of material in the J-3 Unit is not as favourable as in the J-4 Unit.

The maturity parameters correlate to the rank gradients, with the same limitations.

5.9 Conclusions

The J-4 Unit is regarded as the principal source rock for oil in the study area. It is of a considerable thickness and the amount and type of organic matter is favourable. Data from the northern well (I-1), the central well (E-1) and the southern well (M-8) show that: 1) The organic matter is mainly of algal origin. 2) The amount of organic matter is rich to extremely rich in the northern well, and good to rich in the central and southern wells. 3) In the northern well the entire J-4 Unit is within the zone of maximum oil generation. In the central well the upper part of the unit is just within the zone of oil generation, whereas the lower part of the unit is within the zone of maximum oil generation. In the southern well the unit is just approaching this zone. The formation therefore must be regarded as a better oil source rock in the northern well. However, assuming sufficient burial, as seen in the M-8 well, the formation is still a good source rock in the southern area.

The conclusions are severely hampered by the limited number of wells drilled, especially in the northern area. The investigations show that the study area is very complex with respect to the amount of organic matter as well as the maturity conditions. Therefore, a detailed mapping of the source rock potential of the study area is strongly needed.

6.0 Potential hydrocarbon traps

By Jens Ole Koch

The formation of hydrocarbon traps is the result of local depositional and deformational history. The trap formation is governed by three main parameters: the geometry of the reservoir body, the sedimentary sealing history and the tectonic history. In the present chapter is discussed the distribution of potential hydrocarbon traps in different areas, each characterized by a structural style (figs. 47, 48). After a short definition of basic trap types, various areas of the Danish Central Graben, each of which is characterized by a certain structural style, are listed and described with emphasis on the distribution of potential hydrocarbon traps.

6.1 Definition of basic trap types

A hydrocarbon trap is a closed structure with a reservoir rock overlain by impermeable strata. The seal/reservoir interface may conform with the boundary of the two formations, but it is often a complex of unconformities and fault contacts between the reservoir body and various seals. Two basic types of potential traps exist, namely stratigraphic traps and structural traps (fig. 48).

Stratigraphic traps

A stratigraphic trap is a laterally limited reservoir body, sealed by impermeable strata. Inter alia, the reservoir may be alluvial or submarine fans fringing a sub-aerially exposed 'high' area, carbonate reefs, fluvial channel sands, and diagenetic formed high porosity zones. The seal may either be comformably deposited upon the reservoir body, or the reservoir body can be truncated and unconformably overlain by the seal. Consequently, there are two sub-types: Primary and secondary stratigraphic traps (fig. 48).

In primary stratigraphic traps, the reservoir is conformably overlain by the seal. The geometry and size of the trap is delineated by the original upper depositional surface of the reservoir body and possibly also by syn-sedimentary faults.

In secondary stratigraphic traps, the reservoir body is truncated and unconformably overlain by the seal. The geometry and size of the trap is defined by the topography of the erosional surface of the reservoir body.

Stratigraphic traps may retain hydrocarbons in completely undeformed areas, but they may also be deformed, which either improves or reduces their hydrocarbon trapping capability.

Structural traps

A structural trap is a laterally limited or unlimited reservoir body, which is overlain by an impermeable seal. It has been deformed into an upwhelming closed structure capable of trapping hydrocarbons.

Among a number of factors the deformation can be caused by extension, compression, density contrasts, differential loading, wrenching, or uplift. Two basic sub-types of structural traps can be distinguished:

