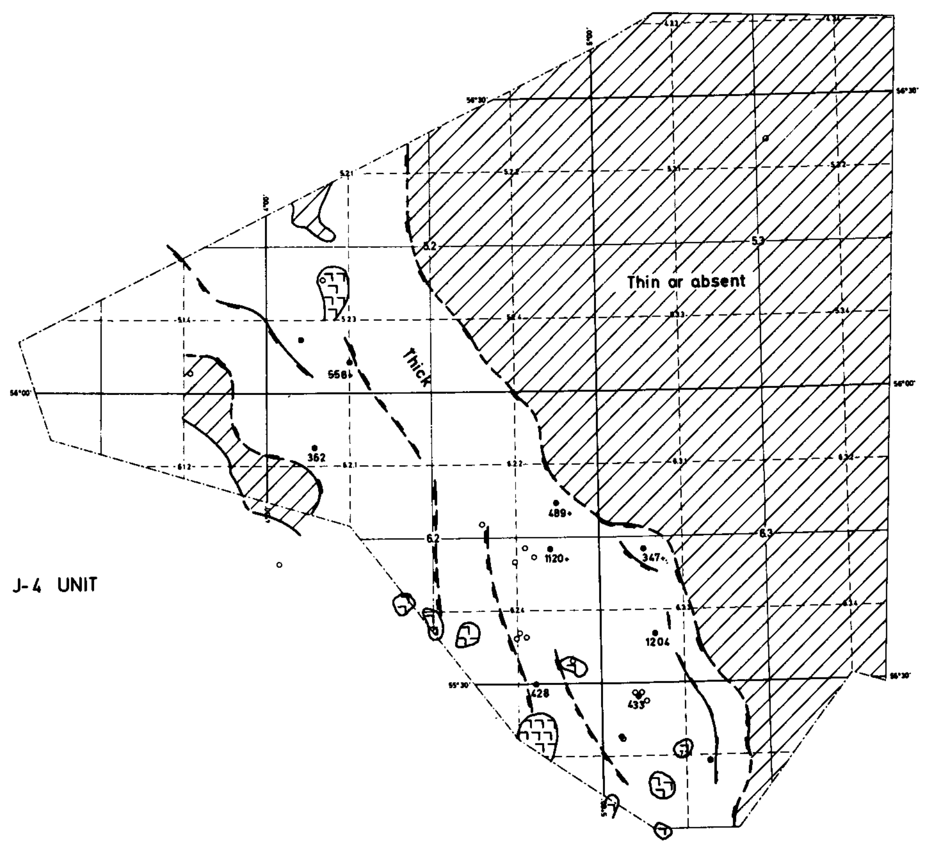


Fig. 22: Distribution and thickness of the a) J-3 Unit and b) the J-4 Unit. – For legend, see fig. 21.

of hard, dark grey, slightly calcareous, silty claystones with pyrite, becoming fissile in places. Downwards the claystones are interbedded with thin, light grey, silty, calcareous claystones and soft marlstones.

Subdivision: On the basis of log correlations the Formation tentatively has been subdivided into three members.

Log characteristics: The Formation is characterized by regular high-level gamma ray readings and a relatively regular sonic velocity pattern. Downwards the sonic velocity becomes more irregular, reflecting more abundant occurrence of thin soft marls and hard silty claystones.

Boundaries: The lower boundary of the Fjerritslev Formation is the contact to the underlying Winterton Formation which is characterized by a very low sonic velocity and a high gamma radiation. This boundary is thus marked by breaks both in the gamma ray and the sonic velocity.

The Fjerritslev Formation is unconformably overlain by the sandy J-2 Unit which is characterized by a low, irregular gamma radiation and a very irregular sonic velocity. Thus the upper boundary of the Fjerritslev Formation also is well marked by characteristic breaks in the sonic velocity as well as in the gamma ray response.

