DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/57

Middle Jurassic - Lower Cretaceous reservoir sandstones in the Danish Central Graben: depositional environments and sequence stratigraphy

Core Workshop,
May 16th 1997 at GEUS

Arranged for:
Phillips Petroleum International Company
Denmark and Licence 5/95 partners

Peter N. Johannessen and Jan Andsbjerg

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

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GEUS

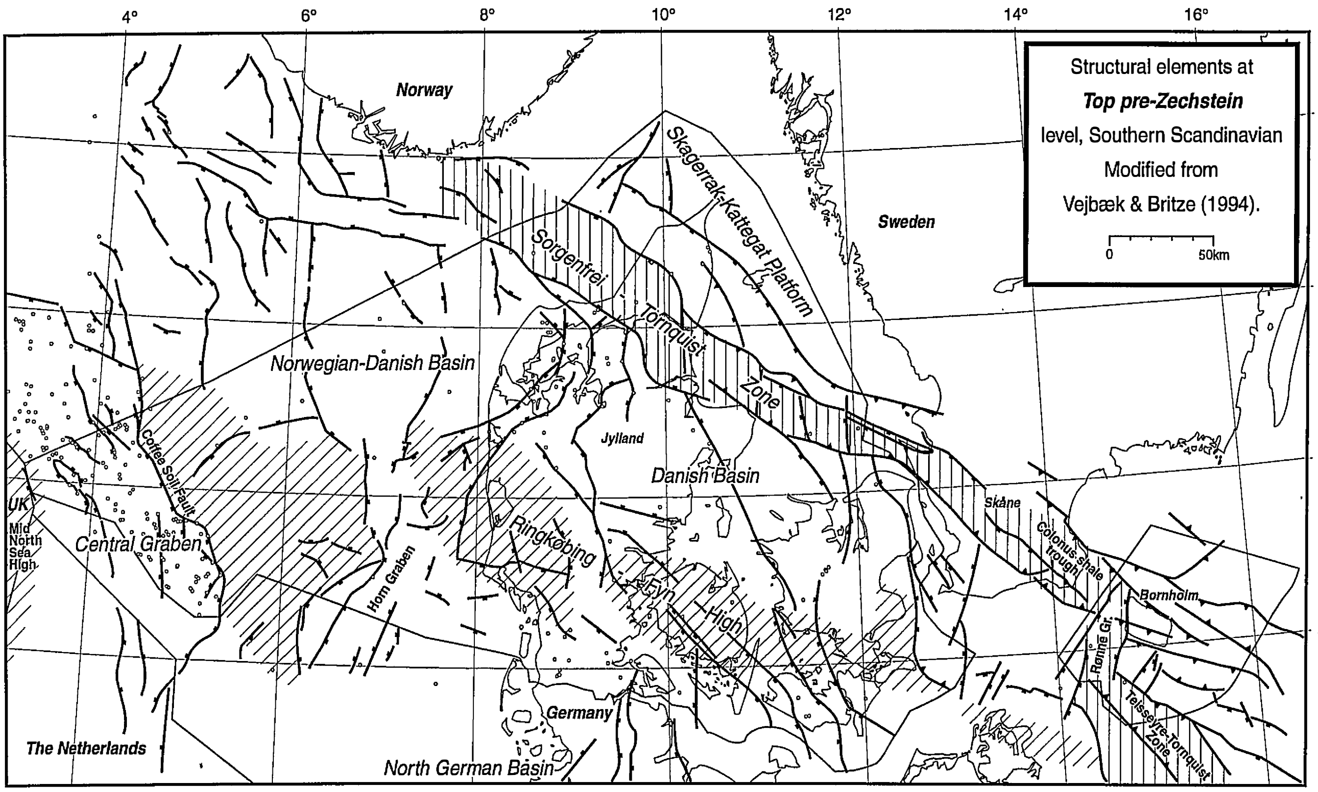
Core Workshop

M. Jurassic - L. Cretaceous sediments

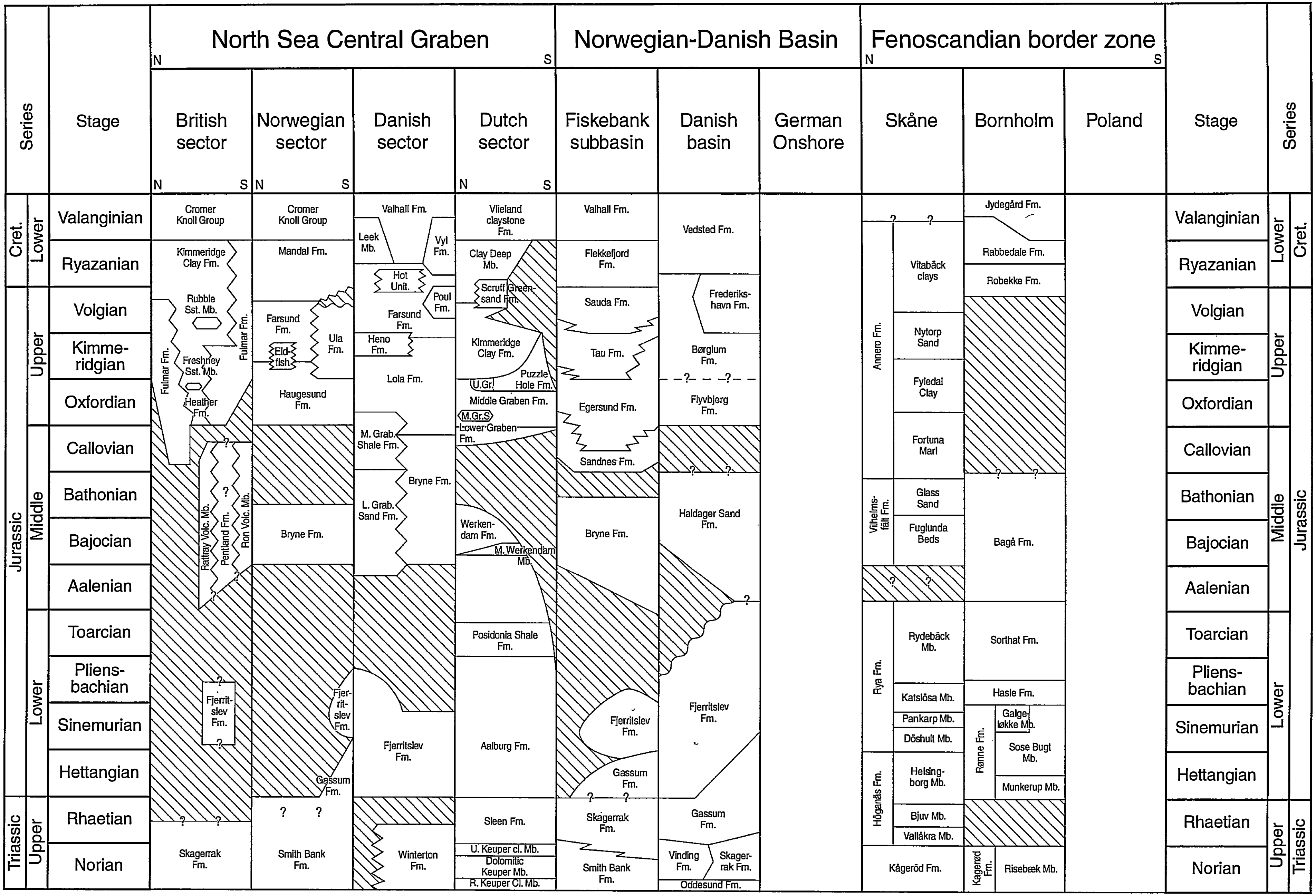
GEUS

16.05.97.

8.30	Arrival to GEUS Core Store, Titangade 9C, Copenhagen NV
8.30 - 8.40	Introduction to Core Workshop. Peter Johannessen
8.40 - 10.00	M. Jurassic sediments: Bryne Formation. Jan Andsbjerg and Henrik I. Petersen
10.00 - 10.20	Coffee break. Discussions
10.20 - 11.20	U. Jurassic sediments: Heno Formation. Peter Johannessen
11.20 - 11.45	U. Jurassic - L. Cretaceous sediments: Poul Formation and Hot Unit. Peter Johannessen
11.45 - 12.00	Taxi's
12.00 - 12.45	Lunch at GEUS, Thoravej 8, Copenhagen NV
12.50 - 16.00	Presentation of ongoing projects at GEUS



Johannessen (in prep)



Johannessen (in prep)

Alluvial plain and paralic sediments of the Middle Jurassic Bryne Formation, Danish Central Graben - a core workshop

Abstract

The Middle Jurassic Bryne Formation of the Søgne Basin (northern part of the Danish Central Graben) consists of fluvial channel and floodplain dominated coastal plain deposits, overlain by interfingering shoreface and tidally-influenced backbarrier deposits. The Bryne formation and the marine mudstones of the overlying Lola Formation shows an overall transgressive development.

The alluvial plain/coastal plain deposits of the lower Bryne Formation are dominated by laterally continuous, mainly upward-fining fluvial channel sandstones. The sandstones are separated by units of fine-grained floodplain sediments showing a characteristic fining/coarsening upward pattern. In the upper part of the lower Bryne Formation the fine grained units may grade into lacustrine mudstones in central and eastern parts of the basin. A large number of mud laminae in some channel sandstones may suggest deposition in the lower tidally influenced part of a river system.

The backbarrier/shoreface dominated upper Bryne Formation is separated from the lower Bryne Formation by the strongly erosional base of stacked estuarine and fluvial channel sandstones. Log correlations suggest that several tens of metres of the lower Bryne Formation have been removed by erosion at this level. Above the erosion surface are channel sandstones up to 10 m thick stacked in sections of up to 45 m thickness. Most channel sandstones in this unit show abundant mud laminae and flasers, and rare herringbone structures, suggestive of a tidal influence. The large thickness of the tidally influenced channel sandstones may indicate deposition in large estuary channels. The stacked estuarine channel sandstones are capped by a succession of coal beds, that attain thicknesses of several metres in the western part of the study area; but change to thin, poorly developed coals in the central part of the basin. Above the coal beds the upper Bryne Formation is dominated by estuarine channel sandstones and other back-barrier deposits in the western part of the study area and by coarsening upward shoreface deposits in central parts of the basin. Evidence for an interfingering relationship between deposits of the two environments is provided by the thin units of upward coarsening shoreface deposits, that can be traced into areas dominated by back-barrier deposits. The back-barrier deposits were deposited during successive transgressions; but partly removed, especially in more distal settings, by erosion at the ravinement surface. The shoreface deposits prograded into deeper parts of the basin during periods with a decreasing rate of sea-level rise, sea level stillstand, or fall. The distal parts of a final progradational shoreface sandstone/siltstone is present in the lowermost Lola Formation.

The Bryne Formation

Middle Jurassic sandstones with interbedded mudstones and coals were encountered by Lulu-, 1 the first exploration well in the Danish part of the Søgne Basin (Fig.). Similar deposits encountered in the Norwegian part of the Central Graben were included in the Bryne Formation, that was established by

Vollset and Doré (1984). The Bryne Formation was extended to the Middle Jurassic deposits of the northern part of the Danish Central Graben by Jensen et al. (1986). Similar and coeval deposits from the southern part of the Danish Central Graben were referred to the Central Graben Group (NAM and RGD, 1980) by Jensen et al. (1986).

In the Søgne Basin the Bryne Formation is separated from Triassic and Permian deposits by a major unconformity. The Bryne Formation is conformably overlain by marine mudstones of the Upper Jurassic Lola Formation (Jensen et al., 1986) and unconformably by Cretaceous deposits on structural highs. The Bryne Formation shows thicknesses from 130 to 300 metres in wells in the Danish part of the Søgne Basin. It wedges out on structural highs, but may possibly attain larger thicknesses in deepest parts of the basin.

A detailed sedimentological analysis of cores from the Lulu-1 well was published by Frandsen (1986), who interpreted the sediments as deposits of a deltaic interdistributary bay overlain by coastal sediments. Middle Jurassic deposits further south in the Danish Central Graben had previously been interpreted as alluvial plain and delta plain deposits by Koch (1983). Damtoft et al. (1992) suggested a fluvial channel and floodplain environment for the Bryne Formation, whereas Johannesen and Andsbjerg (1993) interpreted alluvial plain deposits overlain by tidal and shallow marine deposits.

Base-level changes and deposition in the lower Bryne Formation

Sequence stratigraphy applied to non-marine strata

In coastal plains and in the lower reaches of alluvial plains deposition is strongly influenced by relative sea-level changes (Törnquist et al., 1993; Surlyk et al., 1995). In such areas the use of sequence stratigraphic concepts is somewhat simpler than in intramontane basins, where factors such as tectonics and climate have a pronounced influence, and the sequence stratigraphic concepts and terminology, originally defined for marine and coast-near deposits, can be applied (Vail et al., 1977; Posamentier et al., 1988; Posamentier and Vail, 1988; and Van Wagoner et al., 1988).

The alluvial plain succession of the lower Bryne Formation was deposited in a coast-near setting. In several wells sedimentary structures normally associated with tidal processes, double mud drapes and abundant flasers, have been found in a few beds. A few dinoflagellate cysts have been found in the alluvial plain deposits, and data from the Dutch part of the North Sea indicate that fully marine conditions existed less than 100 km away (Van Adrichem Boogaert and Kouwe, 1993). Thus, the systematic variations in depositional facies and the sediment stacking patterns may in part be ascribed to sea-level changes.

Sequence boundaries in the alluvial plain succession of the lower Bryne Formation are identified as erosion surfaces at the base of laterally extensive, amalgamated fluvial sandstones following Shanley and McCabe (1991; 1993), Dreyer et al. (1995) and Olsen et al. (1995). These surfaces allow the lower part of the Bryne Formation to be subdivided into unconformity bounded units (Figs. 2, 3). Whereas

Shanley et al. (1992) could document an increased tidal influence at their maximum flooding surfaces, this is not the case for the lower Bryne Formation. Here maximum flooding surfaces are located where fluvial channel influence is at a minimum and lacustrine and wet overbank deposits are most extensive, comparable to the examples shown by Olsen et al. (1995) and Surlyk et al. (1995) (Fig. 4).

Sequence boundaries of the alluvial plain/coastal plain succession

Sequence boundaries in the alluvial plain/coastal plain succession of the lower Bryne Formation are recognised as the basal erosion surfaces of the laterally amalgamated fluvial sheet-sand deposits (Figs. 2, 3). The sequence boundaries can be traced in all wells that penetrate the respective stratigraphic levels. The fluvial channel deposits overlying the basal erosion surfaces normally show a coarser grain size than the underlying floodplain deposits (Fig. 5). The basal erosion surfaces also separate successions with contrasting alluvial architecture. The channel sandstones above the surfaces are laterally continuous and amalgamated, whereas the successions below the surfaces normally are dominated by overbank deposits with only a few isolated channel bodies. This suggests that significant changes in aggradation and accommodation generation rate took place synchronously with the formation of the basal erosion surfaces.

Both incision during the base level fall and frequent avulsions during the early base level rise may have contributed to the formation of the sequence bounding unconformity. Detailed correlations of the successions cut by the sequence boundaries indicate that the amount of incision at the most of the sequence boundaries generally was small (Fig. 2).

Amalgamated fluvial channel deposits

The amalgamated, laterally continuous, fluvial sand sheets typically found above the sequence boundary in the alluvial plain (Figs. 4, 5) compares with the low accommodation systems tract of Dreyer et al. (1995), and the amalgamated fluvial sand sheet of Olsen et al. (1995) and Shanley and McCabe (1991, 1993, 1994). In the Bryne Formation the amalgamated fluvial sheet sands most commonly are fining upward but also occur as massive amalgamated sandstones without a fining upward trend at a few locations (e.g. Baj-1A in 3/7-4). The occurrence of multi-storey sandstones at some locations may have been caused by subsidence due to local tectonics. The dominance of fining upward sandstones suggest that the floodplain was extensively reworked by lateral channel migration, reflecting the slow creation of accommodation space at an early stage of base level rise, that effectively prevented floodplain aggradation (Wright and Marriott, 1993). Development of the channels probably was initiated during base level fall or stillstand. However, the combination of laterally migrating channels and a slowly increasing accommodation space during the early base level rise, may have caused erosional removal of most lowstand channel deposits.

Floodplain transgressive deposits

The overbank dominated deposits between the amalgamated sandstone sheets and the MFS consist of interfingering proximal and distal floodplain deposits organised into a fining upward succession with a gradually decreasing sand/shale ratio. Mudstones, probably of lacustrine origin, becomes increasingly common upwards. Soil profiles and root horizons are common. An example of such a succession from the Baj-1B sequence is illustrated in Fig. 4. Fining upward channel sandstones, 2 to 4 m thick, may occur within this type of succession. These channel sandstones cannot be correlated from well to well, and they probably were deposited in non-migrating channels, or in channels that only migrated laterally for short distances (e.g. Bat-1B in 3/7-4, Fig. 2). Tidal influence is noted both in the amalgamated sandstone sheets formed under low accommodation conditions and in the channel fills of non-migrating channels deposited during rising base level. However, it has not been possible to discern any difference in the degree of tidal influence between the two settings, and the degree of tidal influence cannot be used to identify the maximum flooding surface unlike the study of Shanley and McCabe (1991, 1993).

The overall fining upward trend and decreasing sandstone/mudstone ratio is interpreted as a result of a rising base level, that caused rising water table and wetter conditions on the coastal plain. The rising base level resulted in increased accommodation space, and this caused an increased storage of sediment on the floodplain and more isolated fluvial channels in combination with reduced sediment supply due to decreased stream gradients. Both Shanley and McCabe (1993) and Wright and Marriott (1993) similarly described how the increasing accommodation rates during rising base level, favour high levels of storage of floodplain sediments resulting in isolated channels. The transgressive floodplain deposits are equivalent to the heterolithic unit with isolated fluvial sandbodies of Olsen et al. (1995) and the lower part of the high accommodation systems tract of Dreyer et al. (1995).

Floodplain highstand deposits

The highstand floodplain deposits are separated from the floodplain transgressive deposits by a MFS. The MFS occur as an organic mudstone bed or a zone of beds, that can be correlated through most or all wells in the study area. The highstand floodplain deposits occur in a coarsening upward succession, that show an upward increasing sandstone/mudstone ratio and an increasing sandbed thickness. The highstand succession consist of lacustrine and distal floodplain mudstones interbedded with silt- and sandstones, that were deposited as levee deposits, crevasse splays and crevasse deltas. Channel sandstones seem to be less common than in the transgressive floodplain deposits. The highstand floodplain deposits developed as a result of decreasing rates of base level rise and accommodation space generation. The decrease in accommodation space generation eventually caused deposition of laterally extensive, amalgamated channel sandstones in laterally migrating rivers above the SB.

In wells Amalie-1 and Cleo-1, situated in the deeper part of the basin, the HST of the Baj-1B sequence developed a delta-like coarsening upward profile, that represents lake or bay deltas prograded into relatively deep lakes or possibly brackish bays in the axial parts of the basin (Fig. 3). In Cleo-1 a channel sandstone unit similar to those that caps the Baj-1B HST further west is present above the base Bat-1A SB; but such a channel unit is not developed in Amalie-1, where the base Bat-1A SB is directly overlain by a fining upward succession of floodplain to lacustrine deposits of the Bat-1A TST. This development probably was caused by a lower decrease in the rate of accommodation space generation in the wells situated near the basin axis than in the wells further west.

Similar successions are described by Shanley and McCabe (1990, 1993) as their highstand systems tract, by Wright and Marriott (1993) as highstand depositional systems and by Olsen et al. (1995) as their uppermost heterolithic interval.

Base-level and cyclicity

A rhythmic alternation in an alluvial plain succession between levels dominated by laterally coalescent channel sandstones and fine-grained overbank deposits may be ascribed to both autocyclic and allocyclic causes. Autocyclic causes would imply, that a migrating channel belt was present continuously somewhere in the basin. In that case the large channel bodies seen in the wells represent a passage by the migrating channel belt. The thick fining upward successions of overbank deposits represent a channel belt moving away from the well location; the coarsening upward overbank sections result from a channel belt approaching a well location. However, the detailed log correlations indicate that the development of each type of succession: large channel bodies, fining upward and coarsening upward overbank successions, and the mudstone units separating the fining and coarsening upward successions, developed synchronously at well locations in different parts of the basin. It is then highly unlikely that the migrating channel belts, responsible for the tabular channel sand bodies, were present within the study area while the thick overbank successions were deposited. The deposits are rather seen as alternating facies associations controlled by cyclic base-level changes.

Laterally coalescent, erosionally based, thick channel sandstones are overlain by a fining upward floodplain succession increasingly dominated by distal overbank or subaquatic deposits. A distinct mudstone layer separates the fining upward part of the cycle from a coarsening upward succession dominated by crevasse splay and crevasse delta deposits. A full cycle is completed by the next erosionally based channel sandstone. Successions like these compare well with those described by Shanley and McCabe (1991, 1993), Shanley et al. (1992), Dreyer et al. (1995), Hettinger et al. (1995), and by Olsen et al. (1995).

Base level changes and deposition of the upper Bryne Formation

Sequence geometry in the upper Bryne Formation

The LST and lower TST of the Cal-1A sequence consist of mainly estuarine deposits, that are situated in incised valleys and in deeply entrenched estuarine channels (Figs. 2, 3). In the West Lulu area the valley axes were orientated roughly east-west, perpendicular to the basin axis and main faults. The deepest incision is recorded from West Lulu-3 in the westernmost part of the valleys, but the smaller depth of incision recorded from wells further downstream, e.g. West Lulu-1 and Lulu-1 may reflect a marginal position in the valley (Fig. 6). The valley-fill deposits are completely dominated by channel and bay-head delta sandstones in the proximal western part of the incised valleys, whereas the valley-fill in the eastern, more distal part of the valleys consists of tidal channel and tidal delta sandstones interbedded with mudstones and heteroliths of low-energy lagoon, tidal flat and estuary central basin environments. Only one sediment unit, less than 0.5 m thick, in West Lulu-4 can be correlated to the incised valley fill deposits of the Cal-1A sequence in other wells of the study area (Fig. 2). Thus, the West Lulu-4 well may represent an interfluve area.

The upper TST, HST and FRST deposits in the upper part of the Bryne Formation are not constrained by valley sides. However, these systems tracts are not uniformly distributed in the study area. In the upper part of the Cal-1A sequence laterally extensive coal beds constrain correlations. However, when correlations are attempted for the upper TST and HST succession between the coal markers, it is clear, that the systems tracts show a strongly asymmetric distribution. In the wells near the central parts of the basin a very thin upper TST, consisting mainly of transgressive shoreface deposits, is separated from a thick HST, of prograding shoreface deposits by a MFS situated close to the base of the succession. While the upper TST becomes thicker to the west, and changes from shoreface to mainly estuarine deposits, the HST section wedges out towards the west (Fig. 7). In West Lulu-1 and 3/7-4 the MFS is near the top of the succession with only a thin HST above it. In West Lulu-3 in the westernmost part of the study area the HST missing due to erosion at the overlying SB. A similar distribution of systems tracts can be seen in the Cal-1B sequence (Fig. 8). Also in sequence Cal-1B is the proximal western part of the sequence dominated by TST deposits, mainly estuarine, whereas the proportion of HST and FRST deposits, mainly shoreface sediments, shows an increase to the east until they are completely dominant in the wells closest to the basin axis, e.g. Lulu-1 and Amalie-1. In both the Cal-1A and Cal-1B sequences is the deepening upward TST succession separated from the shallowing upward HST/FRST deposits by the MFS, which is situated low in the sequence in the distal wells and high in the sequence in the proximal, western wells. Similar deepening-upward paralic successions asymmetrically overlain by shallowing upward regressive successions has been termed reciprocal sedimentation by Kidwell (1988) and Nummedal and Molenaar (1995).

In the present case, where deposition took place in an active rift basin, the development of reciprocal sedimentation may be related to slope gradients and subsidence patterns during transgression. A relatively high gradient on the hanging wall slope during an event of rift induced subsidence will favour the development of thick TST deposits. If sediment supply and rate of sea-level rise are kept constant during transgression of a low gradient and a high gradient slope, a larger area will be transgressed on the low gradient slope than on the high gradient slope during each time increment. The amount of sediment supplied during each time increment thus will have to cover a larger area on the low gradient slope than on the high gradient slope, resulting in the development of thick package of TST deposits with a relatively small area extent on the high gradient slope and a thin package with a large area extent on the low gradient slope. After completion of TST deposition on a high gradient hanging wall slope much accommodation space is still available in central parts of the basin for deposition of HST and FRST sediments to complete the reciprocal pattern of sediment distribution with thick TST deposits updip on the hanging wall slope separated from the basinwards thickening HST by a MFS.