Fault traps are situated in tilted fault blocks. The

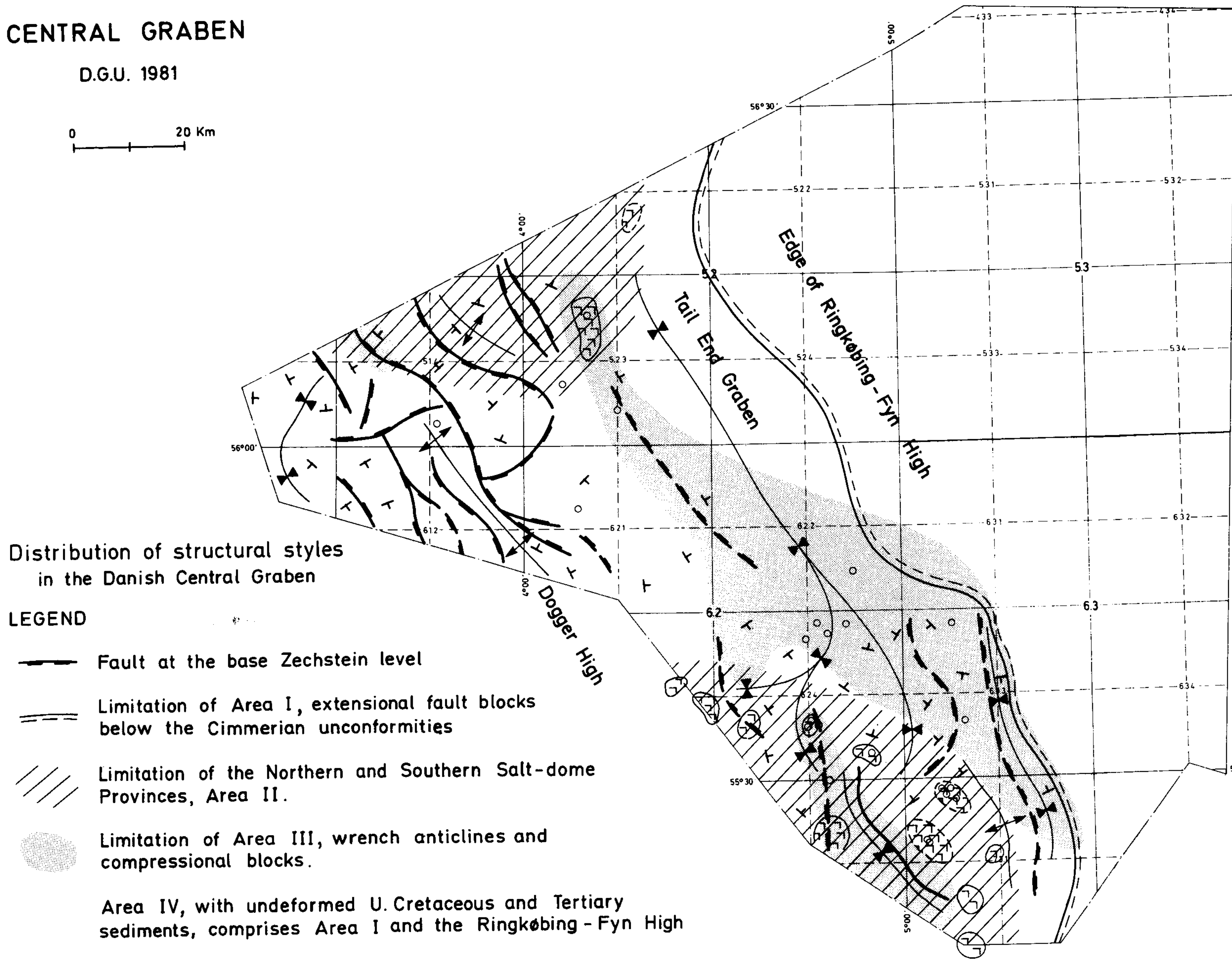

Fig. 47: Regional subdivision of the Central Graben area based on structural styles.

traps are delineated by fault planes, often on several sides, and by the overlying impermeable stratum.

Arch traps are upwhelming domes or arch structures with or without faults. The trap is delineated by the geometry of the domal surface of the reservoir rock.

Various structural traps often co-exist and a structural trap might be composite, e.g. composed by a fault trap on one side and an arch trap on the other (fig. 48).