Distribution: Seismic mapping of reflectors below the 'Late Cimmerian unconformity' has not yet been completed. However, the Fjerritslev Formation has been penetrated by the O-1, U-1, and M-8 wells which are situated in the southern part of the Danish sector (fig. 21).

On the basis of log correlations and datings of the three drilled sections, it is suggested that the Fjerritslev Formation has been differentially eroded during the Mid Cimmerian tectonic episode and that it is unconformably superposed by the J-2 Unit. The Fjerritslev Formation is thickest near the border faults of the Ringkøbing-Fyn High (east of the O-1 well) which probably was syn-sedimentarily active. In the A-2, W-1, Q-1, and V-1 wells, which are situated on domal features in the Central Graben, the Fjerritslev Formation has been almost entirely eroded or possibly never deposited. Hence, on some of these domal features the J-2 Unit directly overlies Triassic or older rocks.

The remaining wells in the Danish sector, either

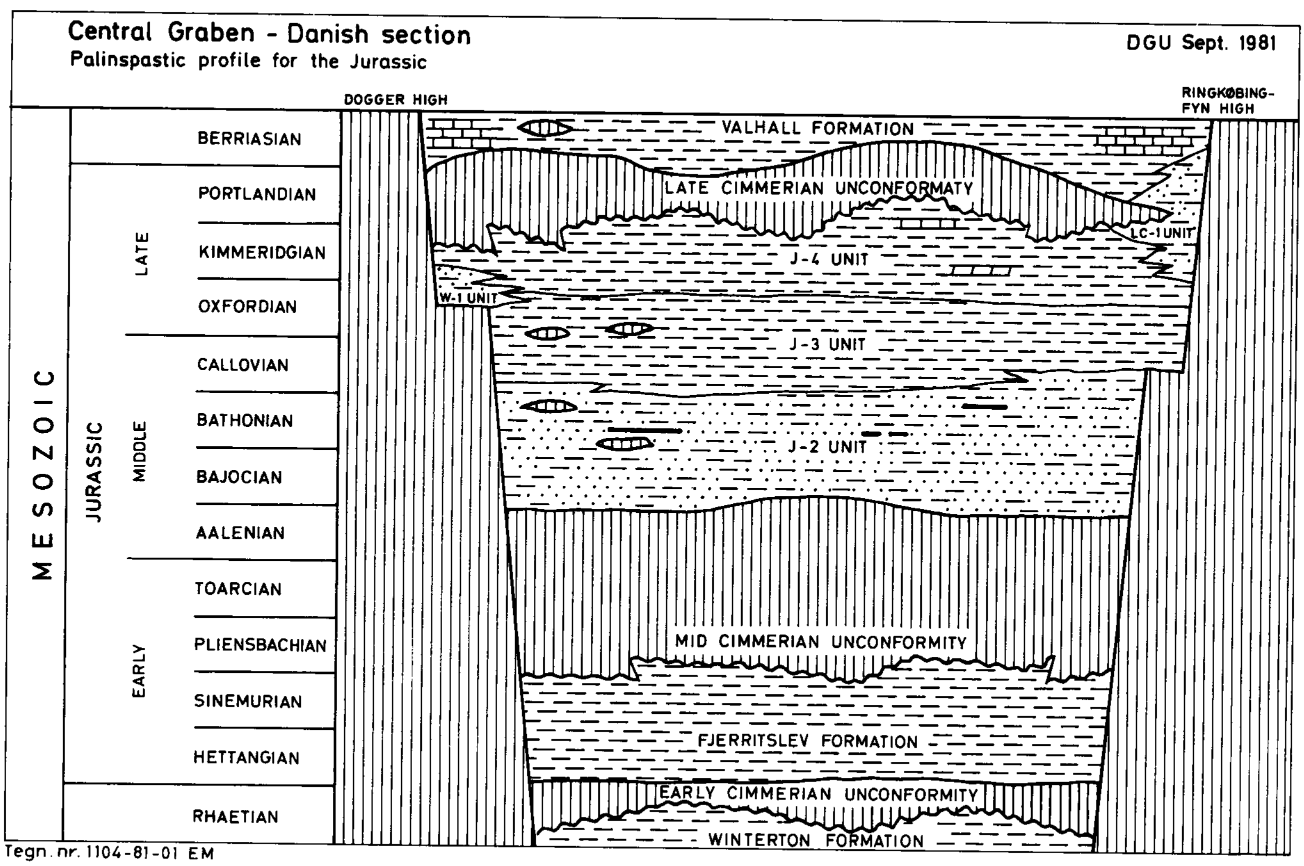


Fig. 23: Palinspastic profile of Jurassic deposits. For legend, see fig. 3.

meet the salt well above the level of the Fjerritslev Formation or they have not been drilled deep enough to reach it. However, seismic mapping and the presence of the Fjerritslev Formation on top of three domal structures in the southern part suggests that the Formation is present in between the domes, at least in the southern part of the Danish sector of the Central Graben.

North of the Danish sector the Fjerritslev Formation was encountered in the Norwegian 7/9-1 well. This might indicate that the Formation may also be present in the northern part of the Danish sector between the domes.

Geological age: On the basis of ostracods and sporomorphs, the Formation is dated to the Hettangian-Sinemurian in the U-1 and O-1 wells (Michelsen 1978a) and to the Sinemurian-Lower Pliensbachian in the M-8 well.

The J-2 Unit unconformably overlies the Fjerritslev Formation. The two formations are separated by a Pliensbachian-Toarcian-Aalenian hiatus.

Depositional environment: The fine-grained sediments and flora/fauna content suggest that the Fjerritslev Formation was deposited by the settling out of suspension of clay and silt below wave-base in a marine water body.