In the Cal-1A sequence the upper TST, situated above regionally extensive coal marker, shows such a reciprocal relationship with the HST of the sequence. In the Cal-1B sequence the main part of the TST shows a reciprocal relationship with the HST and FRST of that sequence. Due to the progressive backstepping of the three Cal-1 sequences the possibility of a reciprocal distribution pattern cannot be evaluated for the Cal-1C sequence, as only relatively distal parts of the sequence are penetrated by wells in the study area.

Depositional history of the upper Bryne Formation

Major incised valleys were cut both at the western fringe of the Søgne Basin and in the south-eastern part of the basin close to the basin axis (Amalie-1) during formation of the base Cal-1A SB. The incised valley fill has been dated to the latest Bathonian - Early Callovian with the observation of the Nannoceratopsis gracilis LOD (Discus Standard Zone) and the LOD of the Cleistosphaeridium varispinosum (Calloviense Standard Zone). Deposition of the incised valley fills at the western fringe of the basin took place mainly in major estuarine and fluvial channels in the proximal western parts of the valleys, and in estuary central basin, tidal flat, tidal creek and flood tidal delta environments in the more distal eastern part. The incised valley fill deposits in Amalie-1 near the basin axis show deposition in major fluvial and estuarine channels followed by a period with deposition of dominantly fine grained sediments in tidal flat and lagoonal environments. The strong, sometimes upward increasing tidal influence in the valley fill deposits suggest that deposition took place during rising sea level.

The development of an extensive coal-forming mire or swamp environment on top of the incised valley fill succession in the western part of the basin, and probably also in an area close to the boundary fault along the eastern edge of the basin, suggests that the supply of siliciclastic sediments diminished abruptly, when sea level stepped over the valley rim. The resulting coal seam shows a stepwise increase in marine influence. A relatively dry peat-forming environment was succeeded by a continuously waterlogged environment with occasional salt water incursions. The extensive peat-forming environment was terminated by the incursion of transgressive coastal sandstones in the east and the spreading of a lagoonal environment with clastic influx from bay head and tidal deltas in association with continued sea level rise and transgression. The coastal sandstones were transgressed in basin central areas, where deposition of shelf mud took over, whereas a lagoonal/estuarine environment continued to exist in the western part of the basin.

At the point of maximum flooding open shelf conditions were established in the central and eastern parts of the Søgne Basin east of the West Lulu-1 and 3/7-4 wells except at a fringe near the eastern boundary fault. Mudstones, heteroliths and sandstones were deposited in a protected embayment, that included the West Lulu-1 and 3/7-4 sites. HST deposits developed during decreasing rates of rising relative sea level. In the West Lulu-1 - 3/7-4 area the HST was deposited as a thin prograding wedge of protected shoreface and mouth bar deposits. A thick wedge of wave dominated shoreface deposits prograded into the central and eastern parts of the basin. The deposits of both the MFS and the HST were removed from the western part of the study area by erosion at the base Cal-1B SB.

The progradational wedge of shoreface deposits was terminated by deposition of a sheet of beach sandstones, and large parts of the basin were turned into a beach ridge plain. The base of the beach deposits is picked as the base Cal-1B SB. This SB can traced into the western parts of the basin as the erosional base of estuary channels. The estuarine channels of Cal-1B were probably deposited in an incised valley of somewhat smaller dimensions than the Cal-1A valley. Also bay head delta deposits and fine-grained estuary sediments were deposited in the incised valley. Thin fluvial or estuarine channel deposits were deposited on the beach ridge plain further east in the central parts of the basin. Whereas the sheet-like channel deposits on the beach ridge plain may have been deposited during relative sea level lowstand, clear evidence for tidal influence in the interpreted incised valley fill in the western part of the basin suggests, that it was deposited during early rise of sea level.

A peat forming environment developed over most of the basin after infill of the incised valley was completed as in the Cal-1A sequence. At locations where the resulting coal seam has split an upwards rising groundwater level and associated increase in marine influence can be seen. Continued sea level rise caused deposition of transgressive shoreface sandstones on top of the coal in all but the westernmost parts of the basin. Shelf conditions were shortly after established in most of that area. A low-energy estuary or lagoon, or a protected embayment was established in the western area.

The estuary and lagoon, that had developed and subsequently been inundated during the transgressive phase, changed into open shelf in the basin axial areas and probably into a tidally influenced embayment or lagoon in the West Lulu area at the time of maximum flooding. The West Lulu embayment was filled by bay muds and prograding bay-head deltas during decreasing rates of sea-level rise (HST). During a subsequent relative sea-level fall a decrease in accommodation space resulted in increased wave scour on the inner shelf. Deposition of the shoreface sediments was forced basinwards, where the shoreface sandstones were deposited abruptly on the RSE, without the gradational profile created by a "normal" regression.

A sequence boundary developed by subaerial erosion at the lowest sea-level. A minor incision may have taken place in the western part of study area at sea-level lowstand. An estuary developed at the beginning of relative sea-level rise. Wave-influenced estuary mouth deposits developed in basin axial areas. The coastal plain was eroded by wave action during continued transgression resulting in the formation of a ravinement surface. The rapid transition from paralic and shallow marine sandstones to offshore mudstones and siltstones indicates a rapid transgression across a low-gradient coastal plain. Sediment sources were effectively removed from the vicinity of the study area at this stage of transgression.

References

Andsbjerg, J. and Dybkjær, K., in prep: Jurassic sequence stratigraphy of the Danish Central Graben.

Damtoft, K., Nielsen, L.H., Johannessen, P.N., Thomsen, E. & Andersen P.R., 1992: Hydrocarbon Plays of the Danish Central Trough. In: Spencer, A.M. (ed.): Generation, Accumulation and Production of Europe's Hydrocarbons II. EAPG Special Publications 2: 35-58.

Dreyer, T., Martinsen, O.J. and Ryseth, A.E., 1995: Sequence stratigraphic analysis of alluvial successions: outcrop examples and subsurface applications. In: NPF; Predictive high resolution stratigraphy, Stavanger 6-8 November 1995, abstracts: p.11.

Frandsen, N., 1986: Middle Jurassic deltaic and coastal deposits in the Lulu-1 well of the Danish Central Trough. Geological Survey of Denmark, Series A, 9: 23pp.

Hettinger, R.D., McCabe, P.J. and Shanley, K.W., 1995: Detailed facies anatomy of transgressive and highstand systems tracts from the Upper Cretaceous of southern Utah, USA In: Weimer, P. and Posamentier, H.W. (eds.); Siliciclastic sequence stratigraphy. AAPG Mem. 58: 235-257.

Hunt, D. and Tucker, M.E., 1992: Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. Sediment.Geol. 81: 1-9.

Hunt, D. and Tucker, M.E., 1995: Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall - reply. Sediment.Geol. 95: 147-160.

Jensen, T.F., Holm, L., Frandsen, N. & Michelsen, O., 1986: Jurassic - Lower Cretaceous lithostratigraphic nomenclature for the Danish Central Trough. Geological Survey of Denmark, Series A, 12: 65pp.

Johannessen, P.N. & Andsbjerg, J., 1993: Middle to Late Jurassic basin evolution and sandstone reservoir distribution in the Danish Central Trough. In: Parker, J.R. (ed.): Petroleum Geology of Northwest Europe. Proceedings of the 4th Conference. The Geological Society, London: 271-283.

Kidwell, S.M., 1988: Reciprocal sedimentation and noncorrelative hiatuses in marine-paralic siliciclastics: Miocene outcrop evidence. Geology 16: 609-612.

Koch, J.-O., 1983: Sedimentology of Middle and Upper Jurassic sandstone reservoirs of Denmark. In: Kaasschieter, J.P.H. & Reigers, T.J.A. (eds.): Petroleum geology of the south-eastern North Sea and the adjacent onshore areas. Geologie en Mijnbouw, 62: 115-129.

NAM & RGD, 1980: Stratigraphic nomenclature of the Netherlands. Verh. Van het Koninklijk Ned. Geologisch Mijnbouwkundig Genootschap, 32, 77pp.

Nummedal, D. and Molenaar, C. M., 1995: Sequence stratigraphy of ramp-setting strand plain successions: the Gallup Sandstone, New Mexico. In: Van Wagoner, J. C. and Bertram, G. T. (eds.): Sequence stratigraphy of foreland basin deposits - outcrop and subsurface examples from the Cretaceous of North America. AAPG Mem. 64: 277-310.

Olsen, T., Steel, R.J., Høgseth, K., Skar, T. and Røe, S-L., 1995: Sequence Architecture in a fluvial succession: sequence stratigraphy in the Upper Cretaceous Mesaverde Group, Price Canyon, Utah. Journal of Sedimentary Research B65: 265-280.

Posamentier, H.W., Jervey, M.T. and Vail, P.R., 1988: Eustatic controls on clastic deposition I - conceptual framework. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C. (eds.); Sea-level changes: an integrated approach. SEPM Spec.Publ. 42: 109-124.

Posamentier, H.W. and Vail, P.R., 1988: Eustatic control on clastic deposition II - sequence and systems tracts. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C. (eds.); Sea-level changes: an integrated approach. SEPM Spec.Publ. 42: 125-154.

Shanley, K.W. and McCabe, P.J., 1991: Predicting facies architecture through sequence stratigraphy - an example from the Kaiparowits Plateau, Utah. Geology 19: 742-745.

Shanley, K.W. and McCabe, P.J., 1993: Alluvial architecture in a sequence stratigraphic framework: a case history from the Upper Cretaceous of southern Utah, USA. IAS Spec.Publ. 15: 21-56.

Shanley, K.W. and McCabe, P.J., 1994: Perspectives on the sequence stratigraphy of continental strata. AAPG Bull. 78: 544-568.

Shanley, K.W., McCabe, P.J. and Hettinger, R.D., 1992: Tidal influence in Cretaceous fluvial strata from Utah, USA: a key to sequence stratigraphic interpretation. Sedimentology, 39: 905-930.

Surlyk, F., Arndorff, L., Hamann, N.-E., Hamberg, L., Johannesen, P.N., Koppelhus, E.B., Nielsen, L.H., Noe-Nygaard, N., Pedersen, G.K. and Petersen, H.I., 1995: High-resolution sequence stratigraphy of a Hettangian - Sinemurian paralic succession, Bornholm, Denmark. Sedimentology 42: 323-354.

Törnqvist, T., van Ree, M. H. M. and Faessen, E. L. J. H., 1993: Longitudinal facies architectural changes of a Middle Holocene anastomosing distributary system (Rhine - Meuse delta, central Netherlands). Sedimentary Geology 85: 203-219.

Vail, P.R., Mitchum, R.M. and Thompson,III, S., 1977: Seismic stratigraphy and global changes of sea level, part 3: relative changes in sea level from coastal onlap. In: Payton, C.W. (Ed.), Seismic stratigraphy applications to hydrocarbon exploration: AAPG Memoir 26. 63-97.

Van Adrichem Boogaert, H.A. and Kouwe, W.F.P., 1993: Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA. Mededelingen Rijks Geologische Dienst, 50, 1993.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S. and Hardenbol, J., 1988: an overview of the fundamentals of sequence stratigraphy and key definitions. In:

Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A. and Van Wagoner, J.C. (eds.); Sea-level changes: an integrated approach. SEPM Spec.Publ. 42: 39-45.

Vollset,J. And Doré, A.G. (Eds.), 1984: A revised Triassic and Jurassic lithostratigraphic nomenclature for the Norwegian North Sea. NPD-Bulletin no.3, 53pp.

Wright, V.P. and Marriot, S.B., 1993: The sequence stratigraphy of fluvial depositional systems: the role of floodplain sediment storage. Sedimentary Geology, 86: 203-210.

Figure captions

Fig.1: Well locations in the Søgne Basin

Fig. 2: West - east well-log panel of the Bryne Formation in the western and central part of the Søgne Basin.

Fig. 3: North - south well-log panel of the Bryne Formation in the eastern and central part of the Søgne Basin.

Fig. 4: Core-GR log of Baj-1B sequence in West Lulu-3; LST/TST/lower HST.

Fig. 5: Core-GR log of Bat-1A sequence in West Lulu-2; basal sequence boundary cuts into HST of Baj-1B; LST/TST of Bat-1A is represented by afining upward fluvial channel fill.

Fig. 6: Core-GR log of Cal-1A sequence in West Lulu-2 and -3, LST/lower TST; stacked channel sandstone's with evidence for tidal influence constitute an incised valley fill.

Fig. 7: Core-GR log of Cal-1A sequence in West Lulu-1 and -3 and Lulu-1, upper TST and HST/FRST; mainly TST deposits to the west in West Lulu-3 separated from the HST/FRST dominated succession to the east in Lulu-1 by an inclined MFS (reciprocal deposition).

Fig. 8: Core-GR log of Cal-1B sequence in West Lulu-2 and Lulu-1; LST/lower TST deposits in West Lulu-2 separated from HST/FRST deposits by thin upper TST and MFS (reciprocal deposition).

Fig. 9: Idealized west - east section of the sequences of the upper Bryne Formation (A), the most complete sequences of the lower Bryne Formation (B), and a schematic representation of the evolving half-graben and salt-dome which may have influenced sedimentation patterns (C).

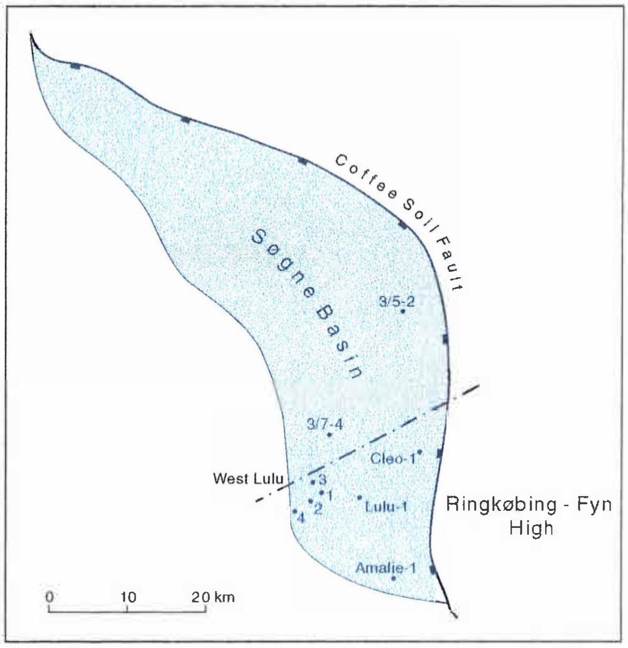

Coffee Soil Fault
Søgne Basin
3/5-2
3/7-4
Cleo-1
West Lulu
3
1
2
4
Lulu-1
Ringkøbing - Fyn
High
Amalie-1
0
10
20 km

Fig. 1

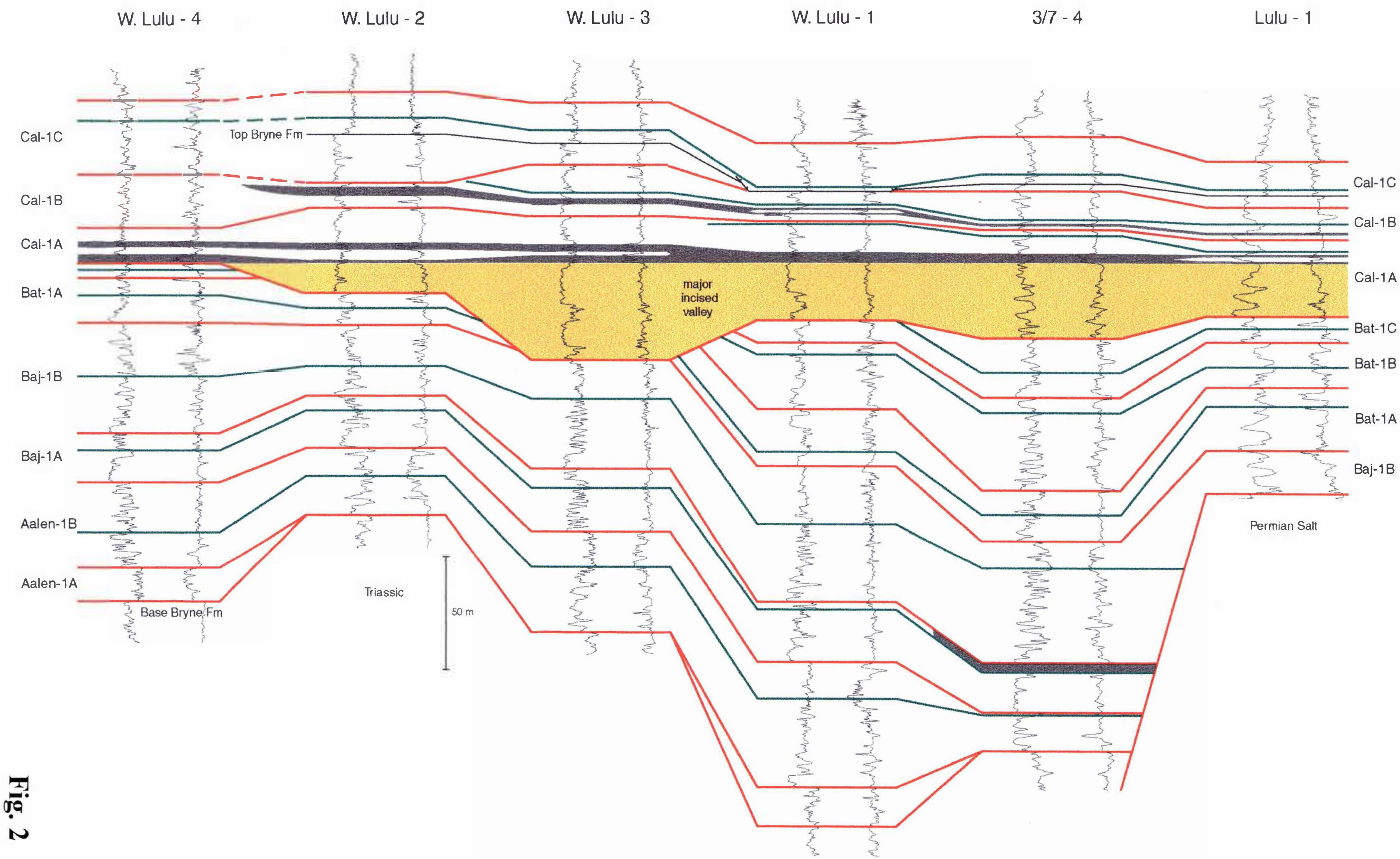

W. Lulu - 4
W. Lulu - 2
W. Lulu - 3
W. Lulu - 1
3/7 - 4
Lulu - 1
Cal-1C
Cal-1B
Cal-1A
Bat-1A
Baj-1B
Baj-1A
Aalen-1B
Aalen-1A
Top Bryne Fm
Base Bryne Fm
Triassic
50 m
major incised valley
Permian Salt
Cal-1C
Cal-1B
Cal-1A
Bat-1C
Bat-1B
Bat-1A
Baj-1B

Fig. 2

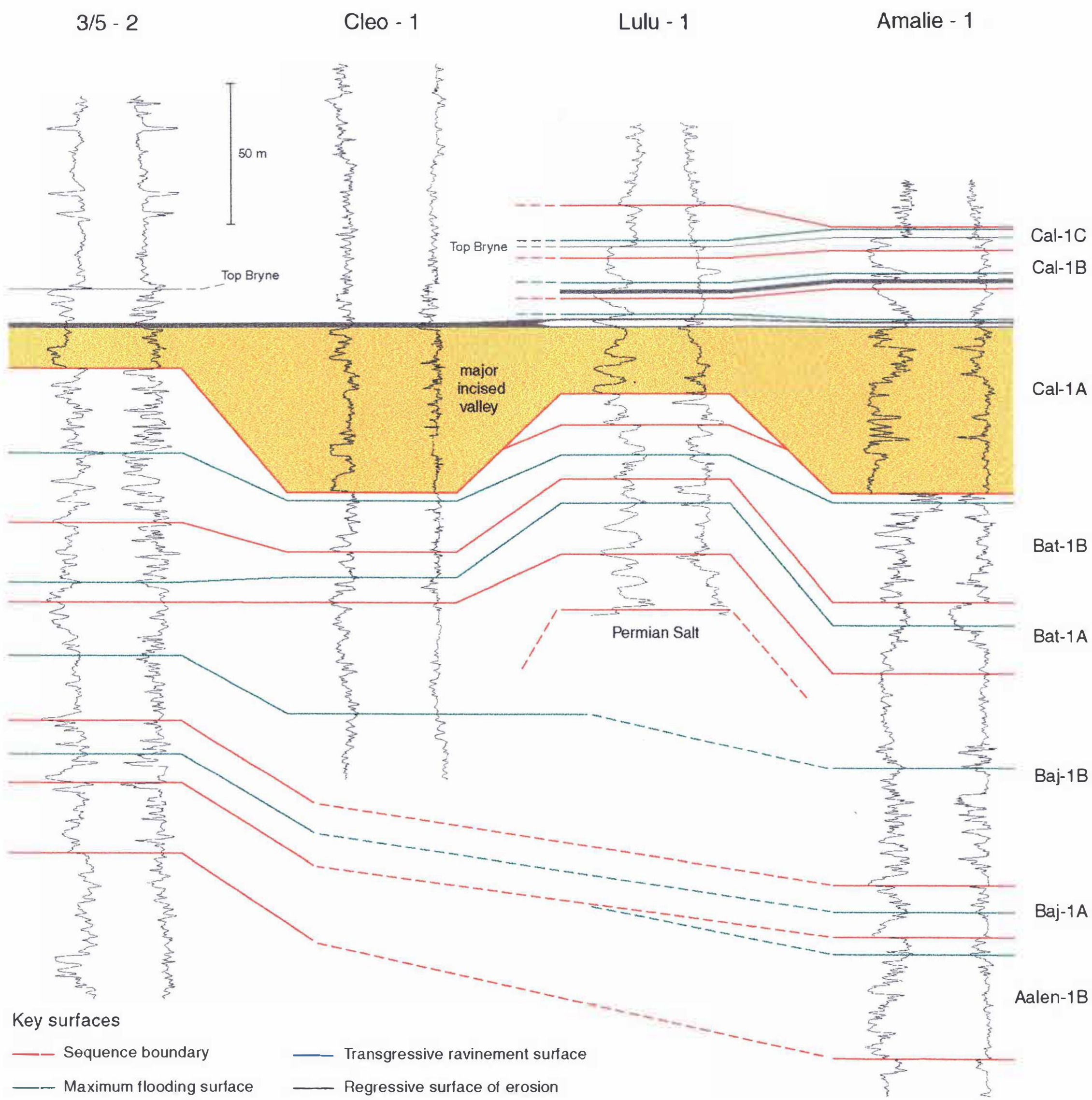
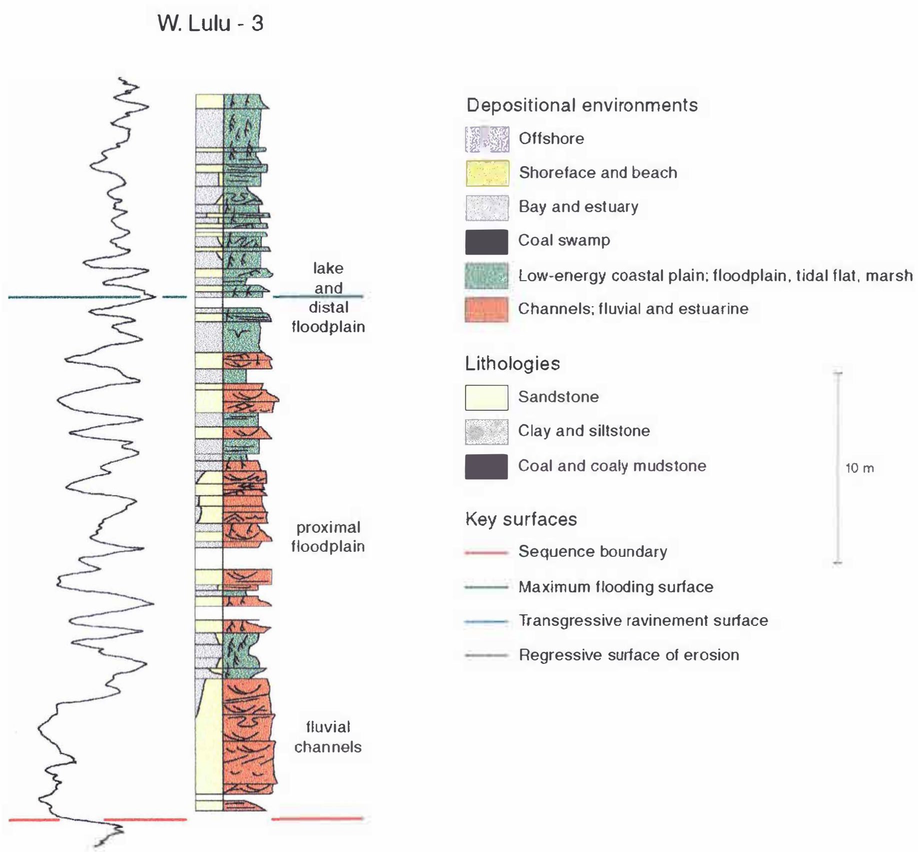