6.2 Distribution of potential hydrocarbon traps

The formation of hydrocarbon traps is the result of the local depositional and structural history. This is, however, to a large degree governed by plate interactions or plate tectonic settings (Dickinson 1974). Harding & Lowell (1979) recognized eight different assemblages of geological structures, which they

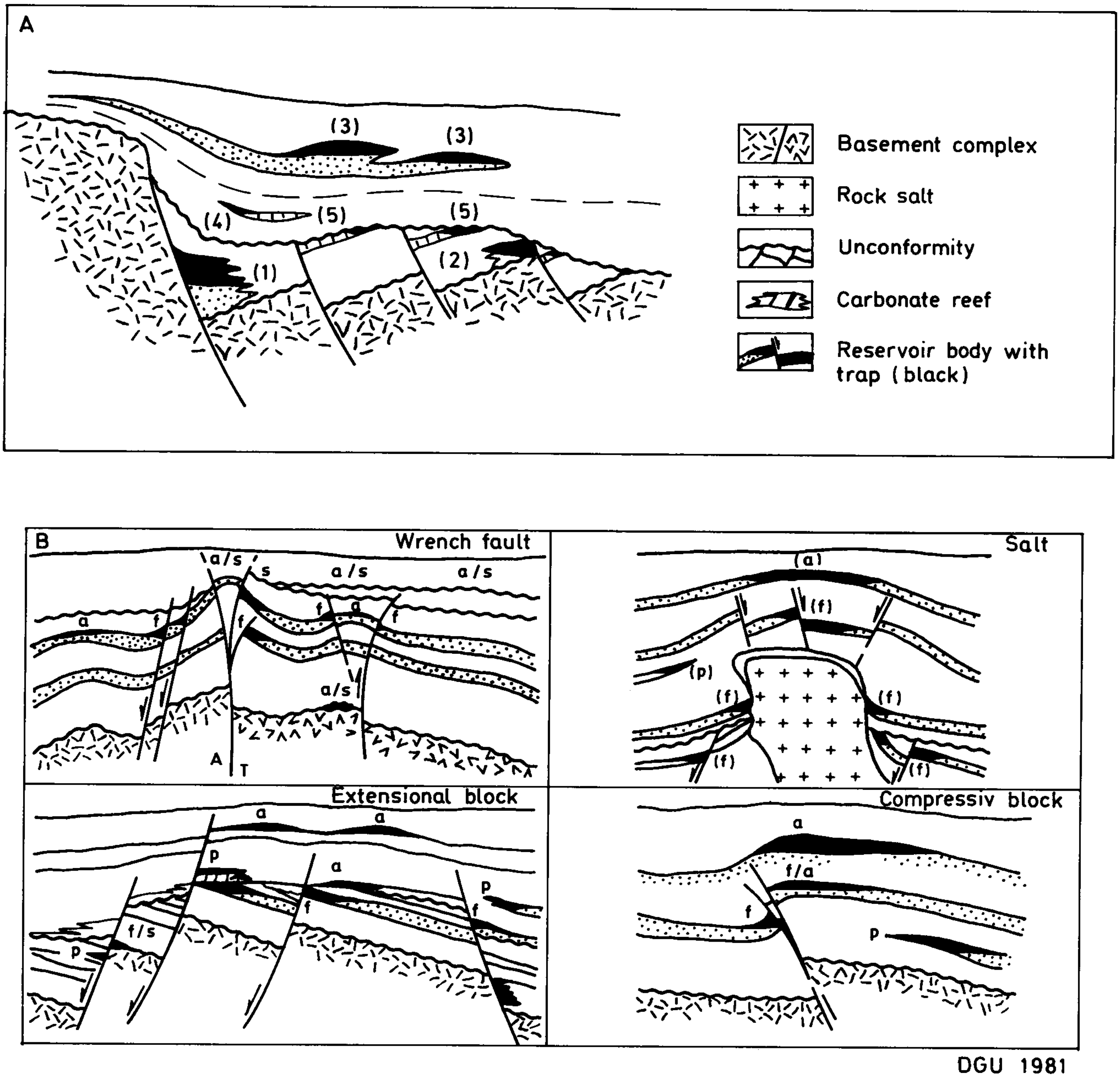

Fig. 48: Schematic diagrams of hydrocarbon traps. a) Stratigraphic trap in mainly undeformed sedimentary strata. (1)–(4) Primary stratigraphic traps: (1) alluvial fan, (2) carbonate reef, (3) submarine fan, (4) high porosity zone, (5) secondary stratigraphic trap. b) Distribution of traps related to wrench faults, salt diapirs, extensional blocks and compressive blocks. a = structural arch trap, f = structural fault trap, p = primary stratigraphic trap, s = secondary stratigraphic trap. T = displacement towards viewer, A = displacement away from viewer. Modified from Harding and Lowell (1979).