The upwards decreasing content of silt- and marlstone beds points to a decreasing silt influx into the basin, or to an increasing distance to the basin margin. This might be a response either to the general Early Jurassic eustatic sea level rise or to differential subsidence of the Central Graben basin, or to a combined effect of both mechanisms.

It has been argued that the Fjerritslev Formation and the equivalent Dunlin Unit (Deegan & Scull 1977, p. 14) should have been deposited in the pro-delta and delta-front environments of the overlying Haldager and Brent Formations. This model, however, implies that the two formations were deposited at the same time and in the same basin. This assumption appears to be erroneous because of the large hiatus between the two formations. It is more likely that the Fjerritslev Formation represents a calm influx of sediments into the subsiding basin during the Early Jurassic eustatic sea level rise, while the superposed Middle Jurassic J-2 Unit was deposited in response to the Mid Cimmerian tectonic episode.

Source rock potential: Investigations of the Fjerritslev Formation in the M-8 well have shown that the organic material is mainly marine, but some terrestial material does occur. The Formation is regarded as a good source rock for oil and gas. Further investigations are needed.

Reservoir potential: Poor, due to the lack of porous permeable intervals.

Sealing potential: Good.

J-2 Unit *(informal name)*

The J-2 Unit is penetrated by the A-1, O-1, M-8, and U-1 wells in the southern part of the Danish Central Graben, and probably also by the Q-1 well in the northern part. The Unit is equivalent to the Haldager Formation (Larsen 1966 and Michelsen 1978b) in the Danish Subbasin and to the Brent Unit (see Deegan & Scull 1977) in the northern North Sea.

Type section: The Danish O-1 well, 8901-9840' b.KB.

Reference sections: The M-8, U-1, and A-2 wells (see chapter 8).

Thickness: The thickness of the J-2 Unit is 286 m (O-1), 117 m (U-1), 99 m (M-8), 39 m (A-2), and 55 m (Q-1).

The above mentioned wells are all situated on domal structures. The influence of halokinesis on the thickness of the Unit has not yet been evaluated.

Lithology: The Unit consists of interbedded clean sandstones, claystones, and heterolithic sand-siltstones with coal seams.

The clean sandstones are white to grey-brown, hard to friable, fine- to medium-grained, slightly calcareous with fair primary porosity.