3/5 - 2
Cleo - 1
Lulu - 1
Amalie - 1
50 m
Top Bryne
Top Bryne
major
incised
valley
Permian Salt
Cal-1C
Cal-1B
Cal-1A
Bat-1B
Bat-1A
Baj-1B
Baj-1A
Aalen-1B
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig. 3



W. Lulu - 3
lake
and
distal
floodplain
proximal
floodplain
fluvial
channels
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
10 m
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig. 4

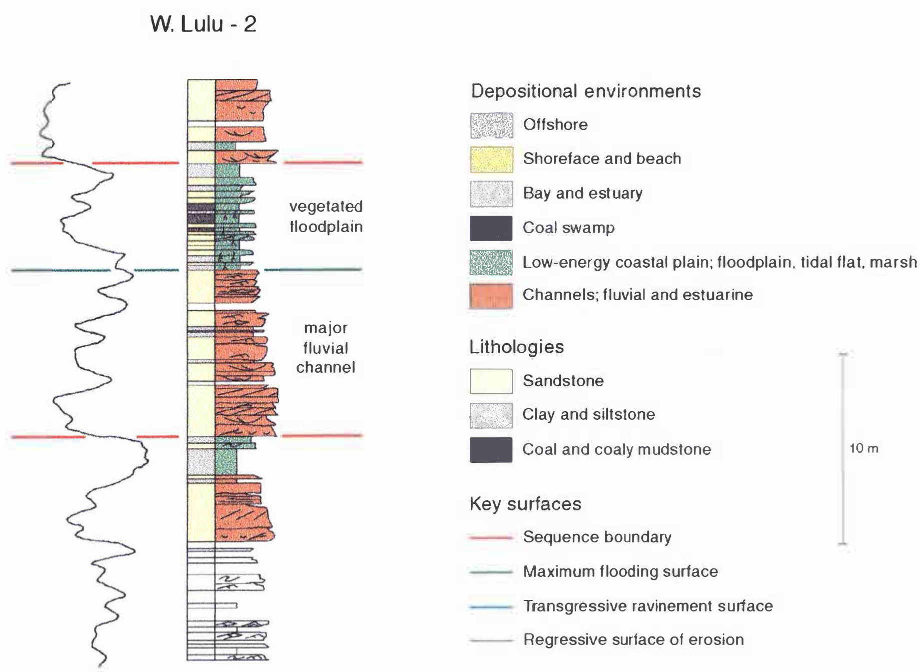

W. Lulu - 2
vegetated floodplain
major fluvial channel
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
10 m
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig. 5

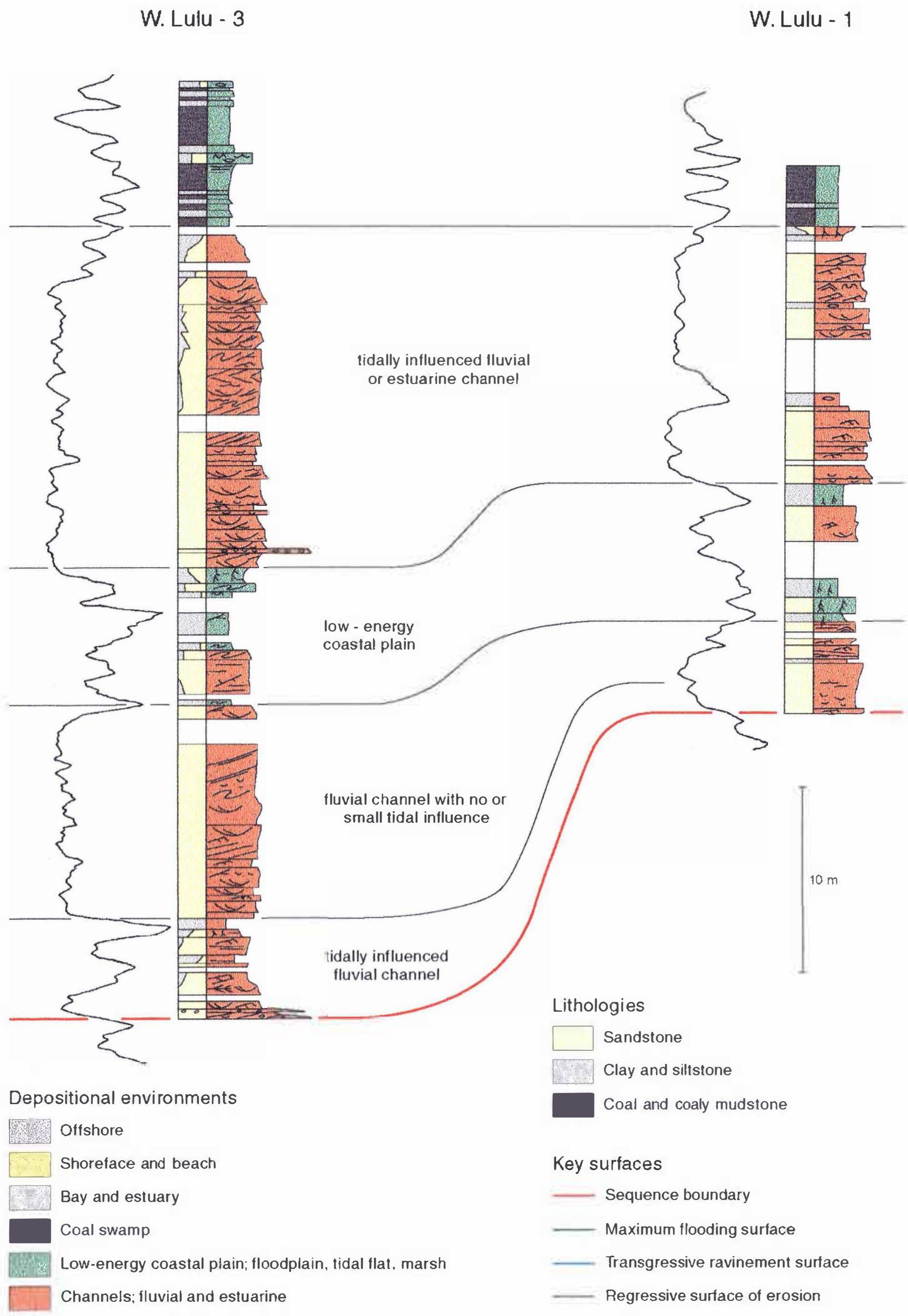

W. Lulu - 3
W. Lulu - 1
tidally influenced fluvial or estuarine channel
low - energy coastal plain
fluvial channel with no or small tidal influence
tidally influenced fluvial channel
10 m
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig. 6

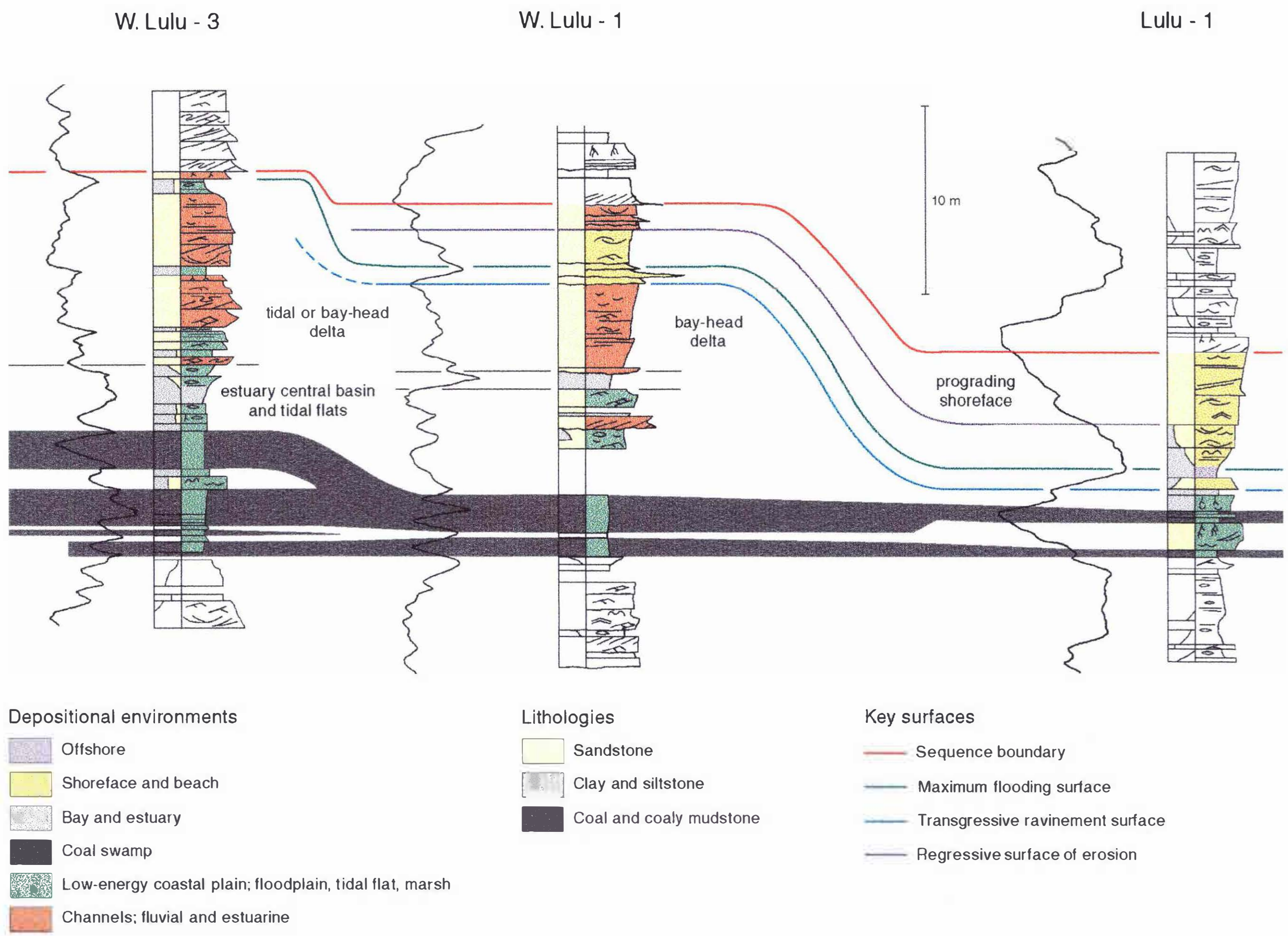

W. Lulu - 3
W. Lulu - 1
Lulu - 1
10 m
tidal or bay-head delta
estuary central basin and tidal flats
bay-head delta
prograding shoreface
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig. 7

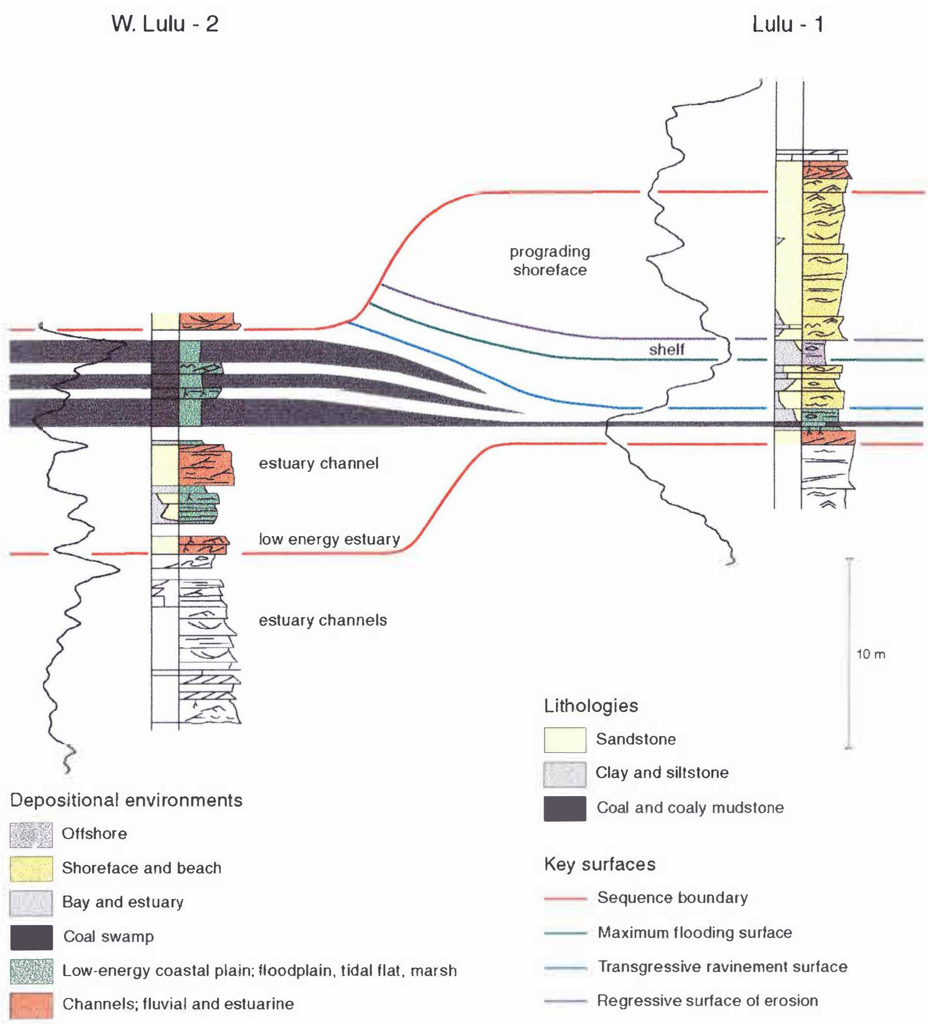

W. Lulu - 2
Lulu - 1
prograding shoreface
shelf
estuary channel
low energy estuary
estuary channels
10 m
Depositional environments
Offshore
Shoreface and beach
Bay and estuary
Coal swamp
Low-energy coastal plain; floodplain, tidal flat, marsh
Channels; fluvial and estuarine
Lithologies
Sandstone
Clay and siltstone
Coal and coaly mudstone
Key surfaces
Sequence boundary
Maximum flooding surface
Transgressive ravinement surface
Regressive surface of erosion

Fig. 8

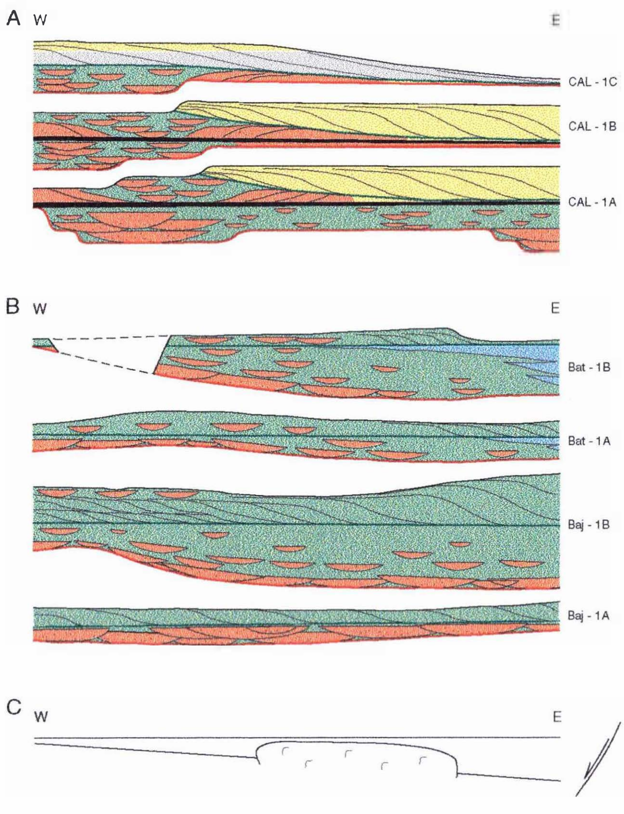


Fig. 9

Upper Jurassic sandstone reservoirs in the northwestern part of Danish Central Graben, North Sea
- a core workshop

Peter N. Johannessen

Geological Survey of Denmark and Greenland, GEUS, Thoravej 8, DK-2400, Copenhagen NV, Denmark

Abstract

Two different marginal marine to marine reservoir sandstones are recognized within the Upper Jurassic in the northern part of the Danish Central Graben. These are in ascending order: 1) Transgressive shallow marine and back-barrier sandstones deposited in the Feda Graben and the Gertrud Plateau during the Late Kimmeridgian. These sediments were formerly assigned to the "basal sandstone unit" but are now regarded as part of the Heno Formation. 2) Regressive-transgressive shallow marine sandstones of the Heno Formation, deposited on the Gertrud Plateau and the Heno Plateau during the Late Kimmeridgian.

Two further Upper Jurassic marine sandstones are recognized in the Danish Central Graben. The Volgian Poul Formation represents fan-delta sandstones which were deposited in the Søgne Basin, Tail End Graben and possible in the west Feda Graben. Thin Volgian turbidite sandstones also occur in the Tail End Graben, interbedded with offshore claystones of the Upper Jurassic Farsund Formation.

The purpose of the present paper is to document the two marginal marine to marine reservoir sandstones in the northern part of the Danish Central Graben. Thin turbidite sandstones will also be described as similar sandstones might constitute reservoir sandstones in other parts of the Danish Central Graben, which have not yet been penetrated by wells.

Upper Jurassic sandstone reservoirs

Introduction

After the publication of Johannessen & Andsbjerg (1993) new biostratigraphic data (Karen Dybkjær in: Johannessen et al. 1996) indicate that the "basal sandstone unit" in the eastern part of the Feda Graben and the Gertrud Plateau (Figs 1 & 2) is not Oxfordian in age but Late Kimmeridgian (Figs 3 & 4). Thus the "basal sandstone unit" in this region is time equivalent to the shoreface sandstones of the Heno Formation upon the Heno Plateau (Jensen et al. 1986), and is therefore now regarded as part of the Heno Formation.

Back-barrier sediments

Gert-1 core description, Feda Graben
The former "basal sandstone unit" consists of a 90 m thick coarsening- and cleaning-upward succession of which the lowermost 56 m were cored (Figs 5 & 6). The cored section consists of very strongly bioturbated interbedded sandstones and mudstones. Rootlets associated with coal beds, 2-15 cm thick, and/or claystone beds occur throughout the cored section. *Ophiomorpha nodusa* is by far the dominant trace fossil (Fig. 6). Marine palynomorphs occur rarely (Fig. 7) (Johannessen et al. 1996).

Several coarsening to fining upward successions, 3-8 m thick, are recognized (Figs 6 & 8-10). The lowermost part of the upward coarsening succession consists of clayey siltstones and very fine-grained sandstones which are heavily bioturbated, especially by *Ophiomorpha nodusa*. Parallel laminated and cross-bedded, fine to medium-grained sandstones overlie the clayey very fine to fine-grained sandstones. Burrows of *Ophiomorpha nodusa* are by far the most frequent trace fossil recognized in these clean sandstones. The upward fining part of the succession consists of bioturbated, very fine to fine-grained sandstones, often characterized by rootlets. The top of the upward fining interval consists of organic rich claystones or coal beds.

Gert-1 core interpretation
The association of rootlets and *in situ* coals together with bioturbated sediments containing *Ophiomorpha nodusa* and rare marine palynomorphs, in the 56 m thick cored succession, indicate a back-barrier setting.

Several coarsening upward to fining upward successions, 3-8 m thick, are recognized in the cored section (Figs 6 & 8-10). The upward coarsening part of the succession, from clayey siltstones and very fine-grained sandstones, indicates deposition in an environment with increasing energy and is probably deposited by a prograding mouthbar or bay head delta. The cross-bedded, medium-grained sandstones represent the highest energy levels during the deposition of the upward coarsening to upward fining cycles. They were probably deposited at the base of channels by migrating mega-ripples or bars. The upward fining part of the succession, composed by bioturbated, faint parallel laminated fine to very fine-grained sandstones and topped by up to 0.5 m thick claystones and/or a thin coal bed probably represents passive channel fill. The claystones record a low-energy environment where clay was deposited from suspension. The thin coal beds, which show associated rootlets indicating that the coal was autochtonous, represent the final phase of abandonment. Thus the upward coarsening to upward fining cycles probably represent coarsening upward mouthbar sediments cut by distributary channels. The occurrence of *Ophiomorpha nodusa* within the distributary fill may indicate some marine influence.

Shoreface sandstones

Gwen-2 core description, Gertrud Plateau
The Heno Formation consists of a coarsening- to fining-upward succession, 70 m thick, of predominantly very fine- to fine-grained sandstones (Fig. 13). A conglomerate, 0.5 m thick, seperates the upward coarsening succession from upward fining succession (Figs 13 & 15). The sandstones are intensely bioturbated, often to such a degree that primary sedimentary structures are blurred. Bivalve shells occur. Several trace fossils such as *Helminthopsis horizontalis, Chondrites, Asterosoma, Skolithos, Planolites, Thalassinoides, Palaeophycus, Rhizocorallium, Teichichnus, Terebellina and Ophiomorpha.* Faint parallel bedding and scattered cross-lamination is seen. An c. 5 m thick interval dominated by parallel laminated, 15-30 cm thick, medium-grained sandstones, underlie the conglomerate (Fig. 13).

Several 5-10 m thick successions which have an upward decreasing amount of clay and silt within the overall upward coarsening part of the sandstone interval are recognized below the conglomerate (Figs 13 & 14).

Outsized quartz clasts, between 0.5-3 mm in diameter, often well rounded and spherical, are frequent and occur scattered within the bioturbated sandstones. The clasts in the conglomerate is most often matrix supported (Figs 13 & 15). The clasts are 0.5-2 cm in diameter and the matrix consists of fine- to medium-grained sandstone and contains pyrite, coal fragments and bivalve shells.

Gwen-2 core interpretation
The intense bioturbation, the trace fossil assemblage and the high relative abundance of marine palynomorphs indicate that the sandstones and the conglomerate were deposited within a well-oxygenated shoreface. The upward coarsening succession represents the progradation of a lower to middle shoreface sandstone. The conglomerate is interpreted as having been deposited at the turnaround point during maximum regression.

The few preserved cross-laminations indicate that traction currents occurred over the sea floor giving rise to migrating small-scale ripples. The 15-30 cm thick parallel laminated medium-grained sandstone beds, underlying the conglomerate, were probably deposited during upper flow regime conditions by storms. Sedimentation rates were either sufficiently large or the amount of burrowing organisms was reduced, resulting in the preservation of primary sedimentary structures..

The bioturbated sandstones characterizing the largest part of the Heno Formation are likewise interpreted to have been deposited by storm-generated currents transporting sand from the beach and out to the middle and lower shoreface. The scattered outsized matrix-supported quartz clasts were probably deposited on scoured surfaces by storm currents that swept across the sea-bottom and then later dispersed in the sediment by burrowing. The five 5-10 m thick upward coarsening intervals within the overall progradational shoreface sandstones may be interpreted as smaller scale prograding shoreface sandstones, each representing a parasequence.

The clast sizes of the conglomerate are much larger than the outsized clasts characteristic of the upward-coarsening shoreface sandstones (Figs 13 & 15). The conglomerates are therefore interpreted to have been originally deposited during maximum regression under maximum energy regimes prior to the transgression. It is not clear whether the conglomerate was deposited by a series of storm events, as discussed above, or by fluvial processes during maximum regression. Erosive shoreface processes active during the later transgression may have obliterated all evidence of individual coarse-grained storm beds or sub-aerial exposure (e.g. palaeosols, coal beds, rootlets and desiccation cracks). The large amount of coal clasts within the conglomerate indicates that land was closely situated. The erosive base of the conglomerate thus represents a sequence boundary (SB) and a marine transgressive surface of erosion (MTSE)(Fig. 13).

Ravn-1 core description, Heno Plateau

The Heno Formation consists of a coarsening- to fining-upward succession, 109 m thick, of predominantly very fine- to fine-grained sandstones (Fig. 5). The middle 67 m of this succession are cored (Fig. 6). The overall CU-FU succession consists of 2-8 m thick CU units of very fine-grained to fine-grained sand characterized by an upward decrease of clay content (Figs 6 & 20).