termed structural styles, and discussed their plate tectonic habitats and the distribution pattern of hydrocarbon traps. Blair (1975) and Ziegler (1977) reviewed the structural styles encountered in the North Sea in general.

The Late Palaeozoic to Mesozoic North Sea Grabens evolved in an intra-plate setting as interlinked rift systems which were dominated by extensional faulting. Thus, extensional fault blocks are recognized as the first structural style in the Danish Central Graben. The rifts failed to evolve further in Early Tertiary time, when active spreading and ocean floor formation took place elsewhere in the incipient Norwegian-Greenland Sea (Whiteman et al. 1975, Ziegler 1975, 1981). Thus, deep-seated NW-SE directed dextral strike-slip movements, probably related to the establishment of the new spreading center and the Laramide orogeny (Ziegler 1981), caused compressional and wrench deformation in certain areas of the Danish Central Graben. Consequently, wrench anticlines and compressional blocks are recognized as the second structural style.

The third structural style is found around salt pillows and salt piercement domes. This structural style is not derived from the large scale tectonic episodes but arises from halokinetic movements.

Undeformed or weakly deformed sediments and late movement structures are recognized as the fourth structural style in the Danish Central Graben.

Each of these four structural styles is distributed in certain areas which, however, to a great extent overlap each other. The distribution within the Danish Central Graben may be summerized as follows (fig. 47):

Area I: The Dogger High area and large parts of the Danish Central Graben floor was affected by extensional normal faulting and, as a result, extensional fault blocks can be found below the Cimmerian unconformities in this area.

Area II: The salt domes are located in a Southern and a Northern Salt-dome Province, which overlap area I. As a consequence, both deep-seated extensional fault blocks and salt structures are present in this area.

Area III: Late Cretaceous-Early Tertiary wrench anticlines and compressional blocks are concentrated in three zones. In these zones, pre-existing normal faults were re-activated, and strike-slip faulting created a complex pattern of anticlines and deformed salt domes.

Area IV: Above the Ringkøbing-Fyn and the Dogger Highs, and in the parts of the Danish Central Graben, which were neither affected by the three wrench zones nor by pronounced halokinesis, the Cretaceous and Tertiary deposits are undeformed.

In the following the four above mentioned structural styles encountered in the Danish Central Graben are described and discussed with respect to their geographical setting, history of development, and capability of forming hydrocarbon traps.

AREA I - Extensional fault blocks

Geographical setting: Extensional fault blocks are generally found in the Dogger High area and in the Central Graben floor outside the wrench zones (area I in fig. 47).

Geological description: In the North Sea Basin, normal faulting of the basement was the main tectonic agent in the formation of the Late Palaeozoic-Mesozoic rift systems. Sedimentation and basin formation was strongly controlled by normal faulting, which acted synsedimentarily along the structural highs. The basin floor was faulted and divided into several rotated fault blocks during the tectonic episodes in Permian, Triassic and Jurassic time.

The NW-SE faults in the Central Graben, outlined on the Base Zechstein structural map (fig. 5), define a system of tilted NW-SE trending elongate fault blocks parallel to the basin axis. The faults are generally normal faults which cut the pre-Permian basement and most of the Mesozoic sequence (fig. 13). These tilted and elongated extensional fault blocks are unconformably overlain by the Cretaceous and Tertiary formations. The fault blocks may be divided into the following three categories depending on their geological setting: The Dogger High horsts, the downfaulted blocks along the margins of the Dogger High and the Ringkøbing-Fyn High, and the extensional fault blocks in the basin floor.