The heterolithic sand- and siltstones consist of interlaminated light sand- or siltstones and dark claystones, occasionally wavy bedded or showing slump, flame, and ball structures.

Usually the claystones are dark grey to black, moderately hard, slightly silty and sideritic.

The coal seams most frequently are 0.5 to 1 foot thick, but seams up to 8 feet occur. The coals are black and lignitic.

Subdivision: In most of these wells, two members can be recognized (see chapter 8). The lower member consists of interbedded thick sandstones, claystones, and heteroliths. The upper member comprises interbedded claystones, sandstones, heteroliths, and coal seams, in most wells showing an upward decreasing occurrence of sandstone beds.

Log characteristics: The J-2 Unit is characterized by very irregular sonic velocity and gamma ray patterns. The thick sandstone bodies separated by thin claystones or coal seams occasionally give the sonic velocity curve a blocky appearance.

Boundaries: The J-2 Unit rests unconformably on rocks of Triassic and Early Jurassic age. The lower boundary therefore tends to be relatively sharp, and it is usually easily recognized on the gamma ray and sonic velocity responses.

The upper boundary is usually recognized as a break in the sonic velocity due to the lower velocity of the overlying claystones of the J-3 Unit.

Distribution: Interpretation of seismic reflections below the Late Cimmerian unconformity has not yet been completed. The J-2 Unit is known from the sections presented in fig. 21. Nevertheless, it may possibly cover most of the Central Graben area.

Geological age: A Bajocian? age is indicated in the A-2 well, and the Unit is assigned to the Bathonian-Bajocian in the U-1 well on the basis of palynomorphs.

Depositional environment: The coal seams in the upper member were probably formed by autochthonous accumulation of plant material in a shallow water swamp environment in a warm, humid climate. The heterolithic nature of the silt- and claystones indicates regular fluctuations in flow regime, e.g. caused by deposition in the intertidal zone or by deposition from fluctuating river discharges.

Dipmeter analysis of sandbeds in the O-1 well shows a concentration of decreasing dip, with depth patterns centering around a dip axis of 215°. A secondary concentration is found with westerly to northerly dip directions.

It has been suggested by several authors (e.g. Ziegler 1978 and Eynon 1981) that the Middle Jurassic sedimentation in the Danish Central Graben was entirely continental, due to the Mid Cimmerian uplift of the volcanic centre in the triple junction between the Central Graben, Viking Graben, and the Moray Firth Basin. Skarpnes et al. (1980), however, suggest a marine connection through the Central Graben in Middle Bathonian time, and Ziegler (1981) has included a small Middle Jurassic marine basin in the southernmost part of the Central Graben.

On the basis of the available data it is difficult to tell whether the J-2 Unit was deposited in a fluvial valley-system, which now and then was invaded by the sea, or if the Unit was accumulated by progradation of a deltaic system into a marine basin. However, it does not appear to be unreasonable to apply the delta model, and consequently interpret the lower member as having been deposited as pro-delta clays and distributary mouthbar sands, while the upper member represents deposition in interdistributary bays and coastal swamps on the subaerial-intertidal deltaplain. Although the dipmeter analysis from the O-1 well most likely points to transport directions towards SW, it is still highly speculative whether the delta system advanced from the north to the south into the West Netherlands Basin, from the south to the north, or simply was spread from the margins into the central part of the Central Graben.

Source rock potential: The claystone beds from the M-8 well were examined in detail. They were found to contain algae-rich organic material which is favourable for oil formation, and the beds were classified as rich source rocks.

Reservoir potential: The J-2 Unit contains several up to 6 metre thick sand- and siltstone beds with good reservoir characteristics.

The sand- and siltstone intervals are listed in the reservoir data sheets along with log porosity evaluations. The log porosity varies between 4 and 45%, the average (chapter 9) being around 20%.

Most wells had gas shows in the J-2 Unit, and tests were performed in the M-8, and U-1 wells.