The sediments are intensely bioturbated, very fine to fine-grained sandstones. Faint parallel lamination is the only recognized primary sediment structure. The section is dominated by burrows of *Asterosoma*, *Teichichnus* and *Ophiomorpha nodusa*. A conglomerate, 2 m thick, consists of quartz clasts ranging from 3-15 mm in a matrix of fine-grained sandstone (Figs 6 & 19). The conglomerate is clast- and matrix-supported and abruptly overlies very fine to fine-grained sandstones. Silty, very fine-grained sandstones abruptly overlie fine-grained sandstones (Fig´s 6 & 19).

Ravn-1 core interpretation

The high degree of bioturbation together with the diverse trace fossil assemblage suggests deposition on a well-oxygenated middle shoreface. The intense bioturbation has obliterated most of the primary sediment stuctures. The 2-10 m thick CU units within the overall progradational shoreface sandstones represent smaller scale prograding shoreface sandstones and are refered to as parasequences. The 2 m thick conglomerate that abruptly overlies very fine to fine-grained shoreface sandstones, indicates a sudden increase in energy. Consequently the base of the conglomerate is interpreted to be the result of a fall in relative sealevel, thus representing a sequence boundary. The conglomerate probably represents a bypass zone where more fine-grained sediments were transported farther out into the basin which in this case would be the Tail End Graben. If the fall in relative sealevel was large, thick shoreface sandstones, representing the lowstand systems tract, would be expected farther out in the Tail End Graben and might constitute a good reservoir (Johannessen & Andsbjerg 1993). A subsequent relative sea level rise may have redeposited the conglomerate and stripped off all evidences of subareal exposures of the sediment. The base of the conglomerate is thus represented by a sequence boundary (SB) and a marine transgressive surface of erosion (MTSE)(Fig. 6).

The silty, very fine-grained sandstones, abruptly overlying fine-grained sandstones indicate an abrupt decrease in energy during deposition of the sediments, indicating a rise of relative sealevel. The tops of the fine-grained sandstones thus represent flooding surfaces.

Elly-2 core description, Tail End Graben
The cored section of the Heno Formation equivalent in the Tail End Graben consists of moderately bioturbated, very fine-grained, glauconitic sandstones and sandy siltstones (Figs 5 & 25). In the sandy intervals, 8-10 cm thick, the diversity of trace fossils is high. Burrows of *Helminthopsis horizontalis, Chondrites, Asterosoma, Skolithos, Planolites, Thalassinoides, Palaeophycus, Rhizocorallium, Teichichnus, Terebellina and Ophiomorpha* are recognized (Figs 26-28). No primary sedimentary structures are preserved in the sandstone beds, probably due to the abundant burrows.

Elly-2 core interpretation
The high diversity, trace fossil assemblage and the high amount of glauconite, indicate that the cored fine-grained sandstones were deposited on a well oxygenated sea floor in a fully marine setting, probably the lower shoreface. The 8-10 cm thick, very fine-grained sandstones were probably deposited by storm generated currents.

The gamma ray radiation of the clayey lower shoreface sandstones is higher than usual for such grain sizes. This is explained by the large content of glauconite in the sandstones. Glauconite contains the radioactive element potassium, which insreases the gamma ray radiation of the sandstones, which may make it render to recognize the correct grain size and the correct amount of sand.

Turbidite sandstones

The Farsund Formation occasionally consists of thin sandstone beds interbedded within organic rich, non-bioturbated claystones (Damtoft et al. 1992). These sandstone beds were deposited by turbidity currents and modified mass flows during the Volgian and Ryazanian. A 17 m thick core with turbidite sandstones and mass flow deposits from the Iris-1 well is shown in Figs 30 & 32.

Iris-1 core description, Tail End Graben
Parallel laminated claystones without any signs of bioturbation are abruptly overlain by a 30 cm thick, upward fining, very disturbed granule bed overlain by a disturbed siltstone bed containing isolated sand grains and strongly inclined and deformed lenses of sandstone (Fig. 30). Another 30 cm thick, upward fining, disturbed granule bed abruptly overlies the siltstone bed. A disturbed siltstone bed, 1.5 m thick, overlies the granule bed. The granule beds are petrographically very immature and are dominated by poorly sorted, subangular to subrounded grains of polycrystalline quartz, feldspathic gneiss fragments, schist and abundant shell debris. No biotubation is recognized in the sediments.

Iris-1 core interpretation
The parallel laminated, non-bioturbated claystone indicates deposition from suspension in an anoxic environment. The sharp based, upward fining granule beds suggest that high energy

currents erosively sweept over the sea bottom before the granule beds were deposited. The fining upward succession suggests waning current velocities during the passage of a single flow, followed by deposition from suspension. The erosive base, the large clast size at the base of the granule beds, the normal grading and the massive character of the granule beds and overlying sandstone beds may suggest that these beds are similar to the Bouma sequence unit A (Bouma 1962)(Fig. 33) or modified grain flows (Lowe 1982). Other granule and sandstone beds in the Iris-1 well represent units ACDE of the Bouma sequence. The many disturbed beds and laminae are caused by water escape and loading processes, producing distinct pods of sand and isolated sand grains, granules and small pebbles floating in a muddy matrix. Some intervals are intensely folded and recumbent folds are also recognised, probably representing slumped units on an unstable inclined sea bottom. Some of the modified mass flow deposits may in fact have been generated by slumping processes (Shanmugam et al. 1995).

As the sediments are interpreted to have been deposited in an anaerobic environment the abundant thin shells and shell debris occurring throughout the sandstone beds must be allochthonous. The shells represent a benthic fauna which lived under aerobic conditions in a shelf area before they were redeposited by turbidity currents farther out into the basin. The mineralogically immature assemblage of rock fragments composed of polycrystalline quartz, feldspar, gneiss and shist indicates a metamorphic terrain as source area, probably the Mandal High.

References

Bouma, A.H. (1962) Sedimentology of Some Flysch Deposits; a graphic approach to facies interpretation. Elsevier, Amsterdam, 264 pp.

Damtoft , K., Nielsen, L.H., Johannessen, P.N. Thomsen, E. & Andersen, P.R. (1992) Hydrocarbon plays of the Danish Central Trough. In: A.M. Spencer (ed.) Generation, Accumulation and Production of Europe's Hydrocarbons II. Springer-Verlag. 35-58.

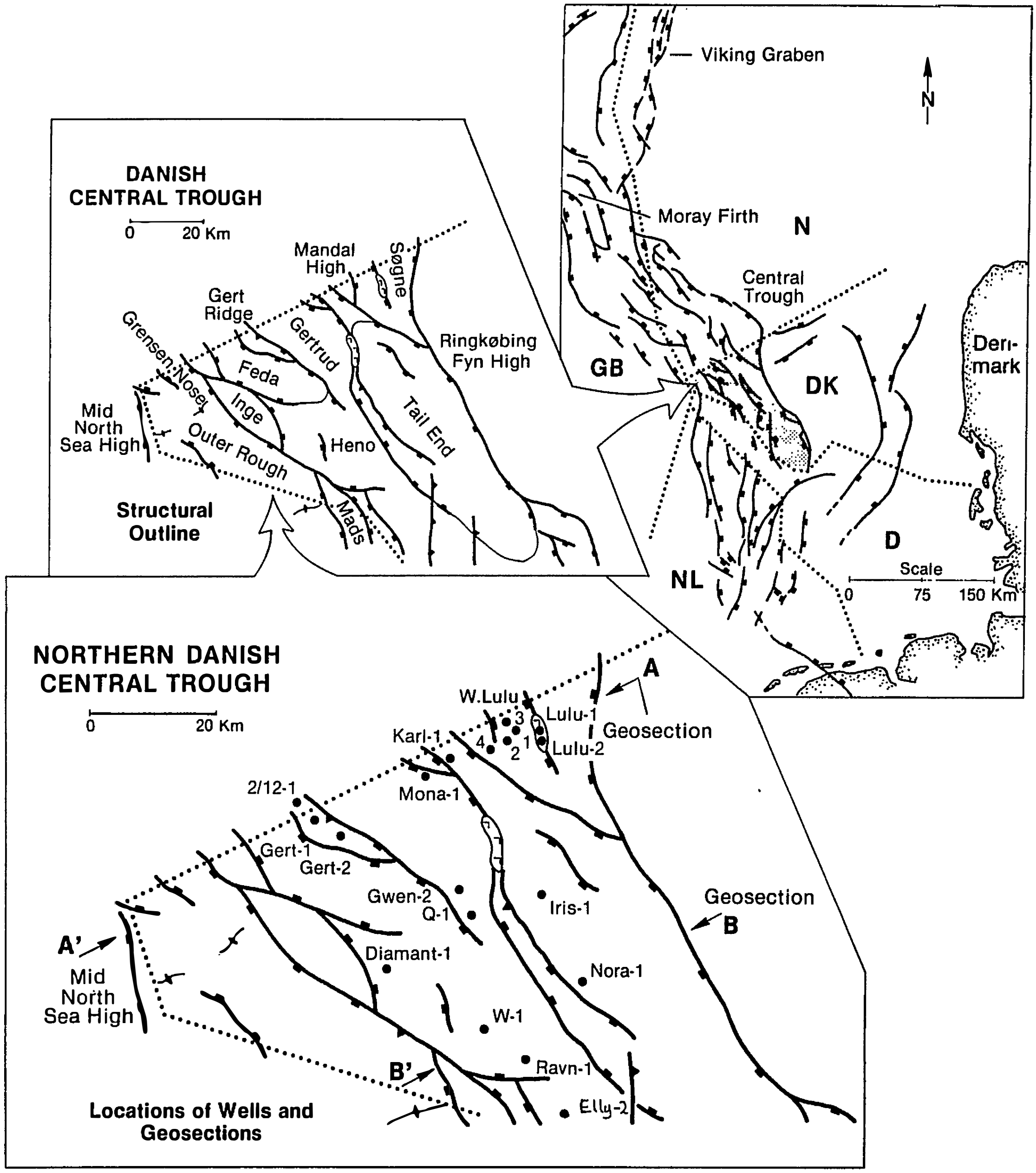
Jensen, T.F., Holm, L., Frandsen, N. & Michelsen, O. (1986) Jurassic - Lower Cretaceous lithostratigraphic nomenclature for the Danish Central Trough. Geol. Surv. Den., Ser A, 12, pp 65.

Johannessen, P.N. & Andsbjerg, J. (1993) Middle to Late Jurassic basin evolution and sandstoe reservoir distribution in the Danish Central Trough. In: J.R. Parker (ed). Petroleum geologyofNorthwest Europe: Proceedings of the 4th conference.

Johannessen, P.N., Dybkjær, K. & Rasmussen, E.S. (1996) Sequence stratigraphy of Upper Jurassic reservoir sandstones in the northern part of the Danish Central Trough. Marine and Petroleum Geology, 13, 755-770.

Lowe, D.R. (1982) Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents, J. sedim. Petrol., 52, 279-297.

Shanmugam; G., Bloch, R.B., Mitchel, S.M., Beamish, G.W.J., Hodgkinson, R.J., Damuth, J.E., Straume, T., Syvertsen, S.E. & Shields, K.E. (1995) Basin-floor fans in the North Sea: Sequence stratigraphic models vs. sedimentary facies. AAPG Bull., 79, 477-512.

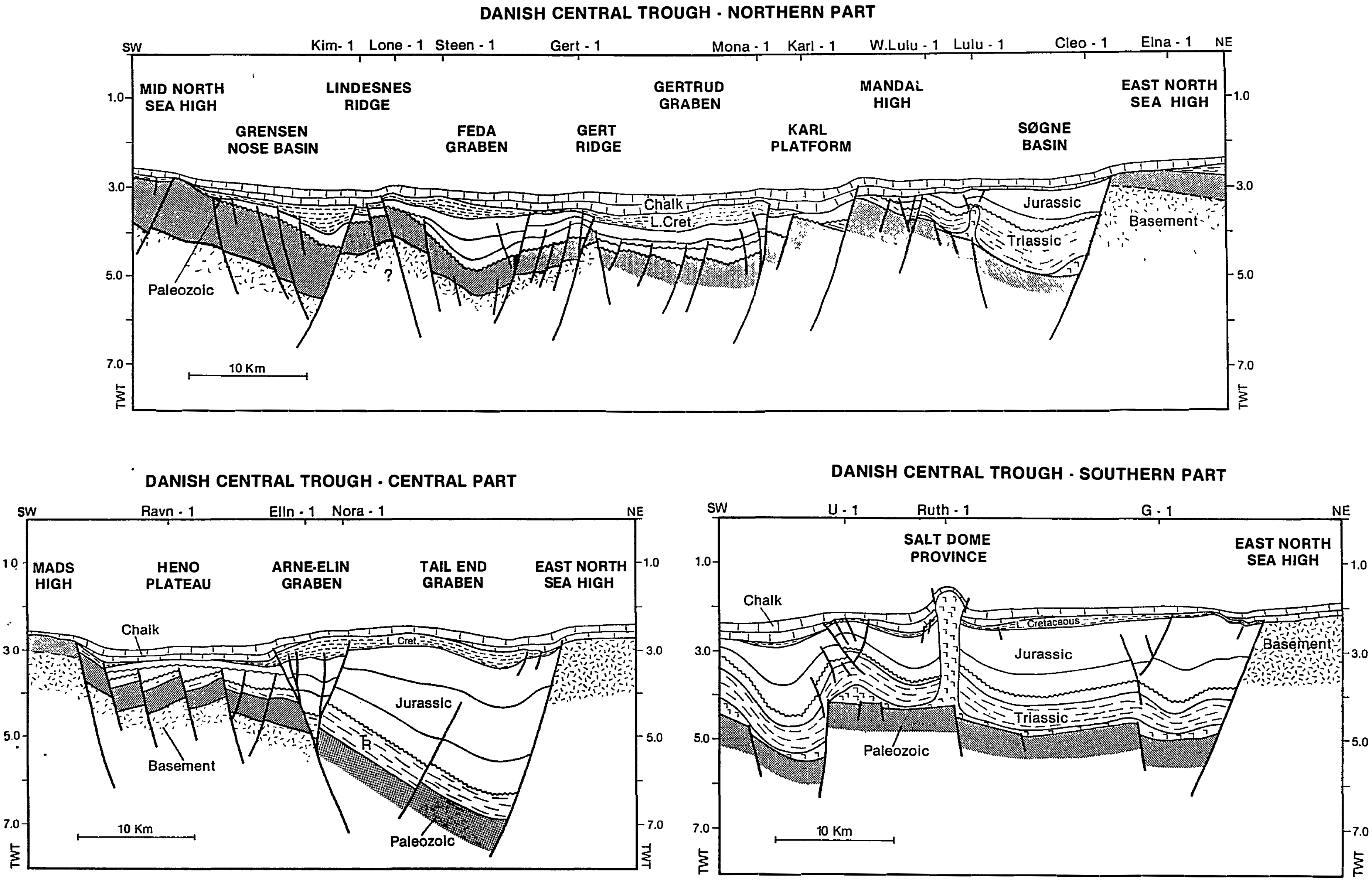


4 Structural outline of the Danish Central Trough, with location of wells and geosections.

Johannessen & Andsbjerg (1993)

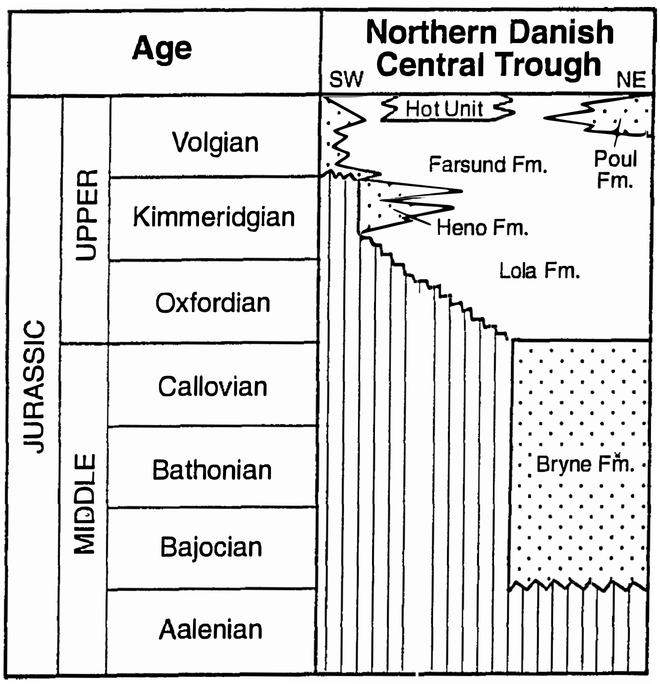
Fig.1

Damtoft et al. (1992)



SW–NE geosections through the northern, central, and southern part of the Danish Central Trough

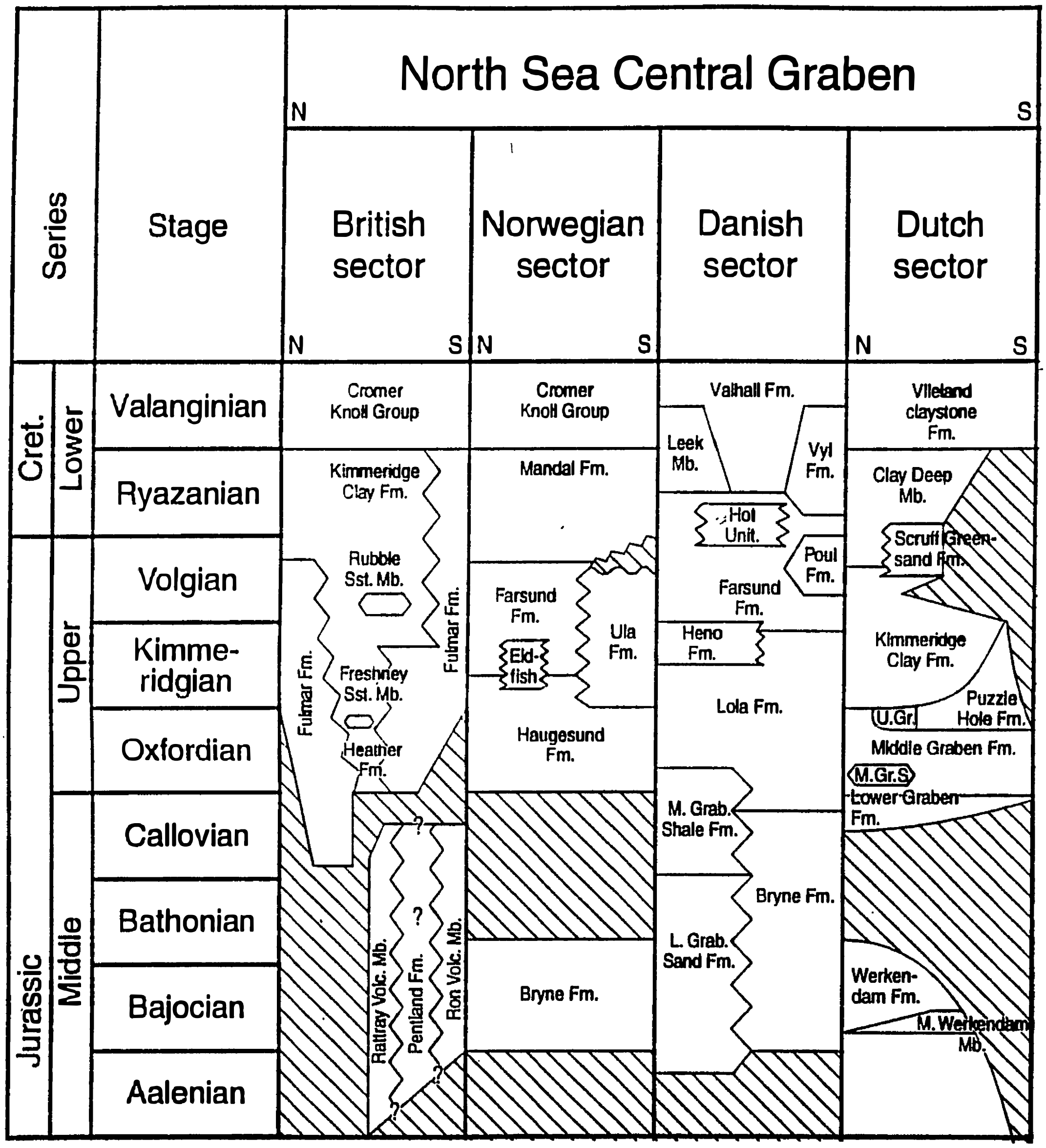
Fig. 2



Jurassic lithostratigraphic scheme for the northern part of the Danish Central Trough.

Johannessen (in prep)

Fig. 3



Johannessen (in prep)

Fig. 4

Johannessen (in prep)

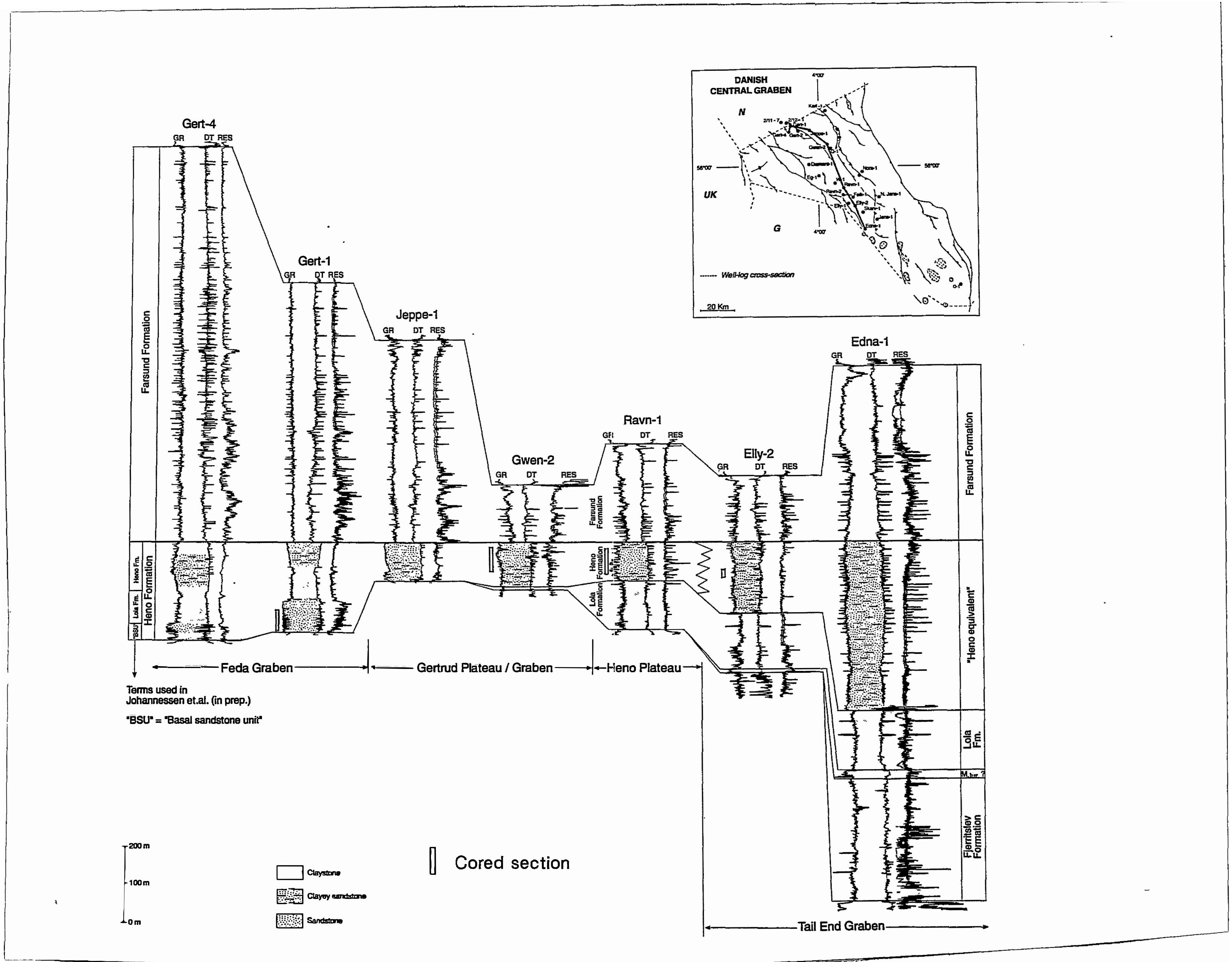
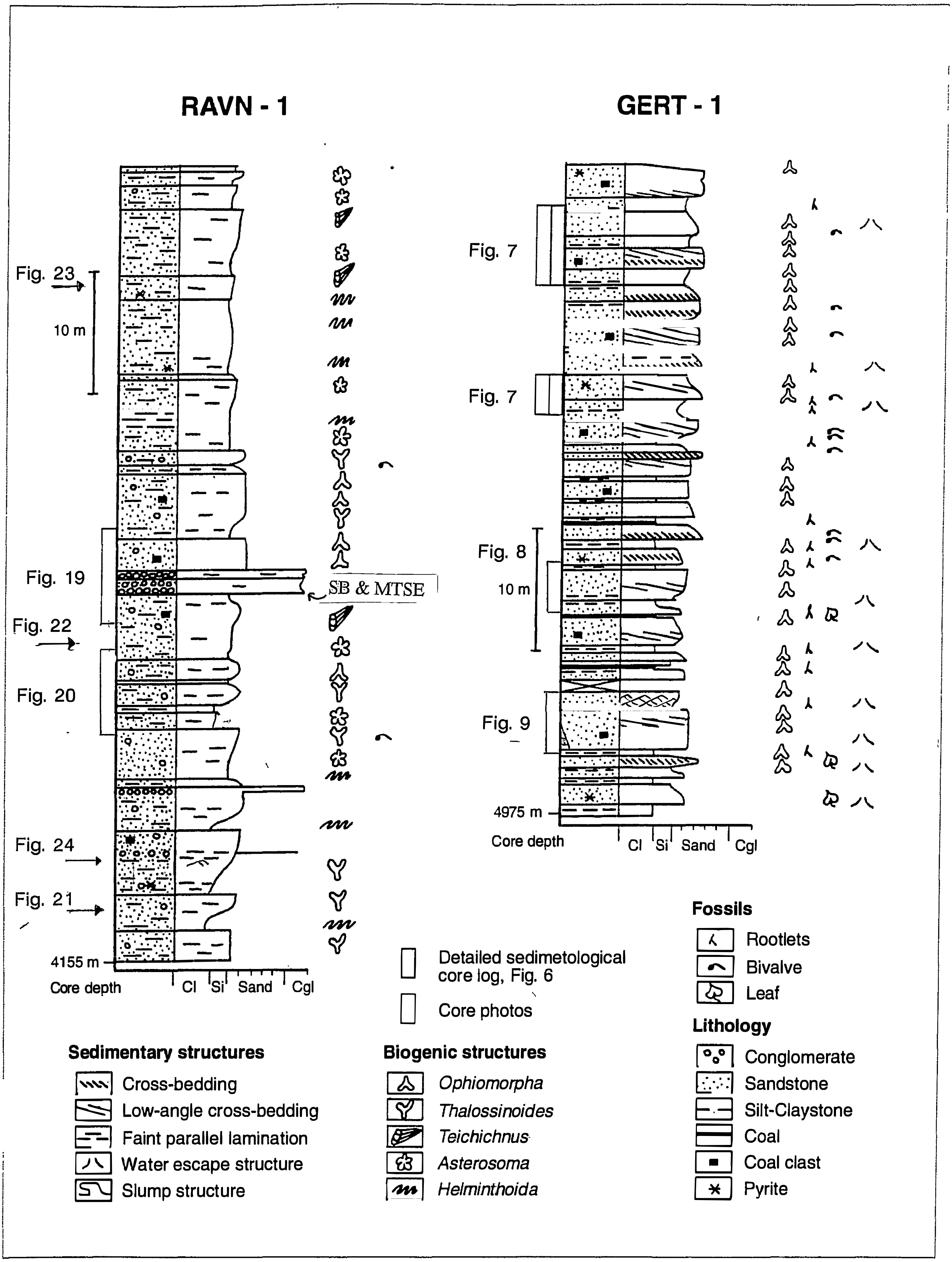