Distribution of potential hydrocarbon traps: Structural fault traps are generally located on the upthrown edge of tilted fault blocks. Closures face the fault plane and conformably overlie impermeable strata (figs. 11, 13). If the crest of the tilted fault block has been truncated by erosion and unconformably overlain by a seal, the trap turns into a secondary stratigraphic trap type. In this type, the geometry of the trap is determined by the shape of the erosional surface. However, these elements are often combined so that a trap is outlined by the unconformity, as well as by fault planes which originated from later reactivations of the extensional faults.

Extensional fault block structures have not so far been drilled in the Danish sector, but the structural style is well exemplified e.g. by the Brent (Bowen 1975), Argyll and Brae (Harms et al. 1981) fields from the U.K. sector.

The Dogger High horsts: In the Dogger High horsts Palaeozoic reservoirs could be present in structural high positions and in lateral contact with Jurassic source rocks. Potential structural traps are present in the up-thrown edges of the horsts, where the old reservoirs might be sealed by the Late Cimmerian unconformity.

The down-faulted marginal blocks: Along the margins of the Dogger and the Ringkøbing-Fyn Highs, stratigraphic traps are probably located in the down-faulted marginal blocks (fig. 11). The reservoirs might for example be alluvial fans, nearshore sands (like the W-1 Unit) or deltas which fringed the highs in Jurassic and Cretaceous time (fig. 12).

The basin floor blocks: The extensional blocks in the basin floor generally trend NW-SE, and tilt towards the basin axis (fig. 47). Thus, potential structural fault traps are located in the upthrown edge of the blocks. The reservoirs might be conformly sealed, or the crest of the tilted fault blocks might be truncated and unconformly sealed. Undulations along the fault plane could create local closures in structural high positions.

AREA II - Salt pillows and salt piercement domes

Geographical setting: Two separate areas of this structural style are encountered in the Danish Central Graben. 1) The Southern Salt-dome Province occupying the southwesternmost part of the Danish sector and 2) the Northern Salt-dome Province occupying the northwestern, central part of the Danish sector (fig. 47).

Geological description: The density of rock salt is lower than the density of most other rocks. Furthermore, rock salt differs from most other rocks in its deformability by viscous flow. Consequently, deeply buried rock salt has a capacity for vertical mobility independent of external tectonic forces. However, deeply buried rock salt generally has been mobilized by an external tectonic event, which has initiated the onset of halokinesis. Structures of this origin are considered here as modifications of the particular structural assemblage with which they have developed.

In the Danish Central Graben, thick strata of rock salt, probably of Zechstein age, are buried below several kilometres of Mesozoic and Cenozoic sediments. The overburden, and the density contrast between overburden and salt, has caused the salt to move upwards by buoyancy. The salt domes have undergone a complex evolution through an initially much broader pillow into the piercement stage, where the salt may have pierced through most of the Mesozoic formations into the Upper Cretaceous Chalk Group. In contrast to the initial pillow stage, the piercement domes are narrower with diameters generally less than half the diameters of the pillows.

The evolution of salt domes has been influenced by accumulation rate, progradation rate, differential loading, regional dip of the base of the salt, density of overburden and salt, original thickness of the salt formations, and by the competance of the salt as well as that of the overburden. As a consequence, the assemblage of salt domes can be divided into two basic types: 1) Salt pillows and 2) salt piercement domes. Among these the salt pillows can be divided into two types, the morphology of which is not well understood at the present stage of investigation: A) Salt pillows formed by active salt flow, and B) salt pillows formed as residual structures, where the surrounding salt masses have flown away into neighbouring salt domes.

Distribution of potential hydrocarbon traps: Salt pillows: In salt pillows the deposits overlying the pillows form gentle arching domes. The crests of the domes are often dissected by normal faults. Hydrocarbons are found in structural arches and fault traps at the top of domes, and might be trapped in several reservoirs at different stratigraphic levels. In the Anne structure and the Dan Field, the oil and gas is trapped in the Maastrichtian-Danian reservoirs, but additional accumulations of oil are present in the Middle Jurassic J-2 Unit.