Sealing potential: Individual claystone beds might be quite impermeable, but the lateral extension is most likely limited. Generally the sealing potential is believed to be poor.

W-1 Unit *(informal name)*

Until now this Unit only has been penetrated by the Danish W-1 well, which is situated on the northeastern flank of the Dogger High. The Unit might be equivalent to the Piper Formation of Deegan & Scull (1977) from the Northern North Sea.

Type section: The Danish W-1 well, 13521-13860' b.KB.

Reference sections: None.

Thickness: 97 m (318') in the type well.

Lithology: The Unit consists of grey to white sandstones, minor siltstones, and conglomerates interbedded with dark grey claystones and heterolithic siltstones and claystones. The sandstones are grey to white, fine-grained, firm, in part friable, moderately sorted, moderately argillaceous, in part conglomeratic. They consist mainly of rounded to sub-angular grains of quartz but contain glauconite and are slightly carbonaceous and calcareous. Loose medium-grained sand beds of clear to milky quartz occur. The conglomerates comprise rounded granular clasts of milky chalcedony and quartz, some dolomitic and granitic clasts, and minor occurrences of light grey siltstone clasts in a medium-grained sand matrix. The interbedded claystones are light to dark grey, soft to firm, slightly silty, and occasionally grading into or interbedded with argillaceous siltstones, blocky to subfissile, slightly to moderate calcareous, micaceous, carbonaceous with traces of glauconite. The claystones and siltstones occasionally contain carbonized plant remains, pyrite, and large bivalves (*Ostrea* sp.).

Log characteristics: The W-1 Unit is characterized by a low gamma ray record and a relative regular sonic velocity pattern. The occurrence of thin claystones interbedded with thicker sandstones and conglomerates, or thin sandstones interbedded with thicker claystones, gives the gamma ray response a somewhat blocky appearance.

Boundaries: In the type section, the Unit rests unconformably on red-brown, probably Permian claystones and volcanics. Downwards the boundary has been defined by a shift to higher sonic velocities in the probably harder Permian rocks. The upper boundary is easily recognized in the type well, as strong breaks occur both in the gamma ray readings and in the sonic velocities because of the shift to the overlying radioactive and soft J-4 Unit.

Distribution: The Unit is known only from the W-1 well. Seismic mapping of the horizon has not yet been performed in the area. However, it is believed that the W-1 Unit is distributed along the northeastern margin of the Dogger High which most probably acted as the source area of the sandstones.

Geological age: No detailed biostratigraphical data are available at present. A completion log, provided by the concessionaires, states that the W-1 Unit and the overlying J-4 Unit span the chronostratigraphic interval Late Oxfordian - Early Kimmeridgian.

Depositional environment: The content of glauconite and bivalves (*Ostrea* sp.) suggests that the Unit was deposited in marine waters. A shallow marine coastal environment is the most likely possibility. The sandstones might represent barrier bars or other shallow marine coastal sand bodies, stacked on top of each other and interbedded with claystones representing more offshore or lagoonal sedimentation.

More detailed sedimentological information is needed for conclusive evidence.

Source rock potential: The claystones might serve as an intraformational source rock, but they contain terrestric plant remains and the net thickness is only approximately 20 metres. No detailed investigations have been performed.

Reservoir potential: Three major sandstone intervals occur in the W-1 Unit in the type section. The net sand thickness is approximately 67 m (219') with a neutron porosity of 12-15% (chapter 9). Two Formation Interval Tests were performed, but no conclusive calculations of the permeability can be made.

Sealing potential: Probably poor.

J-3 Unit *(informal name)*

This Unit is penetrated by the Danish A-2, G-1, M-8, O-1, and U-1 wells, and is probably present in the V-1 well. The Unit might be analogous with the Heather Formation of Deegan & Scull (1977) from the northern North Sea and parts of the central North Sea.

Type section: The Danish M-8 well, 8940-10143' b.KB.

Reference section: The Danish U-1 well, 9595-10665' b.KB.