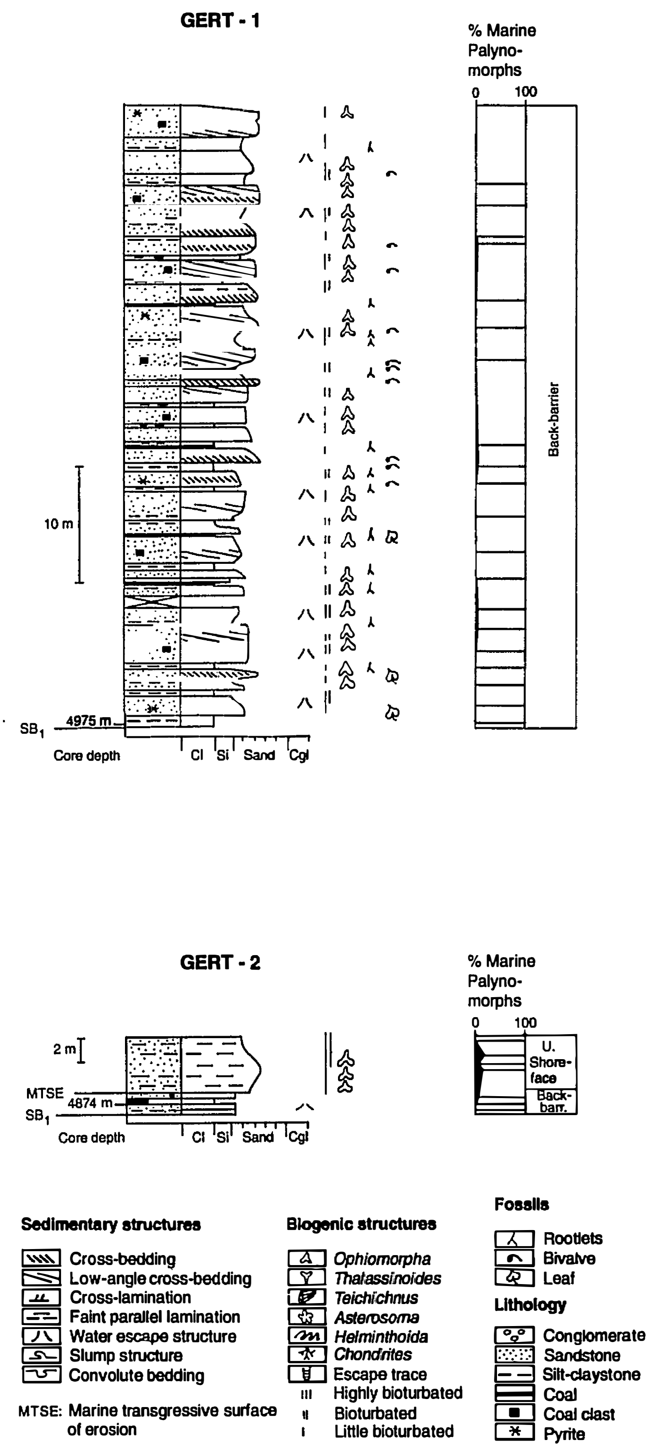
Fig. 5



Sedimentological core logs from the Heno Formation. The cored section in the Gert-1 well consists of back-barrier sandstones. The cored section in the Ravn-1 well consists of lower to middle shoreface sandstones with conglomerates. Several coarsening-upward parasequences are recognized in the Ravn-1 well.

Johannessen & Andsbjerg (1993)

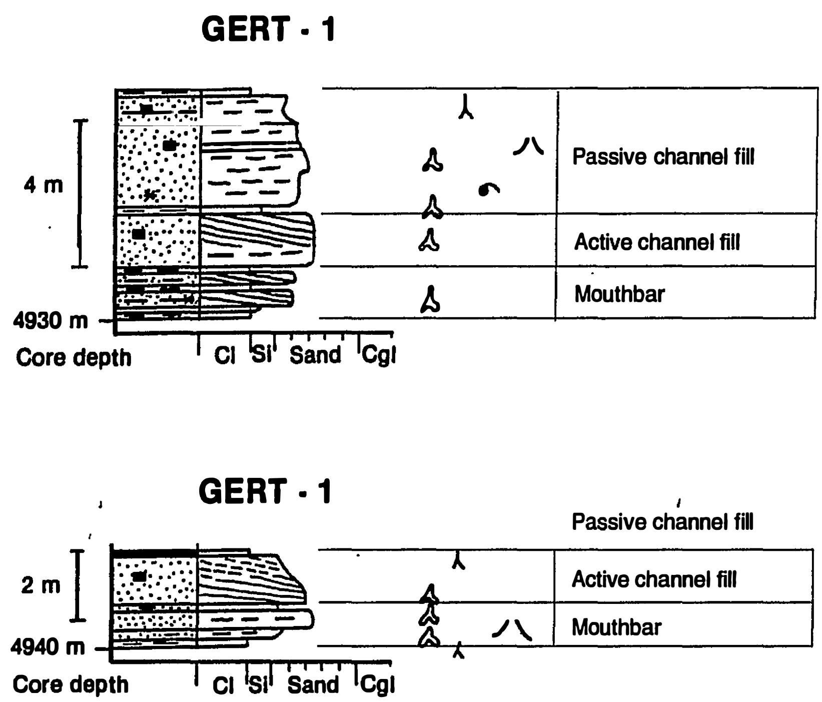
Fig.6



Sedimentological core logs from the 'basal sandstone unit' of the Gert-1 and Gert-2 wells. SB_1: composite sequence boundary

Johannessen et al. (1996)

Fig.7

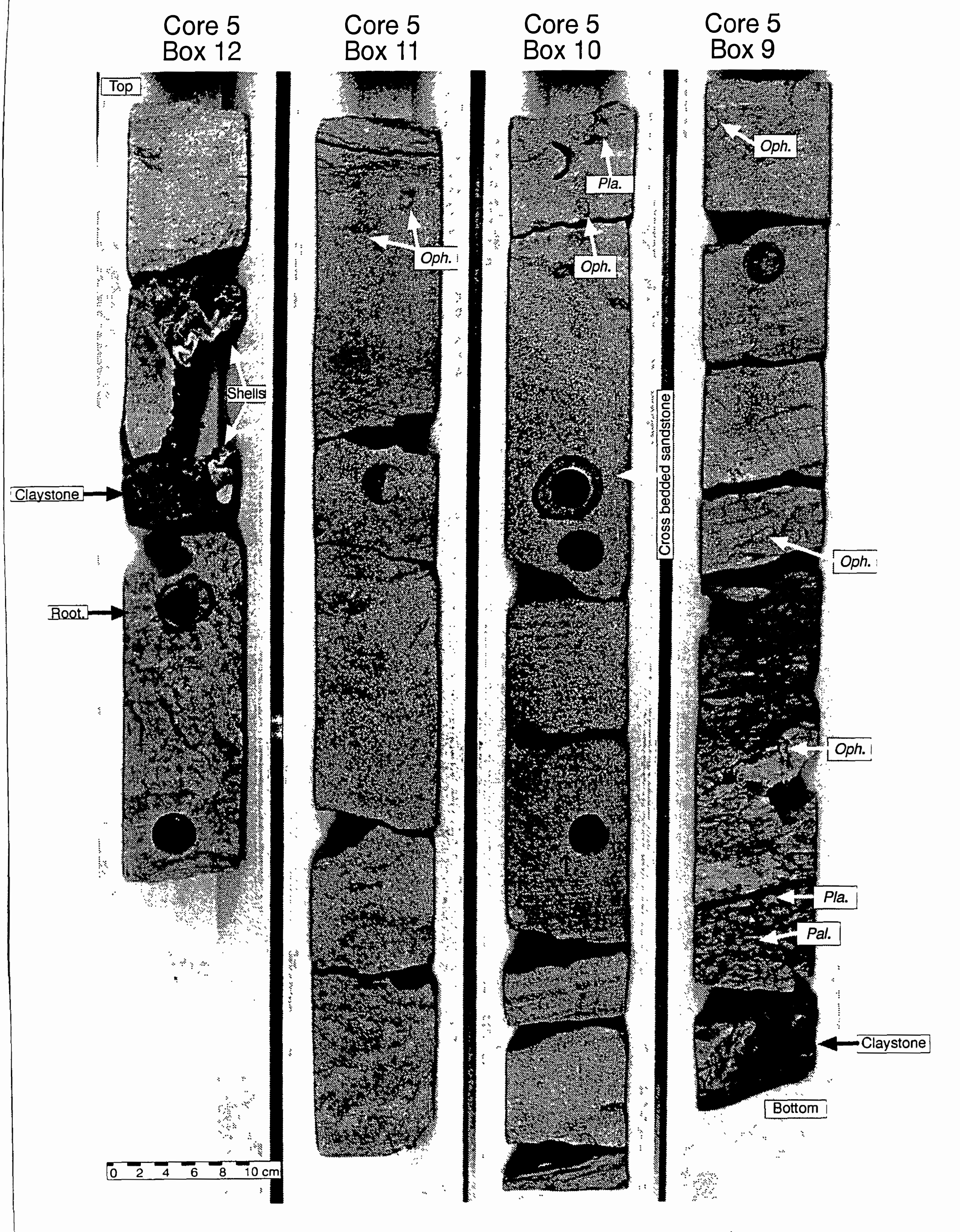


Typical coarsening upward to fining upward successions recognized in the cored section in the Gert-1 well. The coarsening upward succession represents mouthbar siltstones and sandstones with *Ophiomorpha nodusa* burrows. The fining upward interval consists of active and passive channel-fill sandstones, topped by a claystone or a thin coal bed, from which rootlets penetrate into the underlying sandstone.

Johannessen & Andsbjerg (1993)

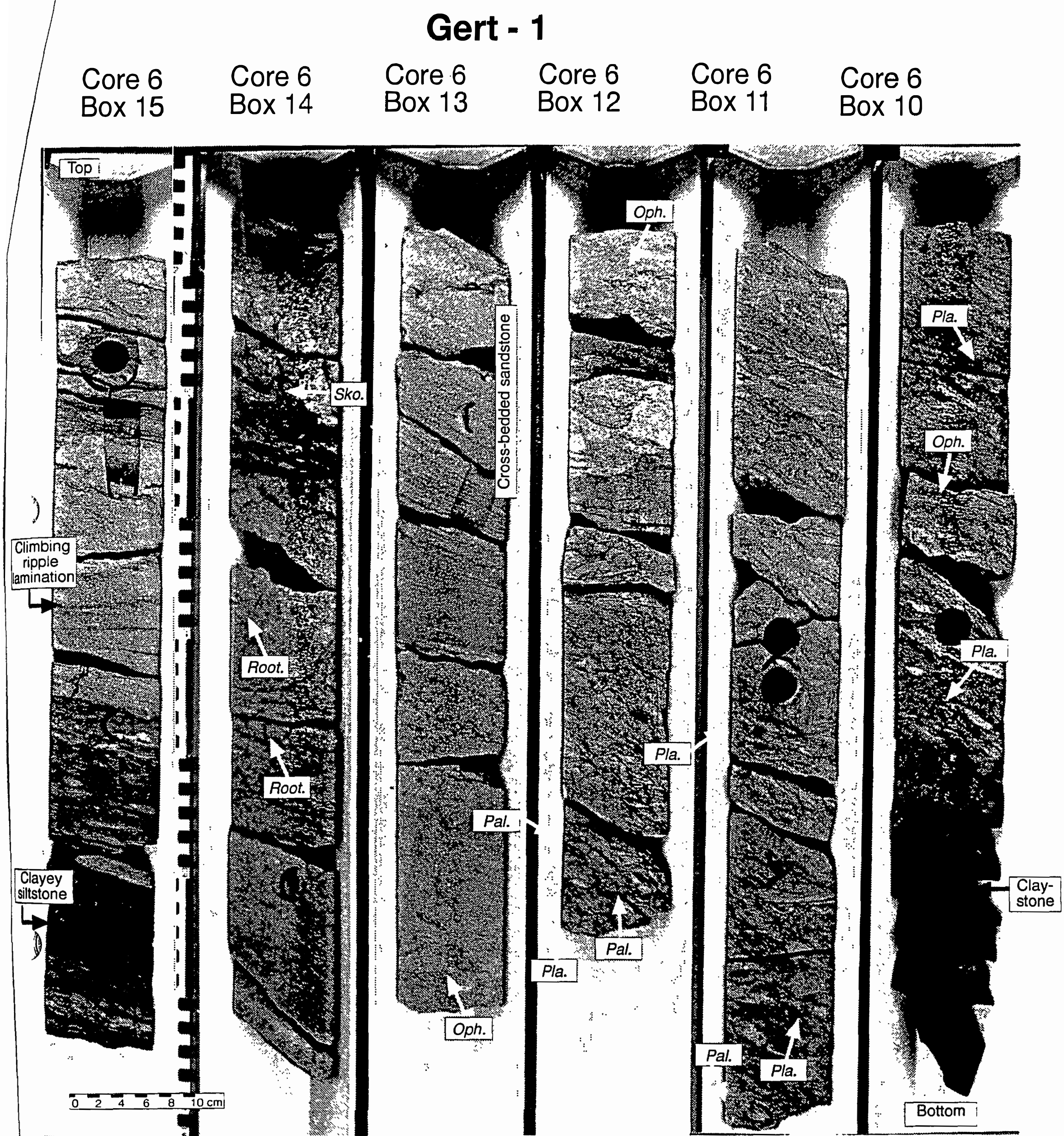
Fig.8

Gert - 1



Johannessen (in prep)

Fig. 9



Johannessen (in prep)

Fig. 10

Legend for core photos

Biogenic structures

Ast.: *Asterosoma*
Cho.: *Chondrites*
Dip.: *Diplocraterion*
Hel.: *Helminthopsis*
Oph.: *Ophiomorpha nodusa*
Pal.: *Palaeophycus heberti*
Pla.: *Planolites*
Rhi.: *Rhizocorallium*
Sko.: *Skolithos*
Tei.: *Teichichnus*
Ter.: *Terebellina*
Tha.: *Thalassinoides*
Zoo.: *Zoophycos*

L. Hel.: Large *Helminthopsis*
S. Hel.: Small *Helminthopsis*

Pla./Hel.: *Planolites* burrow reworked by *Helminthopsis*
Tha./Hel.: *Thalassinoides* burrow reworked by *Helminthopsis*
Tei./Hel.: *Teichichnus* burrow reworked by *Helminthopsis*
Ast./Hel.: *Asterosoma* burrow reworked by *Helminthopsis*
Tha./Cho.: *Thalassinoides* burrow reworked by *Chondrites*

Ast. X Tha.: *Asterosoma* cross-cut by *Thalassinoides*
Ast. X Cho.: *Asterosoma* cross-cut by *Chondrites*

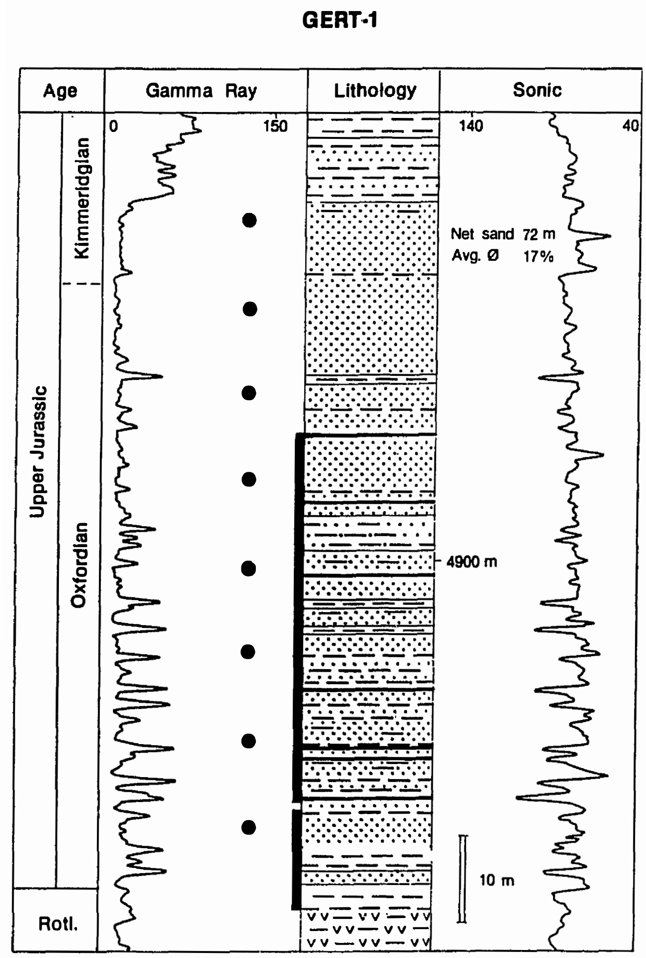
E.T.: Escape trace
Root.: Rootlets

Sedimentological features

B. sst.: Base sandstone
B. ch. sst.: Base channel sandstone
Ch. sst.: Channel sandstone
T. ch. sst.: Top channel sandstone
Cl.: Claystone clasts
OSQC: Out sized quartz clast
Ripl.: Ripple cross-lamination

Key surfaces

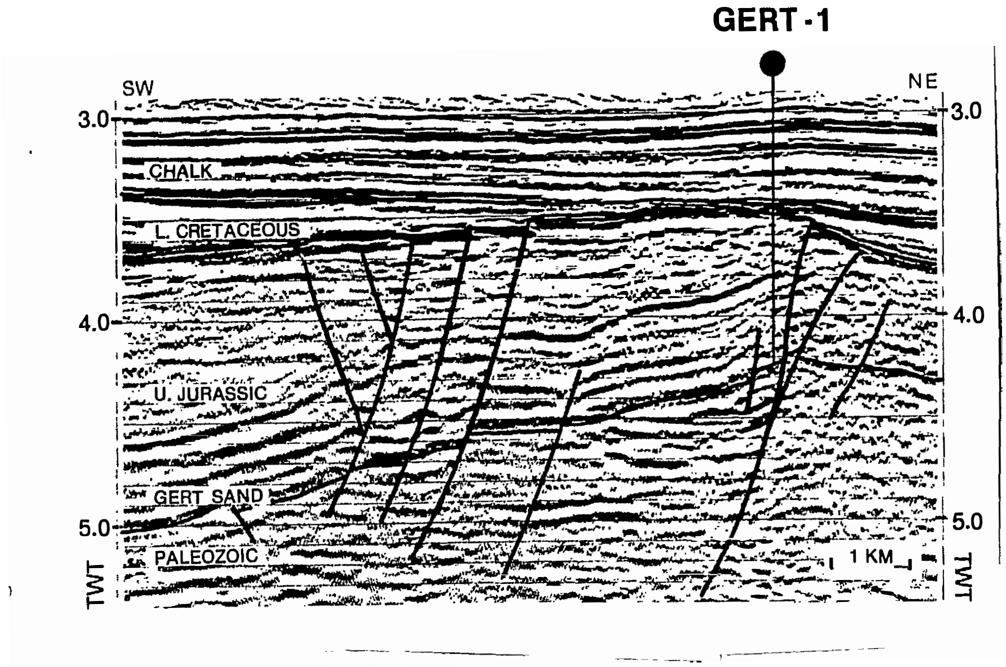
SB: Sequence boundary
MTSE: Marine transgressive surface of erosion
T. par.: Top parasequence



Upper Jurassic shallow marine sandstone reservoir of the Basal Sand Unit in the Gert-1 well, Gert Ridge

Damtoft et al. (1992)