Piercement domes: In piercement domes located in the Danish Central Graben, the Zechstein salt has pierced through or into younger sediments. Typically the level of piercement is within the Chalk Group (fig. 12).

Structural fault and arch traps are located above the crests of the domes in positions similar to those above salt pillows. However, the flanks of piercement domes are steeper, and the top traps are often closed against a circular fault system.

Structural fault traps may occur on the flanks with fault closure against the nearly vertical flanks of the piercement domes. As of the present date, such traps have not been drilled in the Danish Central Graben, although their hydrocarbon potential is well established in other countries.

A third possible trap position is found around the domes, where secondary stratigraphic traps may have been formed below the Early Cimmerian unconformity by truncation of the Triassic during the broader initial salt pillow stage (fig. 12). Such traps are uncomformably sealed by the Lower Jurassic Fjerritslev Formation. Similar secondary stratigraphic traps may also be present at higher stratigraphic levels, e.g. in the J-2 Unit, depending on the age of the pillow stage (fig. 12).

Piercement of salt into overlying formations may create a secondary fracture permeability in the reservoirs. The degree of fracturing is apparently high in structures with large scale piercement and low in structures with little or no piercement (see chapter 7).

AREA III - Wrench anticlines and compressional blocks

Geographic setting: Anticlines and compressional blocks are found in a broad NW-SE trending rhomboid area from the North Arne through the Bo, Adda, Tyra, and Igor structures into the Ringkøbing-Fyn High at an oblique angle. Furthermore, one small anticline is located north of the Dogger High, and one area extends southwards from the Gorm Field through the Lola Structure (fig. 47).

Geological description: The zones are composed by a system of en echelon of alligned anticlines trending NW-SE.

In Late Cretaceous time, five narrow anticlines probably existed inside the wrench areas. These anticlines are outlined as a Late Cretaceous inversion axis. They were presumably formed as a response to deep-seated NW-SE directed dextral strike-slip movements between the Ringkøbing-Fyn High and the NNW-SSE trending fault zone west of the North Arne and Bo structures.

Early Tertiary strike-slip movements continued the deformation and created the recent configuration of anticlines.

The Upper Cretaceous Chalk Group is generally less than 500 metres on the crest of the anticlines.

Distribution of potential hydrocarbon traps: The large rhomboid wrench area, and the smaller area south of the Gorm Field, may apparently be differentiated into three sub-areas, each characterized by a different type of anticline structures:

1) Along the eastern limitation, the very rigid Ringkøbing-Fyn High has been opposed to the less competent sediments of the Central Graben. Compressional strike-slip movements have created characteristic structures where the anticlines meet the High. These structures show good closures in potential structural fault and arch traps along the main fault zone bordering the Ringkøbing-Fyn High. Secondary stratigraphic traps may additionally be present where the Lower Cretaceous sequence pinches out in the marginal areas.

2) At the opposite side of the rhomboidal area, severe deformation has taken place in the fault zones stretching from North Arne southwards to the Bo structure, and southwards from the Gorm Field through the Lola structure. In these zones, older extensional faults were reactivated and locally reversed, and the Mesozoic sequence was folded into the NNW-SSE trending anticlines seen today.

The anticline is fault bounded around the North Arne structure, in which salt has pierced into the Upper Cretaceous Chalk Group. Structural arch traps are located over this structure, and structural fault traps possibly exist along the flanks. The flank faults die out towards the south, through the South Arne structure to the Bo structure, where the anticline has no faults on the flanks. A similar pattern is found in the southern wrench area, in the fault zone south of the Gorm Field through the Lola structure. The Gorm Field apparently occupies a position similar to that of the North Arne structure in the northern fault zone.

Potential structural arch traps are located in local culminations of the anticlines, but potential flank traps disappear with flank faults.