Thickness: 367 m in the type section. This order of thickness is known from the wells penetrating the Unit. However, from seismic data the thickness is expected to be much greater in the Tail End Graben.

Lithology: Claystone, often slightly silty, dark grey, brownish-grey, grey, slightly calcareous, with micro-lignite, plant remains, and traces of pyrite. Siltstone, medium to coarse-grained, greyish-brown, and marlstone, light greyish-brown, occur subordinately.

Log characteristics: The J-3 Unit is characterized by a fairly constant high gamma ray response and low sonic velocity.

Subdivision: At the moment no subdivision has been carried out.

Boundaries: In the southern well sections, the J-3 Unit rests on the J-2 Unit. The lower boundary here is defined on the sonic log as a decrease in the velocity from the J-2 to the J-3 Unit.

The upper boundary is marked by an increase in the sonic velocity and a small decrease in the gamma ray response in the J-4 Unit. In the V-1 well, the Upper Jurassic sediments rest unconformably on Triassic rocks. The presence of a J-3 Unit here is proposed but the log-pattern is not typical.

Geological age: Based on ostracods and palynomorfs, the Unit is dated to Oxfordian and probably Callovian.

Depositional environment: The fine-grained nature of the J-3 Unit and the flora/fauna content suggests that the Unit was deposited by the settling out of suspension of clay and silt below wave base in a marine water body. The presence of siltstone and plant remains shows that the basin margin was not too far away. The open marine claystone of the J-3 Unit represents the condition that prevailed after the transgression which followed the Mid Cimmerian uplift.

Distribution: Seismic mapping of the internal reflectors in the Jurassic has not yet been carried out. Further, as the J-3 Unit is known only from few wells, all situated in the southern part of the Danish Central Graben, no accurate distribution can be mapped. However, based on the general regional pattern, the Unit is thought to be present in most parts of the Danish Central Graben basin (fig. 22).

In the Q-1 and W-1 wells, both situated on domal features, the J-3 Unit has been totally removed or never deposited, and the J-4 Unit directly overlies the J-2 Unit and the W-1 Unit respectively.

Source rock potential: Only the M-8 well has been investigated. The Unit is not a promising source rock for oil, due to an unfavourable type of organic matter. It might be a potential gas source rock. In M-8 the Unit is just within the zone of oil generation.

Reservoir potential: Poor, due to the absence of porous layers within the clay sequence.

Sealing potential: Good, due to the thick and homogeneous claystone sequence.

J-4 Unit *(informal name)*

The J-4 Unit is known from 13 wells in the Danish sector, of which 8 penetrated the Unit. It is equivalent to the Kimmeridge Clay Formation described by Deegan & Scull (1977) and known from most of the North Sea area.

Type section: In order to cover the main part of the Unit, two well sections have been established as type sections. The Danish G-1 well (8088-12037' b.KB) is the type well for the lower part of the Unit. The Danish E-1 well (9727-13403' b.KB) is the type well for the upper part.

Reference section: The Danish U-1 well, 8190-9595' b.KB.

Thickness: See below.

Lithology: Claystone, shaly, laminated, dark grey, slightly silty, calcareous, with mica, microlignite, and pyrite. The organic carbon content is normally high and of marine origin. Numerous thin lime- and dolostone beds are characteristic according to the gamma ray and sonic velocity responses. The uppermost part of the Unit is characterized by a highly radioactive shale.

Log characteristics: The J-4 Unit is characterized by a high gamma ray response and a low sonic velocity, often with many high velocity peaks. The uppermost part has a very high gamma response.

Subdivision: In one well (E-1) the uppermost part of the J-4 Unit has a very high radioactivity, but no formal subunits have at present been established for this interval.

Boundaries: The J-4 Unit rests in the main part of the Central Graben on the J-3 Unit, and the lower boundary is marked by an increase in sonic velocity and a small decrease in the gamma ray response. The upper boundary is an unconformity (the Late Cimmerian unconformity), normally overlain by Early Cretaceous sediments of varying age. The Cretaceous sediments normally have a higher sonic velocity and lower radioactivity than the J-4 Unit, so there are often strong log breaks at this boundary.