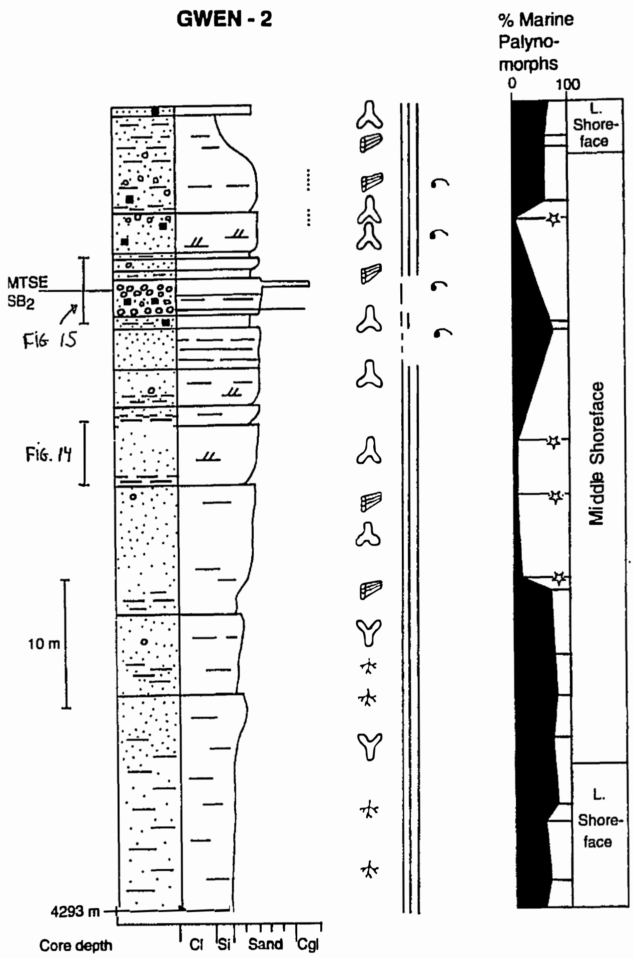
Fig. 11



Seismic section through the Gert structure on the Gert Ridge

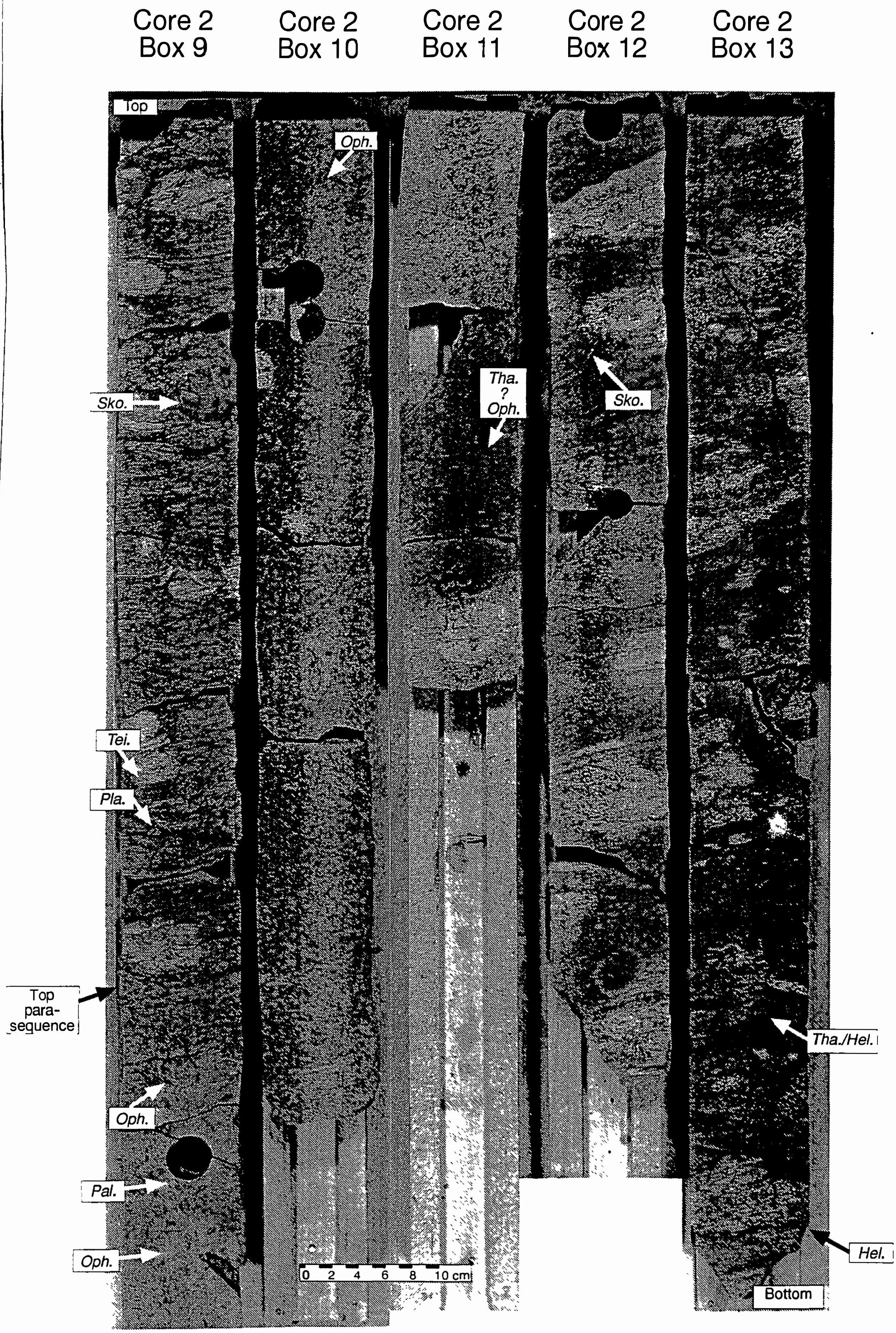
Damtoft et al. (1992)

Fig. 12



Sedimentological core log from the Heno Formation of the Gwen-2 well. Asterisks indicate samples where the percentage of marine palynomorphs probably is surpressed due to reworked Lower Jurassic clay clasts (2 mm in diameter) containing high amounts of terrestrial palynomorphs. SB_2: sequence boundary no. 2

Gwen - 2



Johannessen (in prep)

Fig. 14

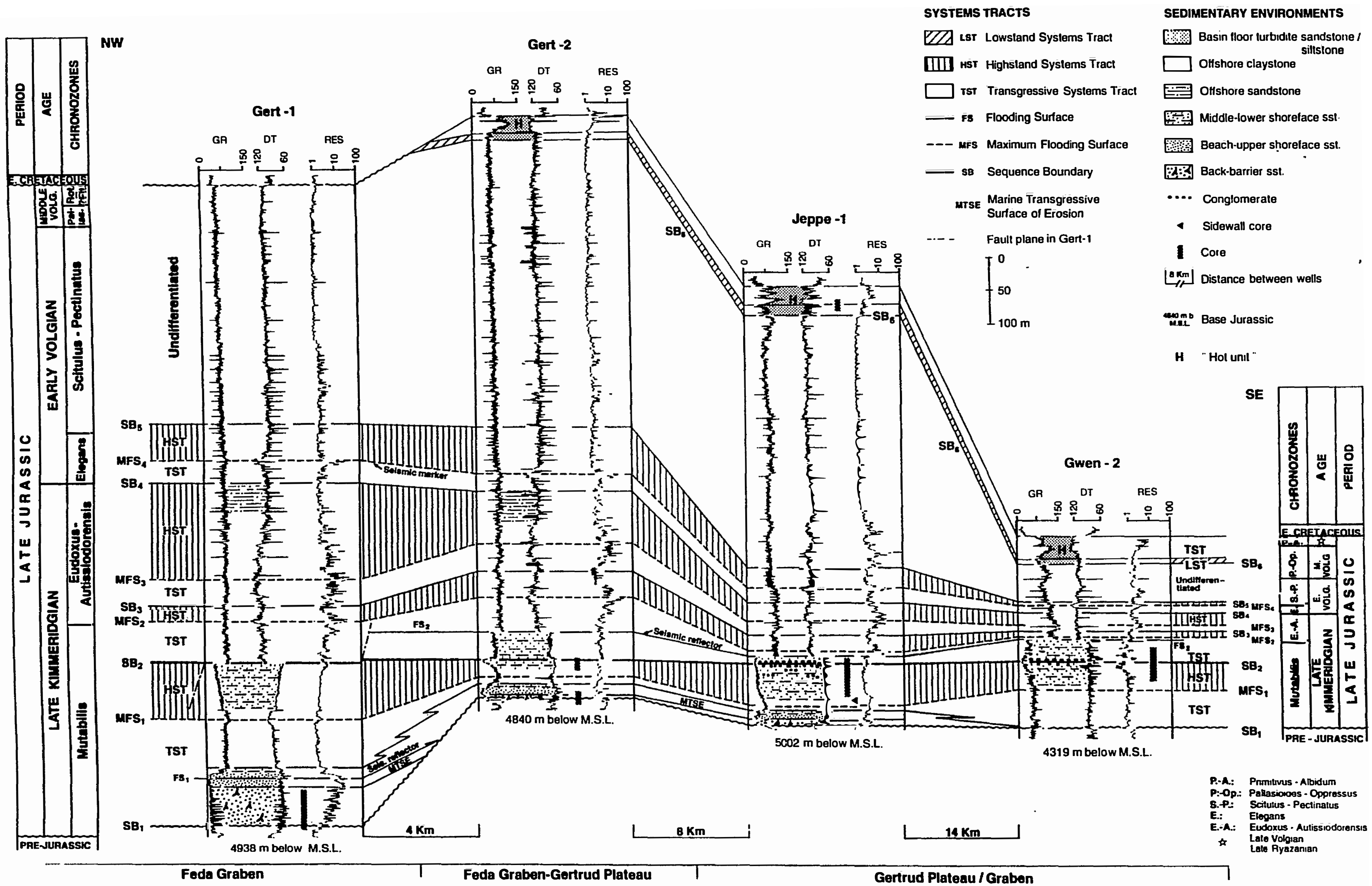
Gwen - 2

Johannessen (in prep)

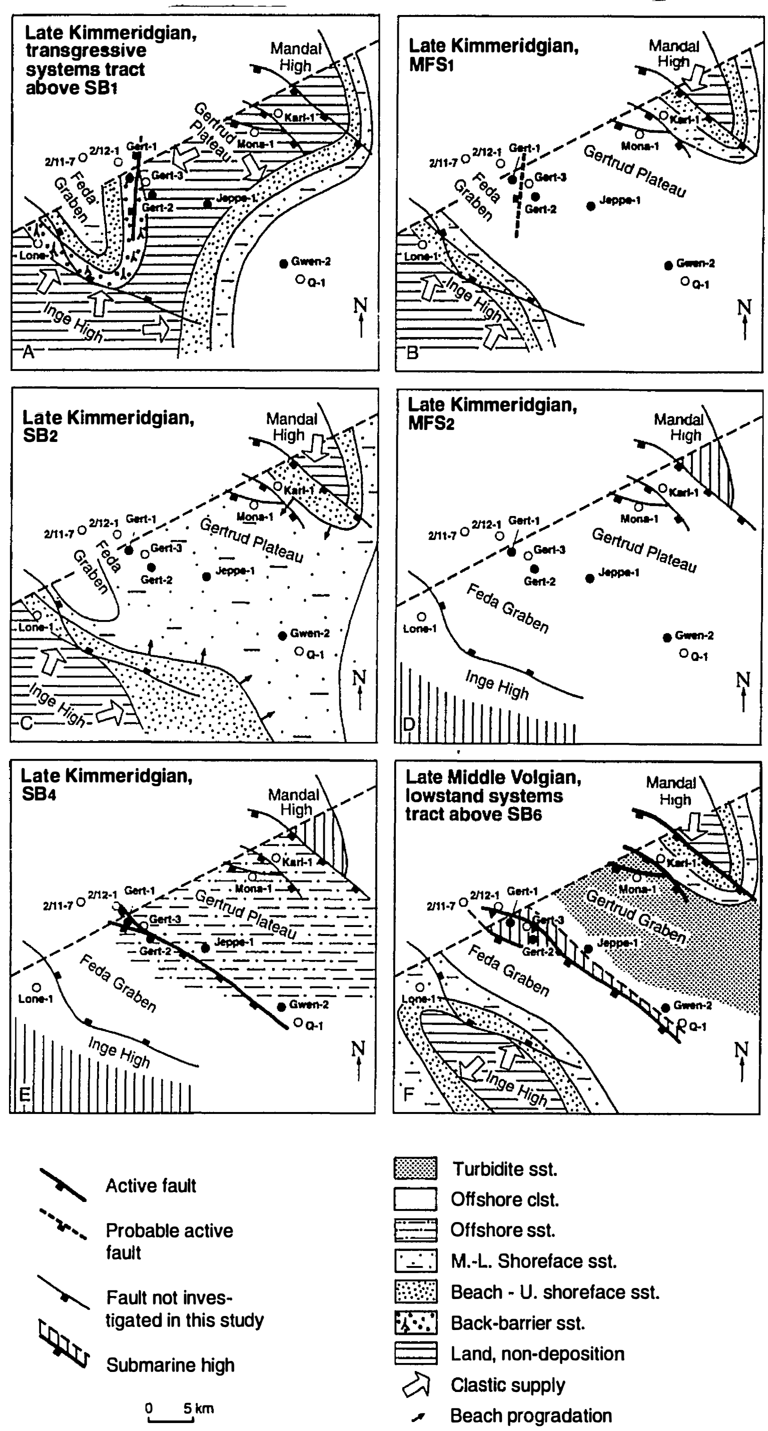
Fig. 15

Johannessen et al. (1996)

Fig. 16



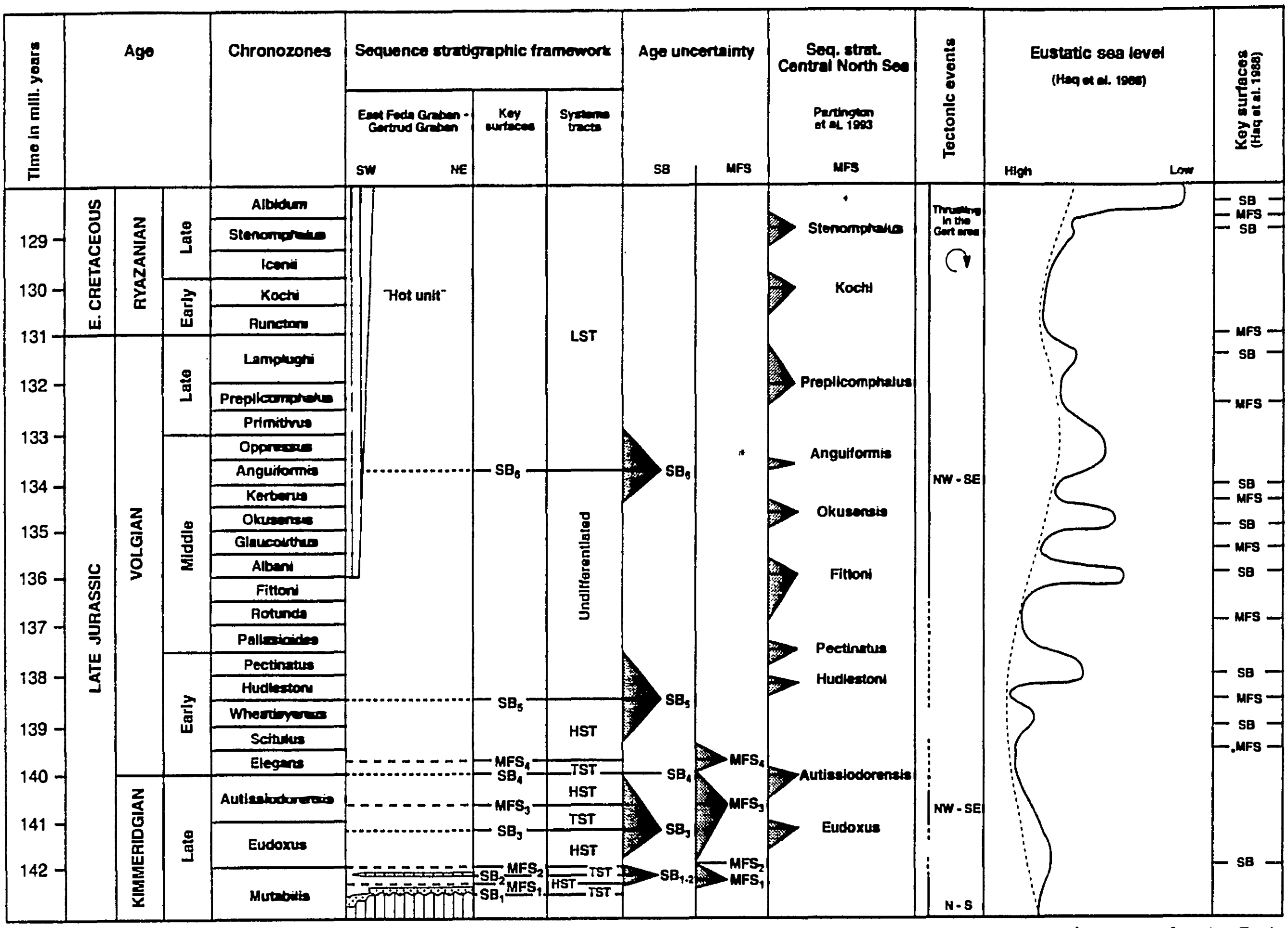
Sequence stratigraphic correlations of the Upper Jurassic succession of the eastern Feda Graben and the Gertrud Plateau/Graben. For location see *Figure 1*



Late Jurassic palaeogeography of the northernmost part of the Danish Central Trough

Johannessen et al. (1996)

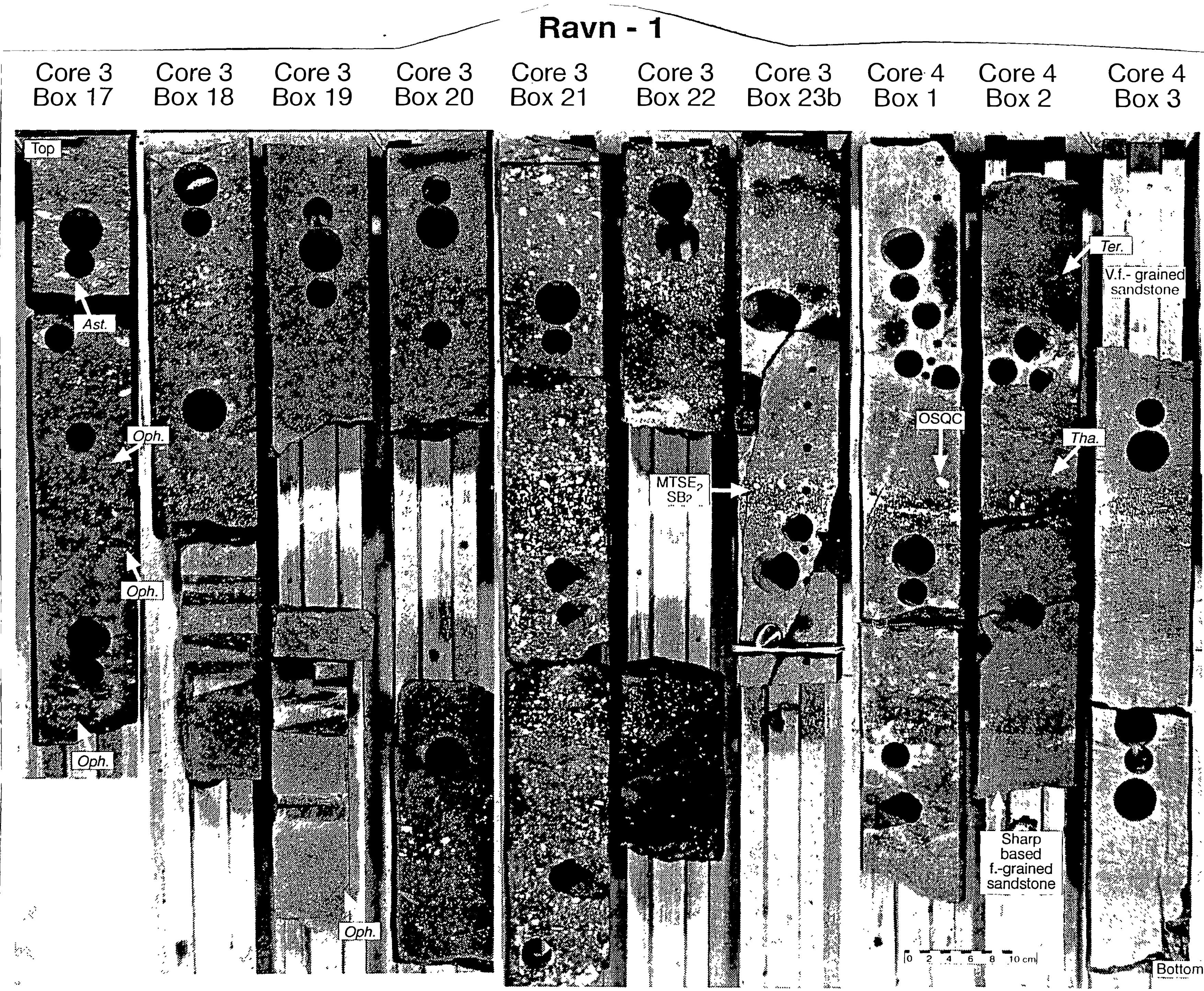
Fig. 17



Time stratigraphic correlation chart of sequence stratigraphic key surfaces, systems tracts and tectonic events for the Feda Graben–Gertrud Graben area. The eustatic sea-level curve and key surfaces of Haq *et al.* (1988) are presented so comparison is possible. The absolute ages are from Haq *et al.* (1988)

Johannessen et al (1996)

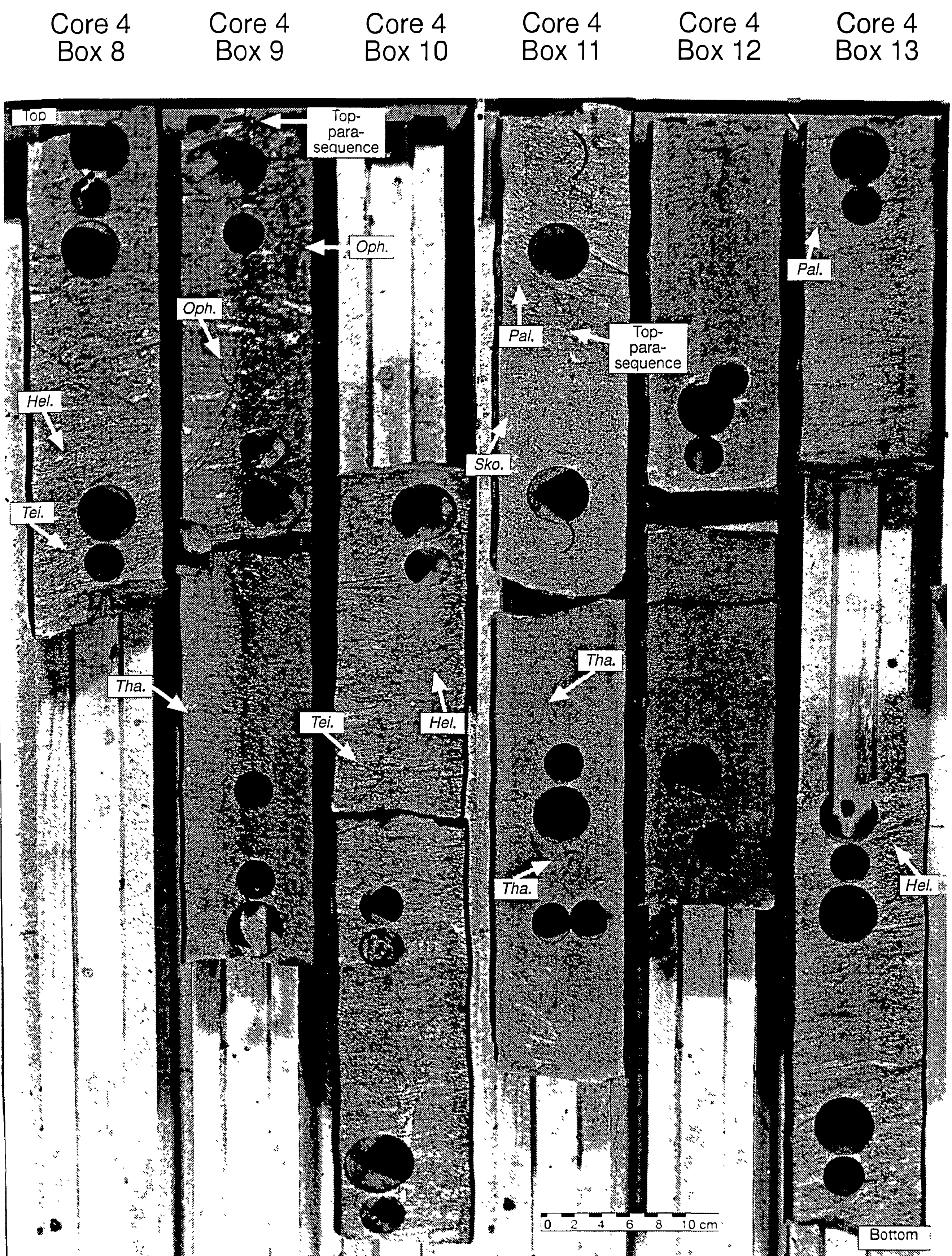
Fig. 18



Johannessen (in prep)