In parts of the NNW-SSE trending anticlines, faults are only present on one flank, as in the Lola structure and part of the South Arne structure. Due to the reverse compressional faults, good closures might be present both in the top of the anticlines and on the faulted flanks. Furthermore, secondary stratigraphic traps may be present on the flanks, where the Lower Cretaceous sequence pinches out against the anticline.

3) In the intermediate area between the Ringkøbing-Fyn High and the North Arne to Bo fault zone, the trend is a system of parallel-alligned gentle anticlines through the Tyra Field and the Igor and Per structures. In these anticlines, structural arch traps are located in local culminations, probably at several stratigraphic levels within the anticlines.

AREA IV - Undeformed sediments and late movement structures

Geographical setting: Weakly or non-deformed Cretaceous and Tertiary sediments cover the entire Danish sector outside the wrench zones (figs. 10, 13, 47).

Geological description: In Permian, Triassic and Jurassic times, the individual fault blocks of the Central Graben subsided differentially along normal faults. In Cretaceous and Tertiary times, however, this pattern changed into a more general non-fault controlled subsidence of the entire North Sea area. Therefore non- or weakly deformed Upper Cretaceous and Tertiary sediments cover large parts of the Danish North Sea. In these sediments, stratigraphic traps are expected to be present.

In some areas, however, late movements along old deep-seated faults resulted in uplift, which in some cases has created gentle structural arch traps. This mechanism is also termed 'drape' (Blair 1975).

Distribution of potential hydrocarbon traps: In non-deformed sediments, hydrocarbons may be trapped in primary stratigraphic traps. These are often expected to be located along structural highs, but e.g. Paleocene submarine fans cover most of the northern Viking Graben. Stratigraphic traps might be improved by differential compaction. This mechanism is based on the assumption that there is less lithostatic pressure on the crest of the reservoir body than on the flanks. As a result sediments on the flanks undergo greater compaction, and the vertical closure of the stratigaphical trap is improved.

Unlimited reservoirs and stratigraphic traps may in addition be weakly deformed by drape into gentle structural arch traps or late movement structures. Simple drape, as defined by Blair (1975), is caused by re-juvenation of deep-seated old faults, resulting in uplift and creating a gentle dome structure.

An example of this type of late movement structure is the Inge structure which is located over the crest of the Dogger High. This structure is characterized by a rather large areal closure and a relatively small vertical closure, which were probably induced by late movements along the Dogger High faults.

7.0 Reservoir rocks

By Finn Jacoben, Kirsten Lieberkind & Erik Nygaard

The present chapter contains a review of the potential reservoir rocks drilled in the Danish Central Graben. The source data for this descriptive summary originates primarily from wells drilled to explore chalk reservoirs. The main part of possible chalk reservoirs has been evaluated only by using wire line logs, since few cores have been cut and very few tests performed. Therefore, further investigations are necessary to evaluate and describe these possible reservoir rocks properly.

In this chapter, each zone in which shows have been recorded, and each porosity zone, is described. This is done with reference to the formations/log-units given earlier in the paper. The characteristics relevant to reservoir evaluation, such as the extension, thickness, depth, porosity, and permeability, are described. The characterizing terms (good, fair, etc.) used for reservoir parameters in sandstone reservoirs cannot be applied automatically to chalk reservoirs. The descriptions are accompanied by maps showing the known occurrences.

7.1 CA-1 Unit (Early Carboniferous)

Lithologic characteristics: Sandstone, siltstone, carbonaceous shales and sporadic coal seams.

Extension, thickness, and depth: According to Ziegler (1977), Carboniferous deposits are present in the major part of the Central Graben, but due to lack of data a delineation of the extension in the Danish sector is not possible. The thickness recorded in the P-1 well is 67 m, but the regional thickness may well be 100 to 200 m. Away from the highs, the deposits are mostly very deeply seated.

Reservoir parameters (fig. 49): Only the sandstones may be considered as potential reservoirs (net reservoir rock 13.5 m). The sandstones vary from fine to medium-grained, occassionally silty. The porosity varies from 5 to 15% (average 11%). Calcite cement has been found and may reduce the porosity.

Remarks: The section is stratigraphically below the