Geological age: The Unit ranges from Late Oxfordian to Portlandian in age.

Depositional environment: The fine-grained sediment, the flora/fauna, and the high organic content suggest that the J-4 Unit was deposited in a marine environment with high organic productivity and restricted bottom circulation, probably deeper shelf.

Distribution and thickness: Seismic mapping of the internal reflectors in the Jurassic sequence has not yet been carried out. A two way time to the Top Jurassic has been mapped, but no depth conversion has been made. This means that the regional depths and thicknesses mentioned below are only very approximate.

The J-4 Unit is present in most of the area (fig. 22). Only on salt structures and on structural highs is it likely to be absent. In the southern part of the Danish Central Graben, the thickness is several hundred metres and the Unit lies within the depth interval 2 1/2 to 5 kilometres, depending on its location in relation to the salt structures. The Unit is thinnest and situated highest on the structures, while in the rim-synclines it is thickest and deepest situated.

In the Tail End Graben the J-4 Unit reaches its greatest thickness. In the G-1 well, situated in the transition zone between the southern part of Central Graben and the Tail End Graben, the thickness is 1204 m .The thickness is expected to increase northwards in the Tail End Graben. Locally it might exceed two thousand metres. The depth to the top of the Unit is 3 kilometres in the southern part of the Tail End Graben, and the top dips to 4 kilometres towards the north.

In the areas north and south of the Dogger High, the depth to the Top Jurassic is generally from 3 to 4 kilometres and it can exceed 5 kilometres locally. The thickness of the J-4 Unit in these areas is not yet known.

Source rock potential: Investigations of the M-8 and I-1 sections have shown that the J-4 Unit must be regarded as the most important source rock for oil generation. It is potentially good in M-8, and rich to extremely rich in I-1. It is immature in M-8, but probably mature in the adjacent basinal areas of this structure. It is mature in I-1.

Reservoir potential: Generally poor, but hydrocarbon shows have been reported from the lime- and dolostone stringer, which thus might have reservoir characteristics.

Sealing potential: Good, due to the thick and homogeneous claystone sequence.

3.5 Early Cretaceous

By Jens Morten Hansen & Arne Buch

The Early Cretaceous sea primarily covered the same basinal regions as the Late Jurassic sea but, late in the Early Cretaceous the sea also covered Late Jurassic land masses. During Early Cretaceous time the topography of the North Sea region became gradually buried. The following major transgression comprises the transition Early/Late Cretaceous. At the Jurassic/Cretaceous transition, the Late Cimmerian unconformity is a significant feature (fig. 24), known from large parts of the North Sea region. The subsequent transgression and sedimentation of marine clay (the Valhall Formation), and marine sand (the LC-1 Unit), started late in Late Jurassic. Therefore, the formations described in the present chapter also comprise sediments of Late Jurassic age. Thicknesses of the Lower Cretaceous sediments are given in fig. 15.

LC-1 Unit *(informal name)*

The LC-1 Unit has been established in order to treat the Early Cretaceous - Late Jurassic sandstones in the V-1 well. These sandstones cannot be considered to be a part of any other formation known from the Central Graben, but they are probably equivalent to the Devil's Hole Formation (see Deegan & Scull 1977).

Type section: The Danish V-1 well, 8947-9462' b.KB.

Reference section: None at present.

Thickness: The Unit interfingers with other formations and comprises only sandstones, siltstones, carbonate-cemented siltstones (?marls), and marls. The total thickness of these sandstones, siltstones, and marly beds (excluding clay beds) is 61.5 m in V-1.

Lithology: Sand- and siltstones, silty sandstones, sandy siltstone, and sandy marl. It is grey to dark grey with thin subordinate grey to dark grey shales and clays. Calcareous and pyritic.

Log characteristics: The Unit is characterized by low gamma ray readings and very irregular sonic velocities.