Fig. 19

Ravn - 1

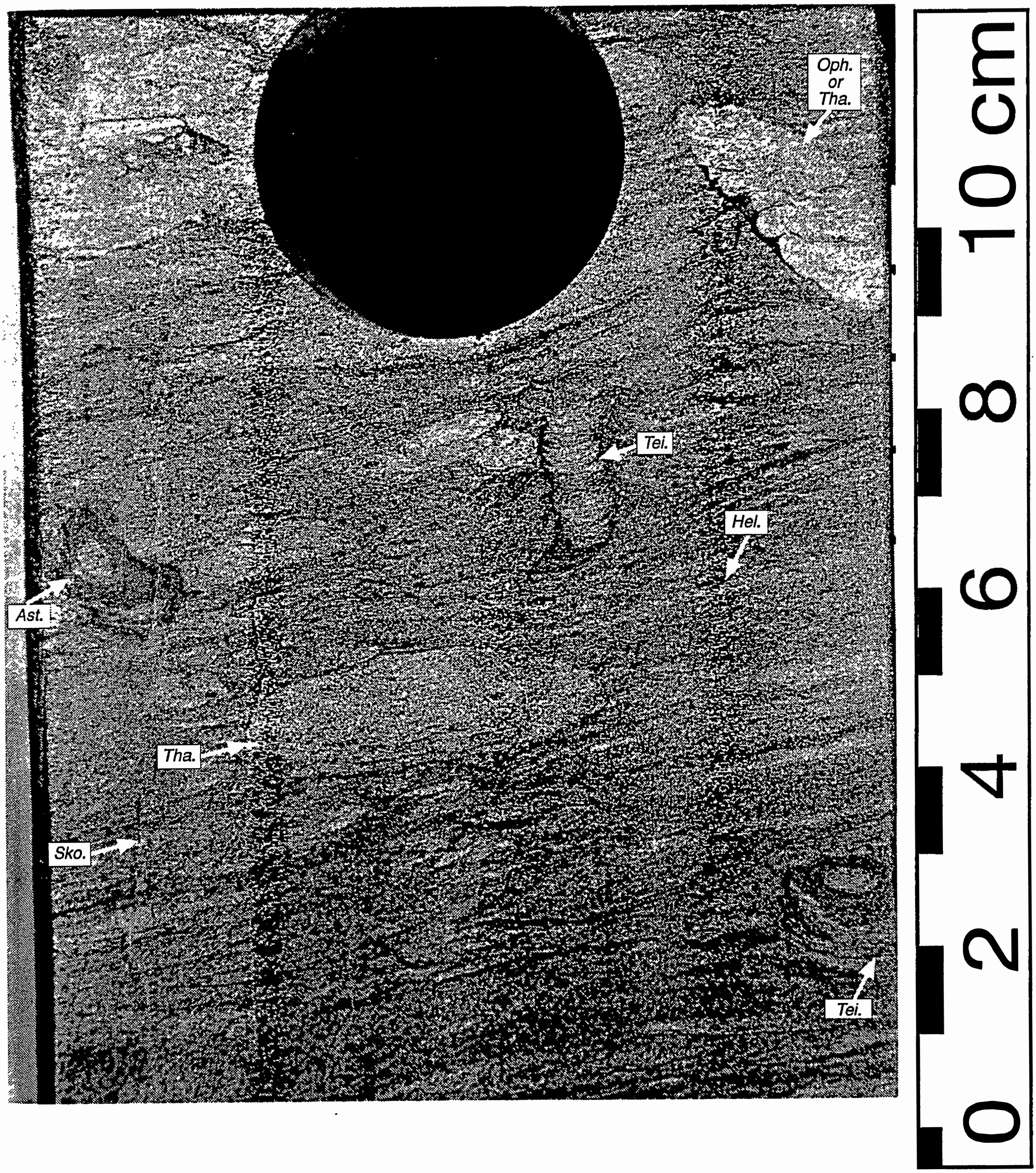


Johannessen (in prep)

Fig. 20

Ravn - 1

Core 5
Box 10

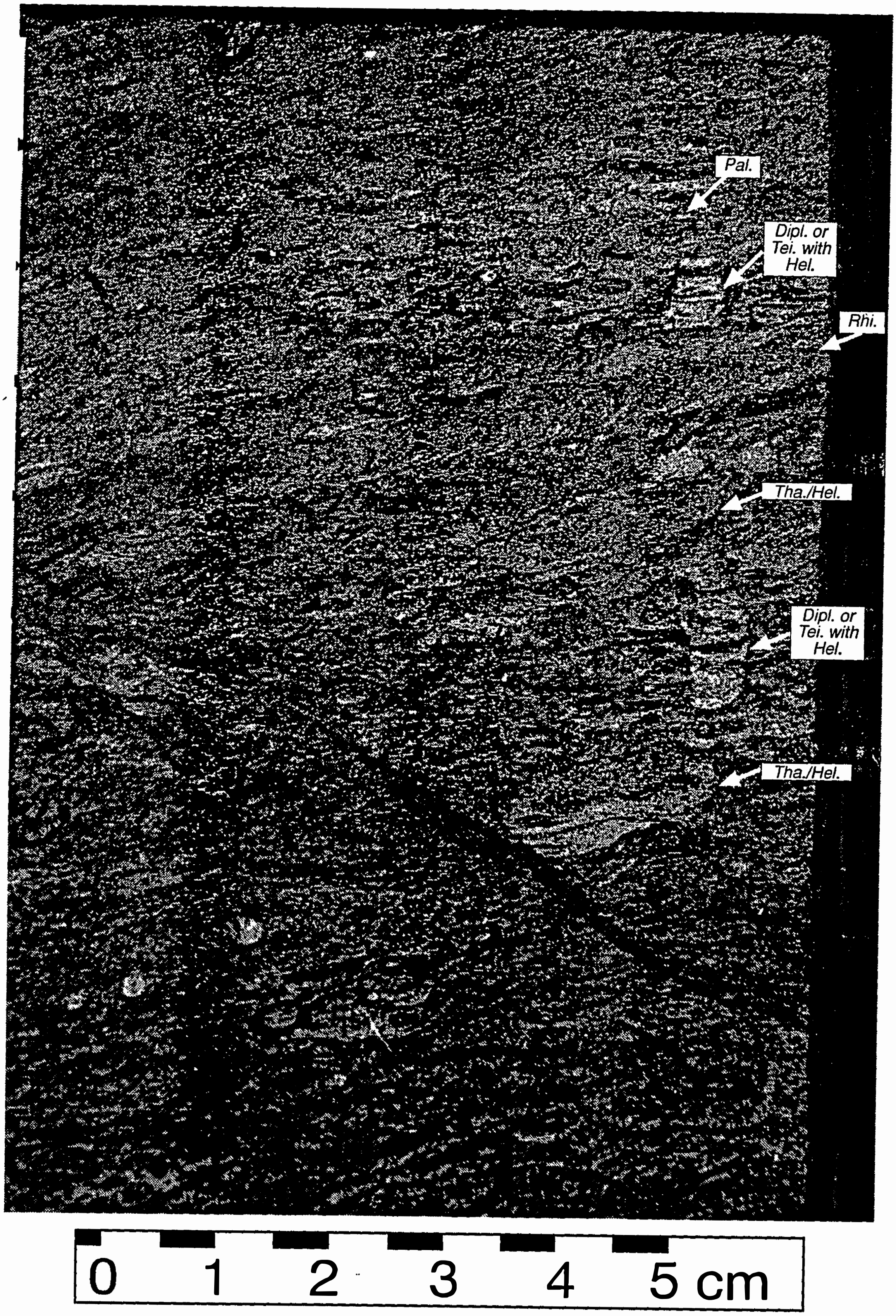


Johannessen (in prep)

Fig. 21

Ravn - 1

Core 4
Box 8

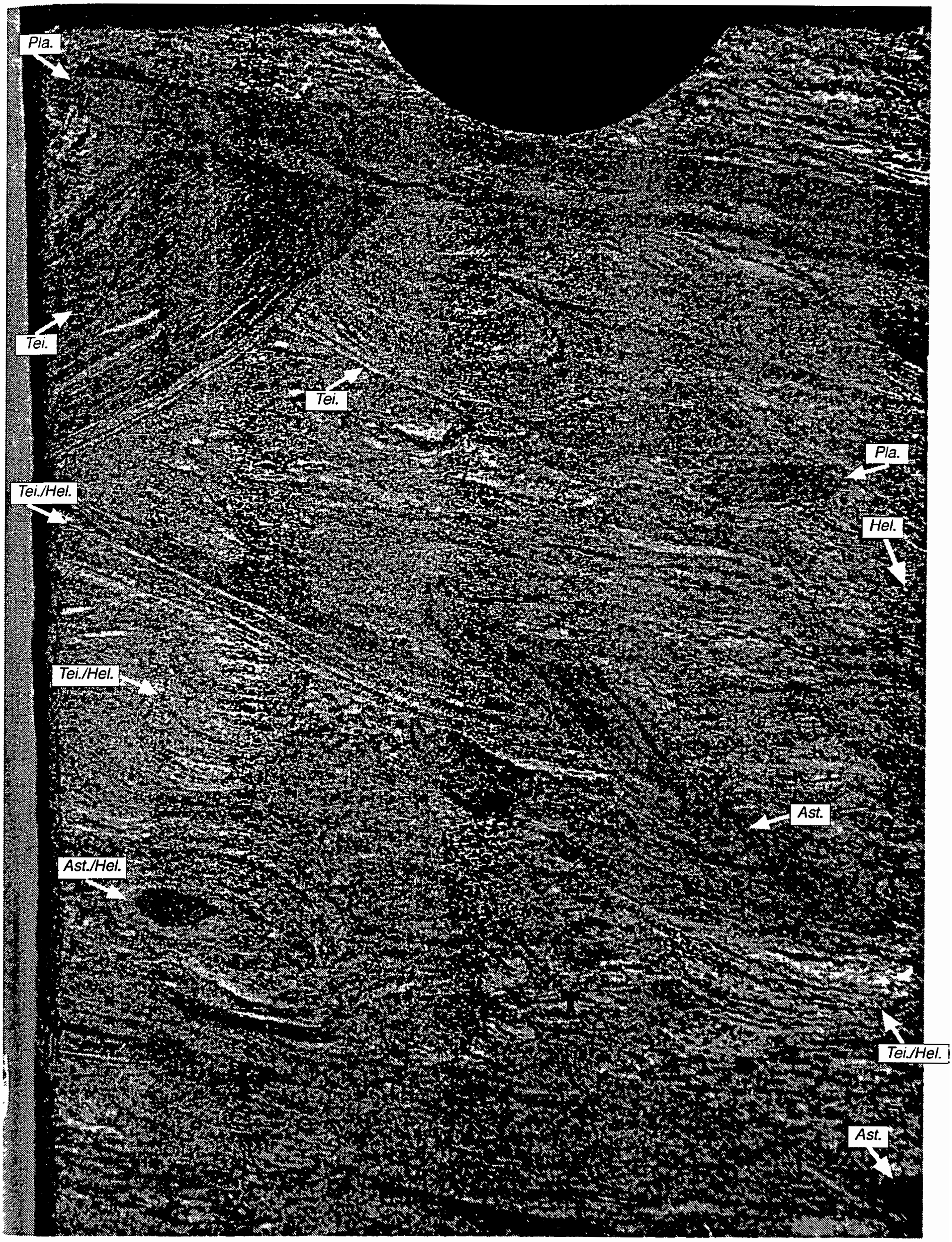


Johannessen (in prep)

Fig. 22

Ravn - 1

Core 2
Box 12



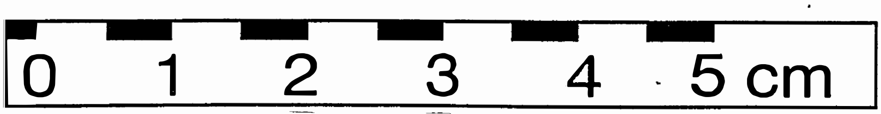
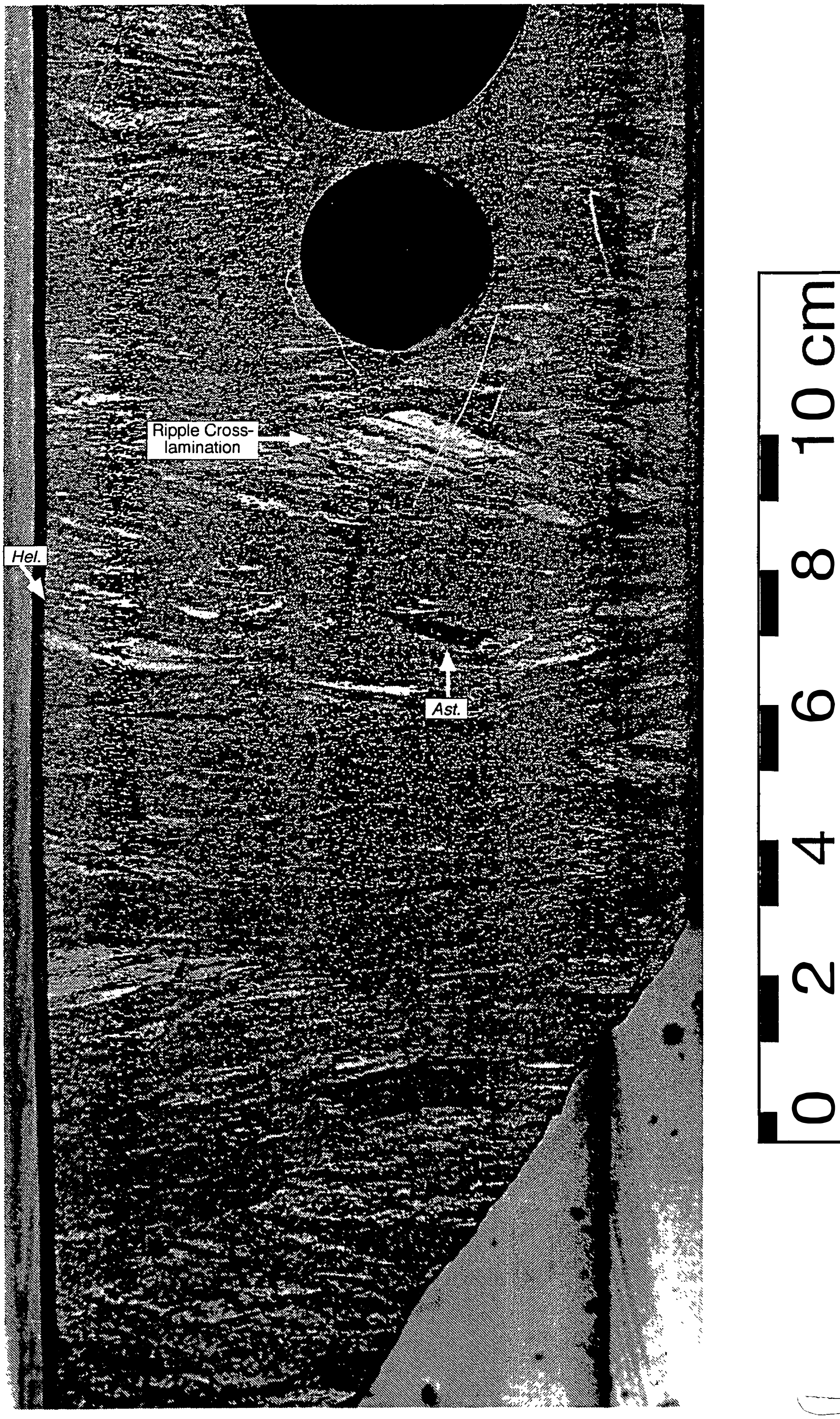


Fig. 23

Johannessen (in prep)

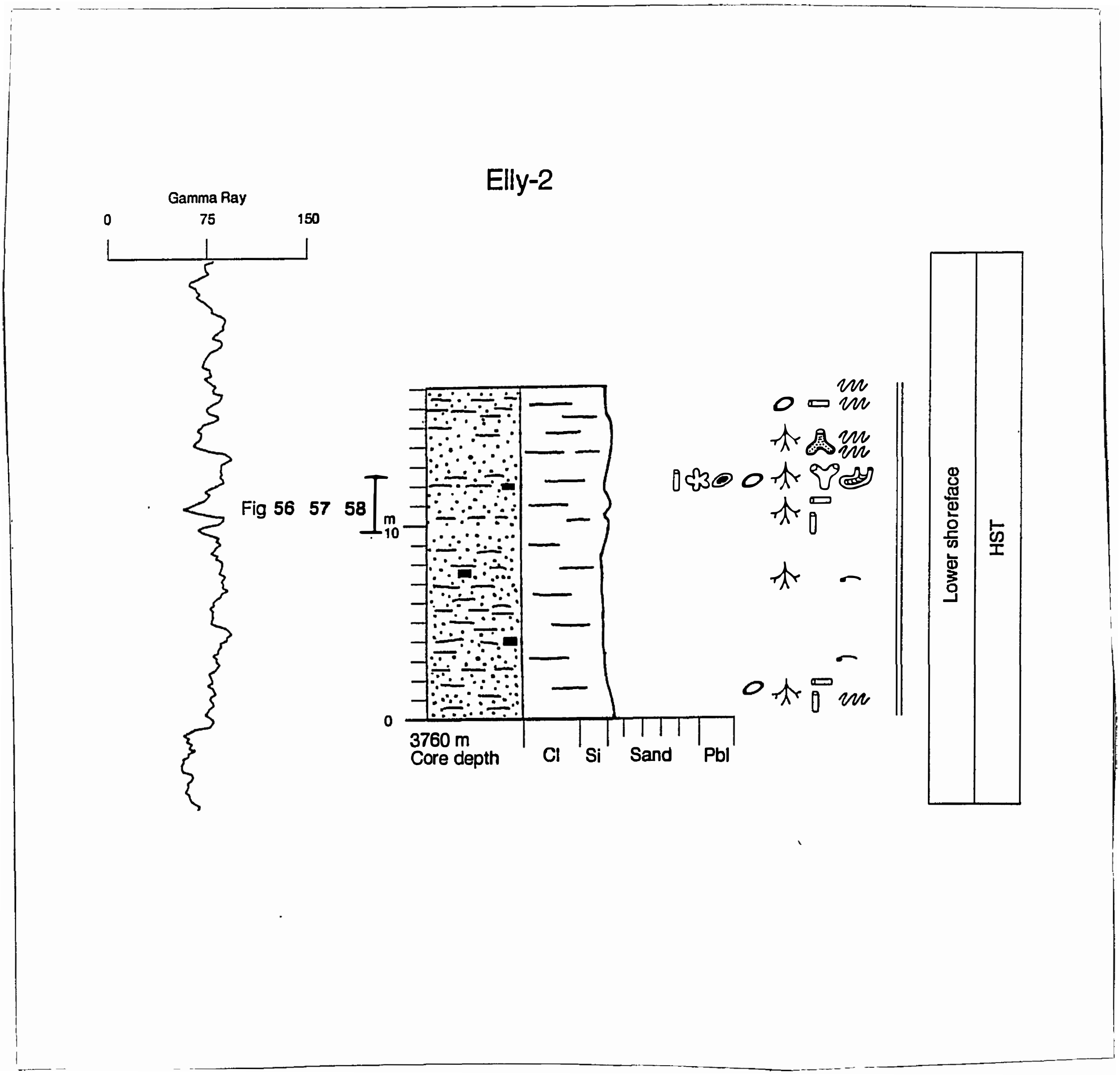
Ravn - 1

Core 5
Box 5



Johannessen (in prep)

Fig. 24



Johannessen (in prep)

Fig. 25

Elly - 2

Core 1 Box 7 | Core 1 Box 8 | Core 1 Box 9

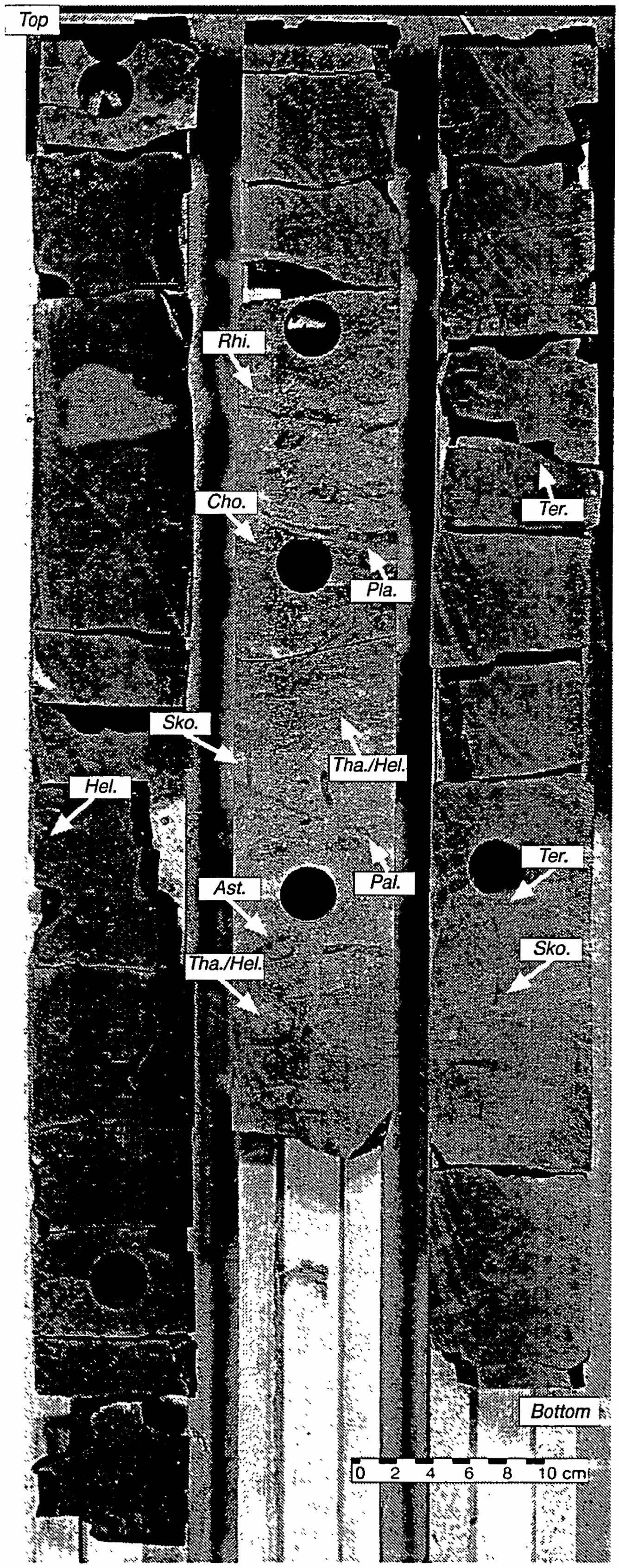
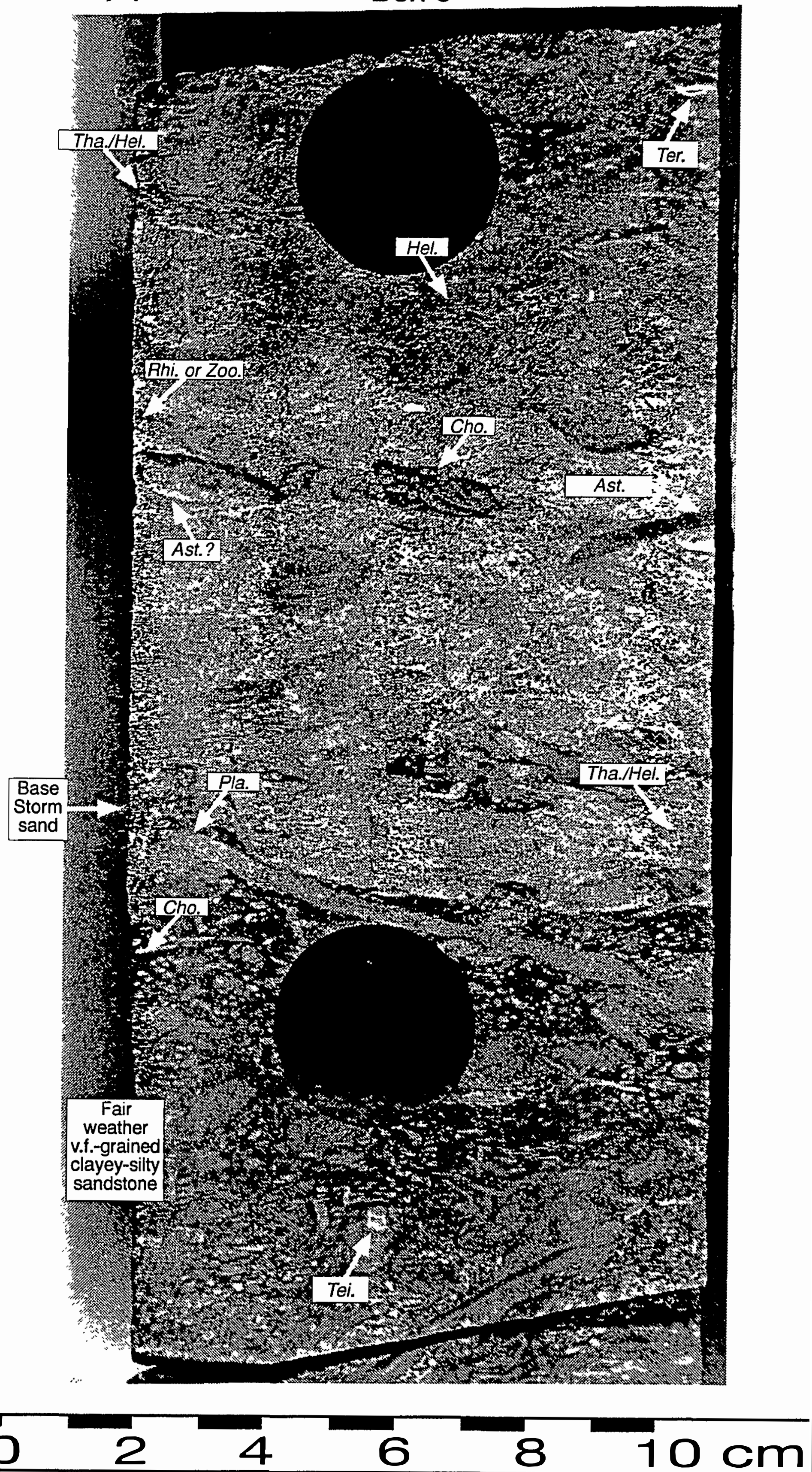


Fig. 26

Johannessen (in prep)

Elly - 2

Core 1
Box 8

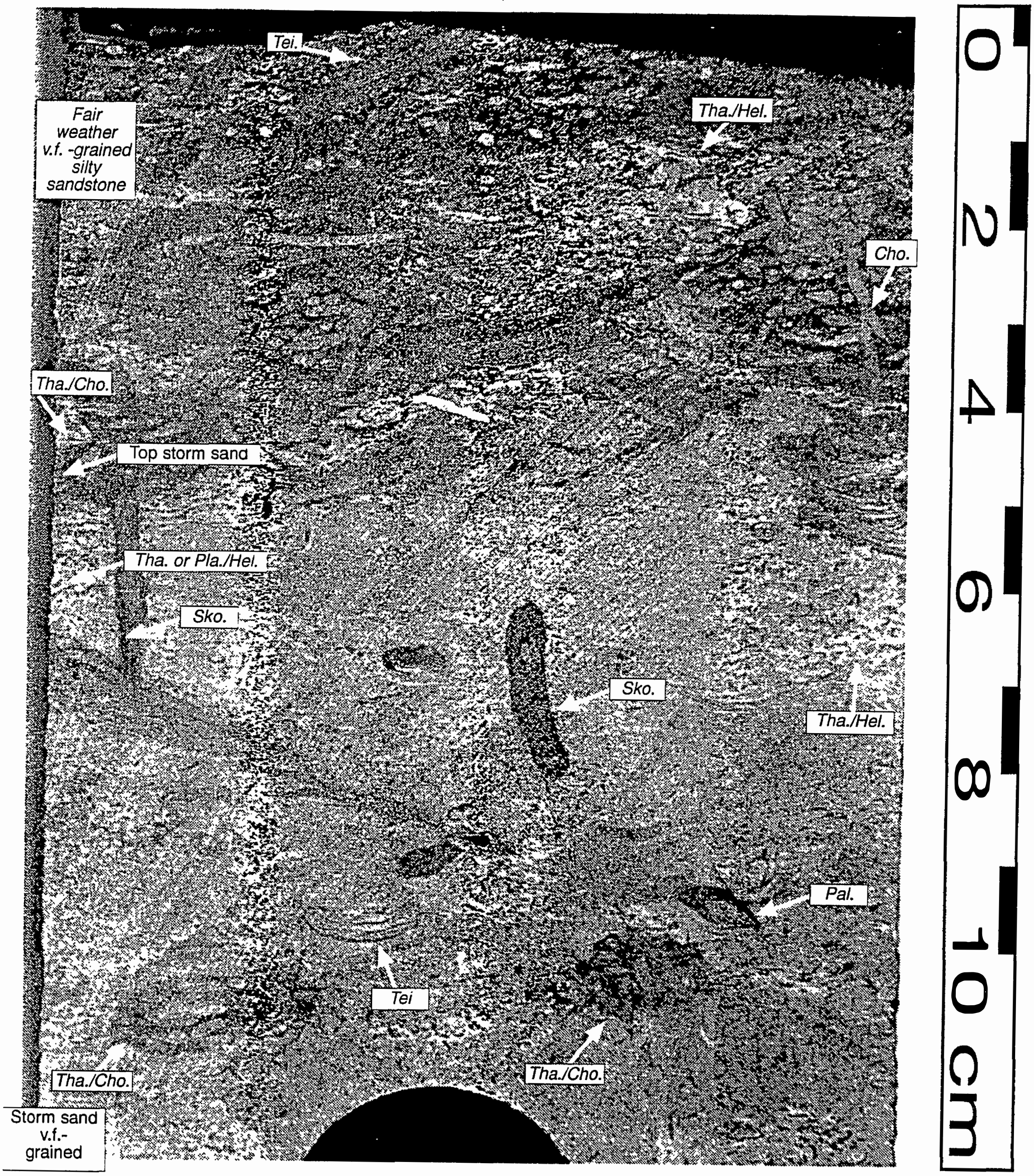


Johannessen (in prep)

Fig. 27

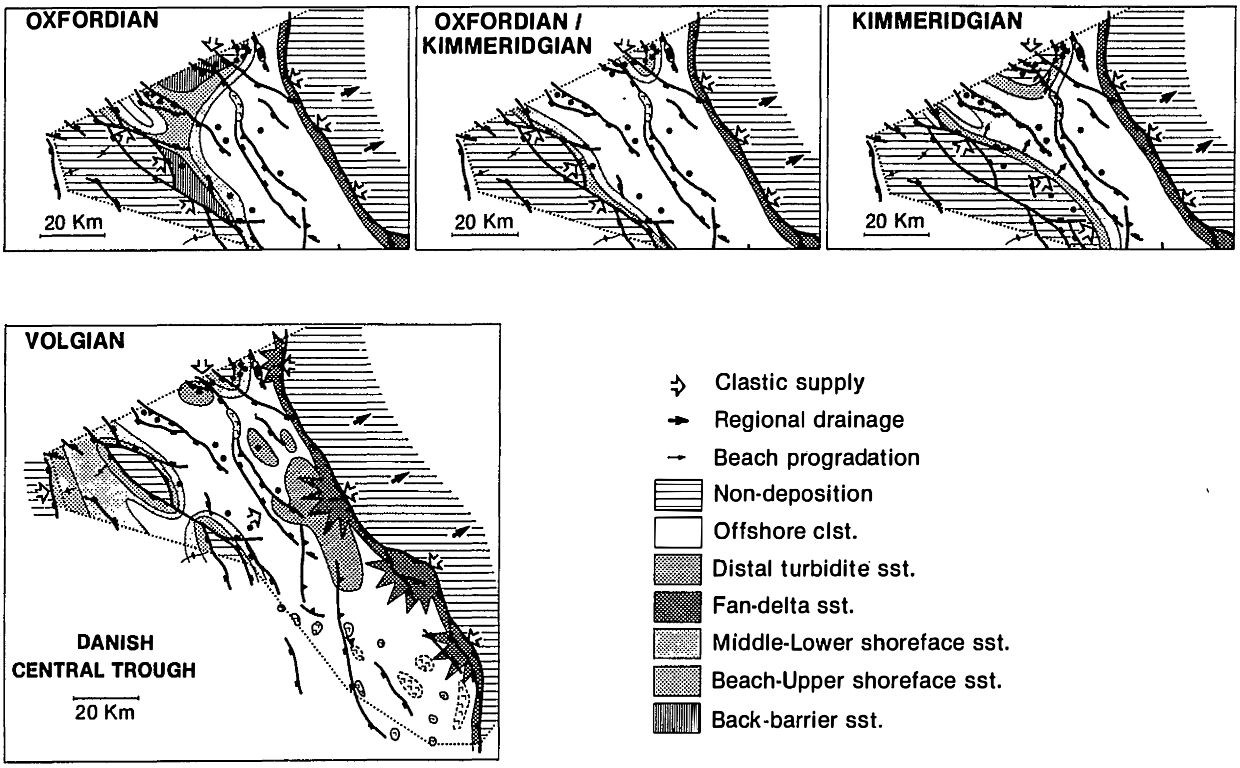
Elly - 2

Core 1
Box 8



Johannessen (in prep)

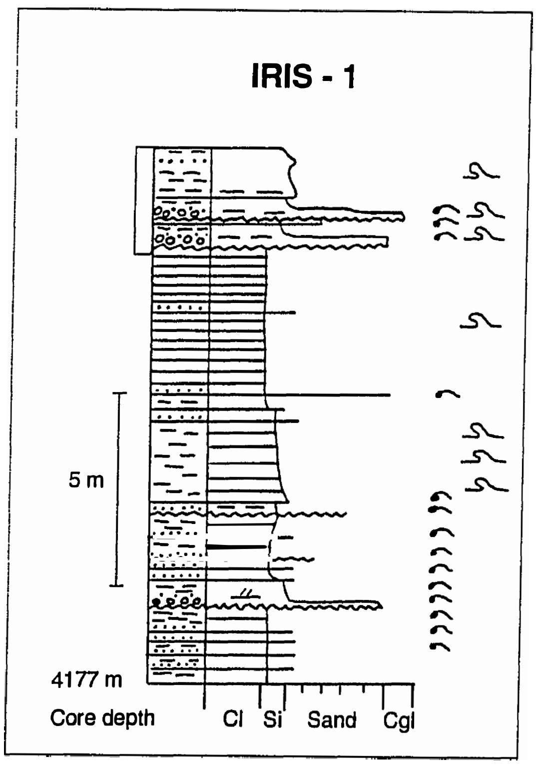
Fig. 28



Late Jurassic palaeogeography of the northernmost part of the Danish Central Trough. Transgressive upper shoreface and back-barrier sandstones of the basal sandstone unit were deposited during the Late Oxfordian. Maximum transgression occurred during the Oxfordian–Kimmeridgian transition when the offshore claystones of the Lola Formation were deposited. Regressive middle to upper shoreface sandstones of the Heno Formation were deposited during the Late Kimmeridgian. The shoreface prograded towards the SW on the Gertrud Plateau. On the Heno Plateau, the shoreface prograded towards the NE. Shoreface sandstones were probably deposited in the westernmost part of the Danish Central Trough simultaneously with the onset of subsidence of the Grensen Nose and Outer Rough Basin during the Middle Volgian. Fan-delta and distal turbidite sandstones were also deposited at the easternmost margin of the Central Trough against the Ringkøbing Fyn High, during the Middle Volgian.

Johannessen & Andsbjerg (1993)

Fig. 29

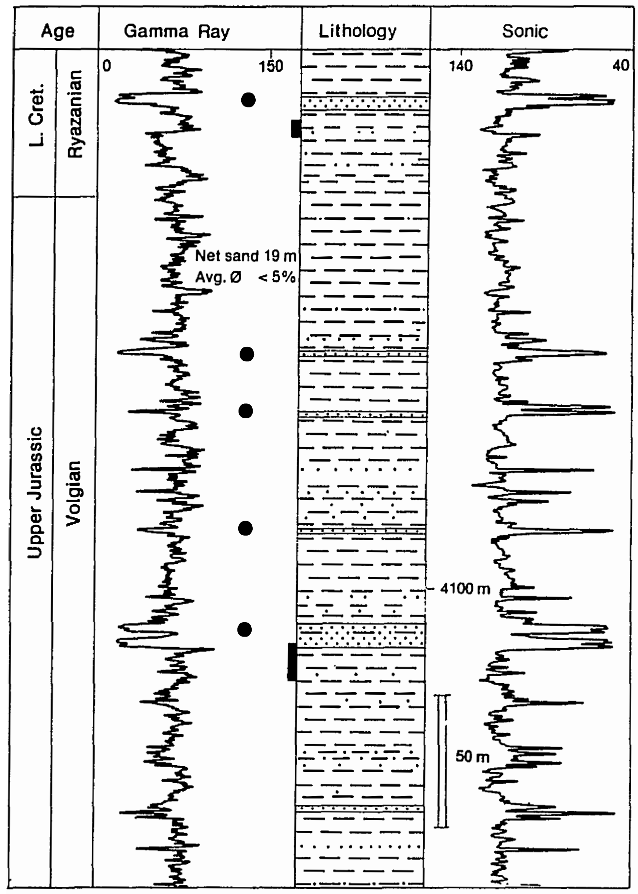


Sedimentological core logs from the Farsund Formation of the Iris-1 well representing turbidite sandstones.

Johannessen (in prep)

Fig. 30

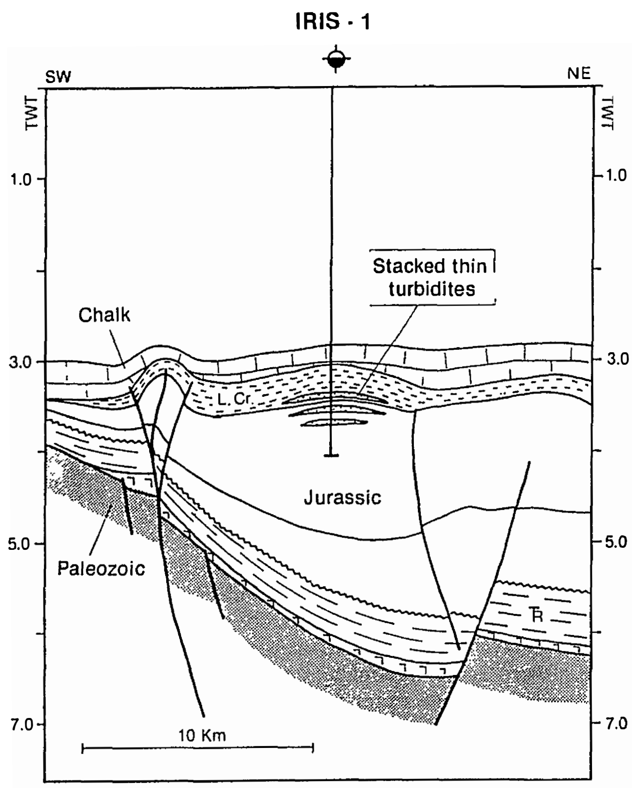
IRIS-1



Upper Jurassic to Lower Cretaceous distal turbidite sandstone reservoirs within the claystones of the Farsund Formation in the Iris-1 well, Tail End Graben

Damtoft et al. (1992)

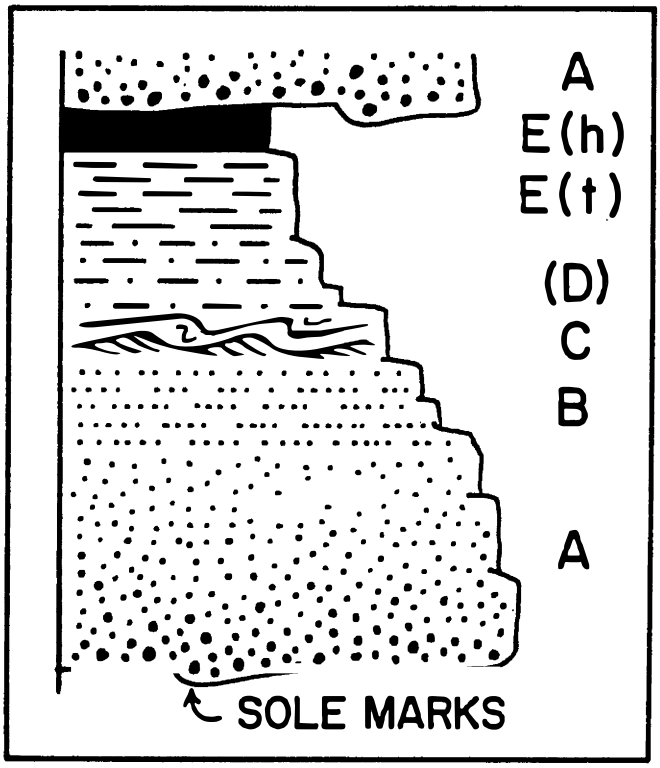
Fig. 31



Geosection through the Iris structure in the northern part of the Tail End Graben

Damtoft et al. (1992)

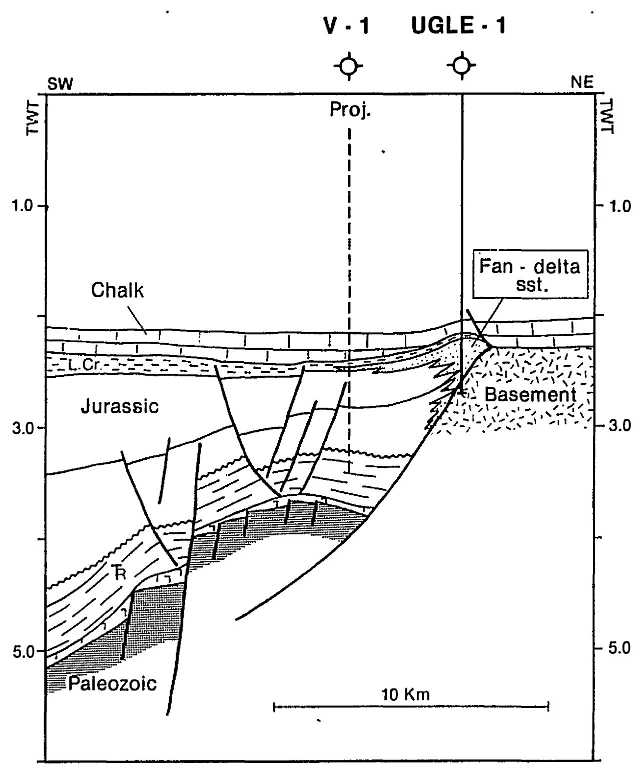
Fig. 32



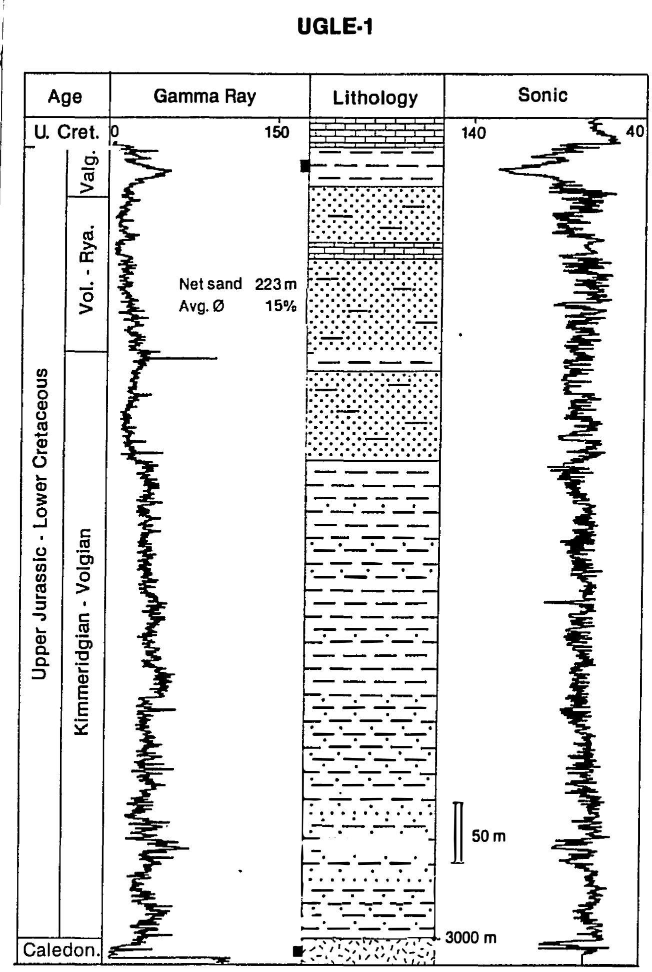
Bouma (1962) sequence; division A is structureless, B is parallel-laminated sand, C is rippled and/or convoluted, (D) is hard to see in weathered or tectonized outcrops, and consists of parallel-laminated silt and mud. The pelitic interval E is partly of turbidite origin (t) and partly hemipelagic (h).

Bouma (1962)

Fig. 33



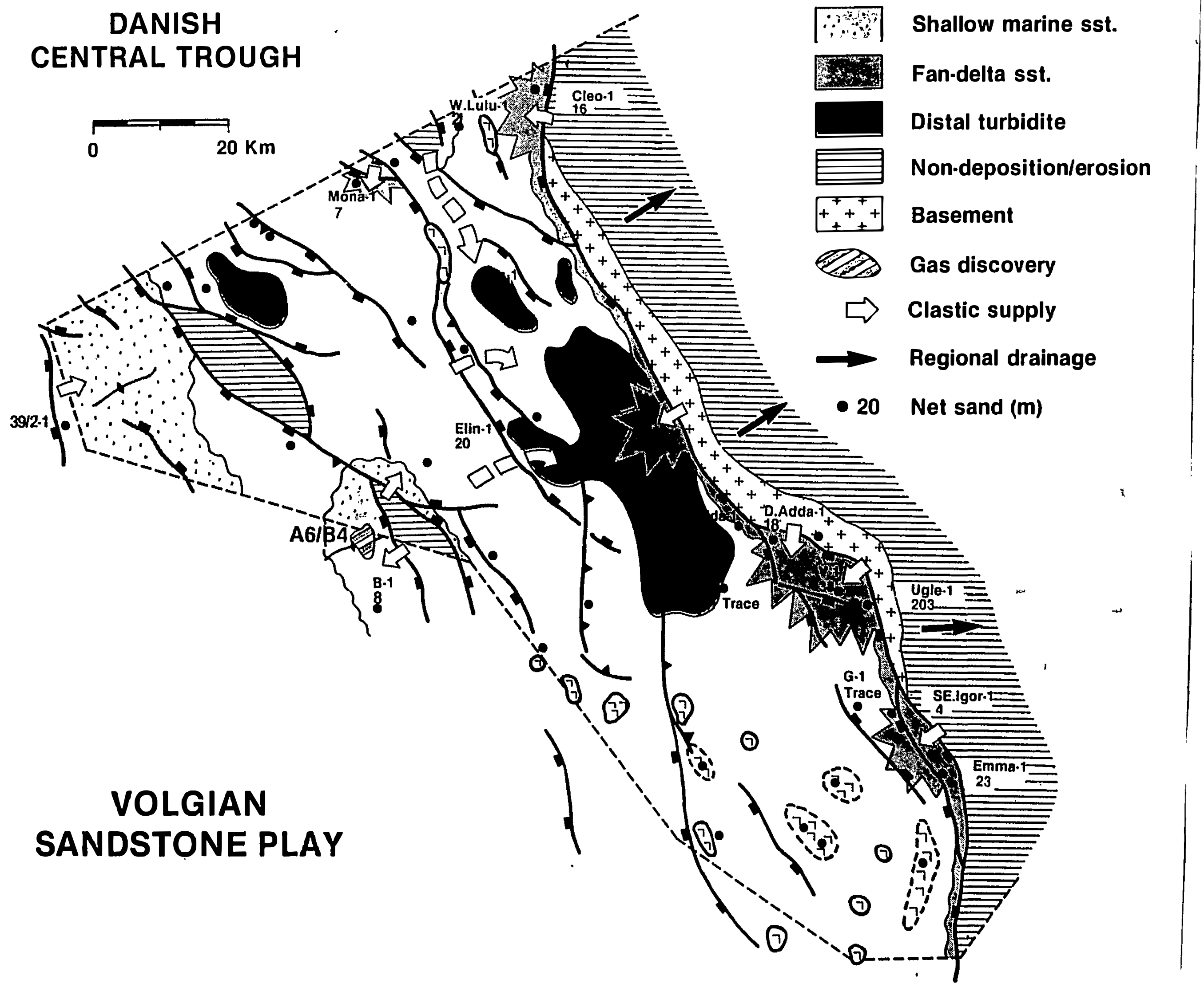
Geosection through the Ugle structure along the main graben edge fault on the Poul Plateau



. Upper Jurassic to Lower Cretaceous fan-delta sandstone reservoir of the Poul and Vyl Formations in the Ugle-1 well, Poul Plateau. Visual inspection of sidewall cores indicates a lower porosity than the log-derived porosity of 15%

Damtoft et al. (1992)

Fig.34



Upper Jurassic – Lower Cretaceous, Volgian to Valanginian sandstone play map

Damtoft et al. (1992)

Fig.35