Wandel Sea Basin, eastern North Greenland

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The Wandel Sea Basin in eastern North Greenland is the northernmost of a series of fault-bounded Late Palaeozoic – Early Tertiary basins exposed along the eastern and northern margin of Greenland (Fig. 1). The basin and the surrounding shelf areas are located in a geologically complex region at the junction between the N–S trending Caledonian fold belt in East Greenland and the E–W trending Ellesmerian fold belt in North

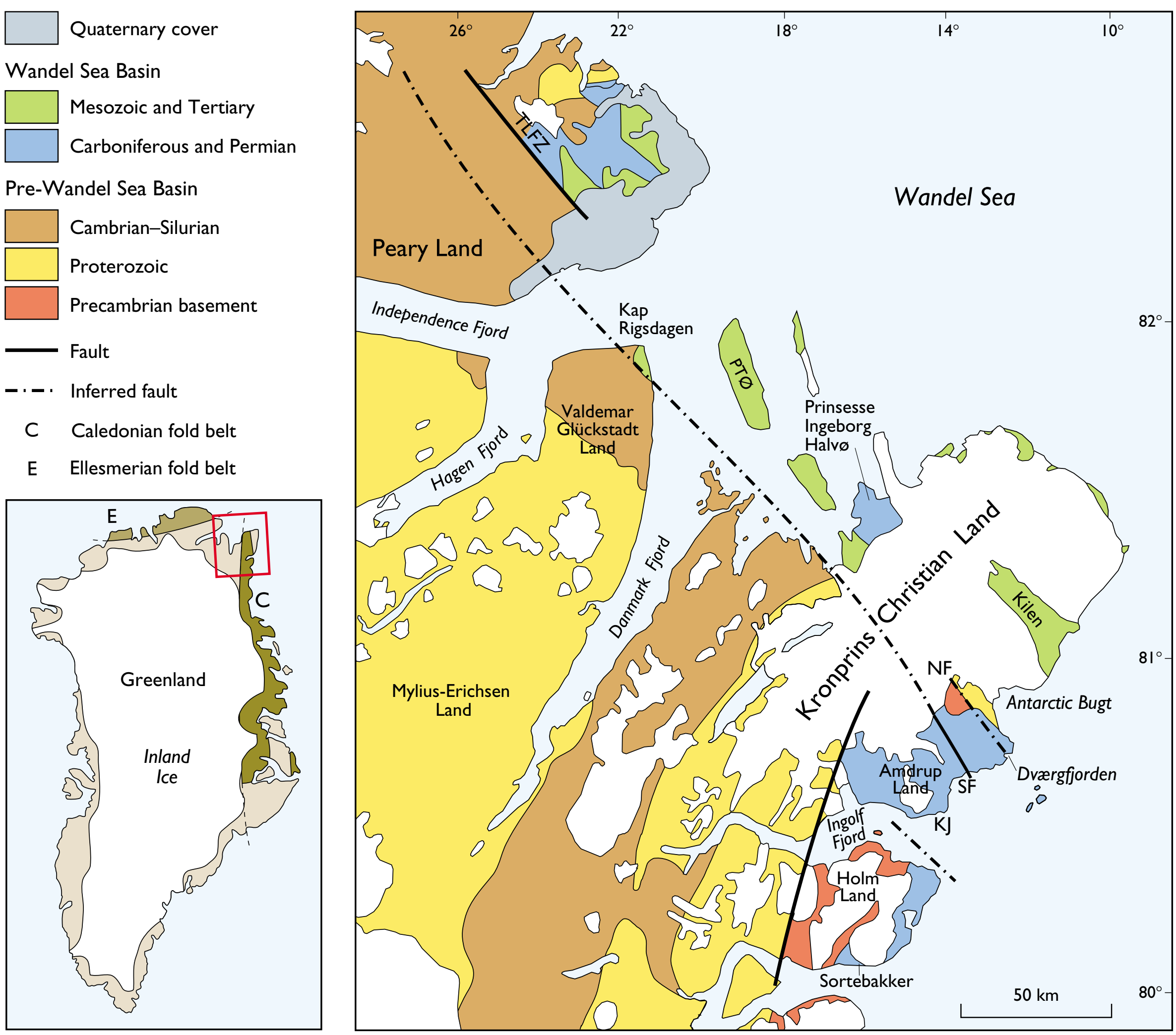
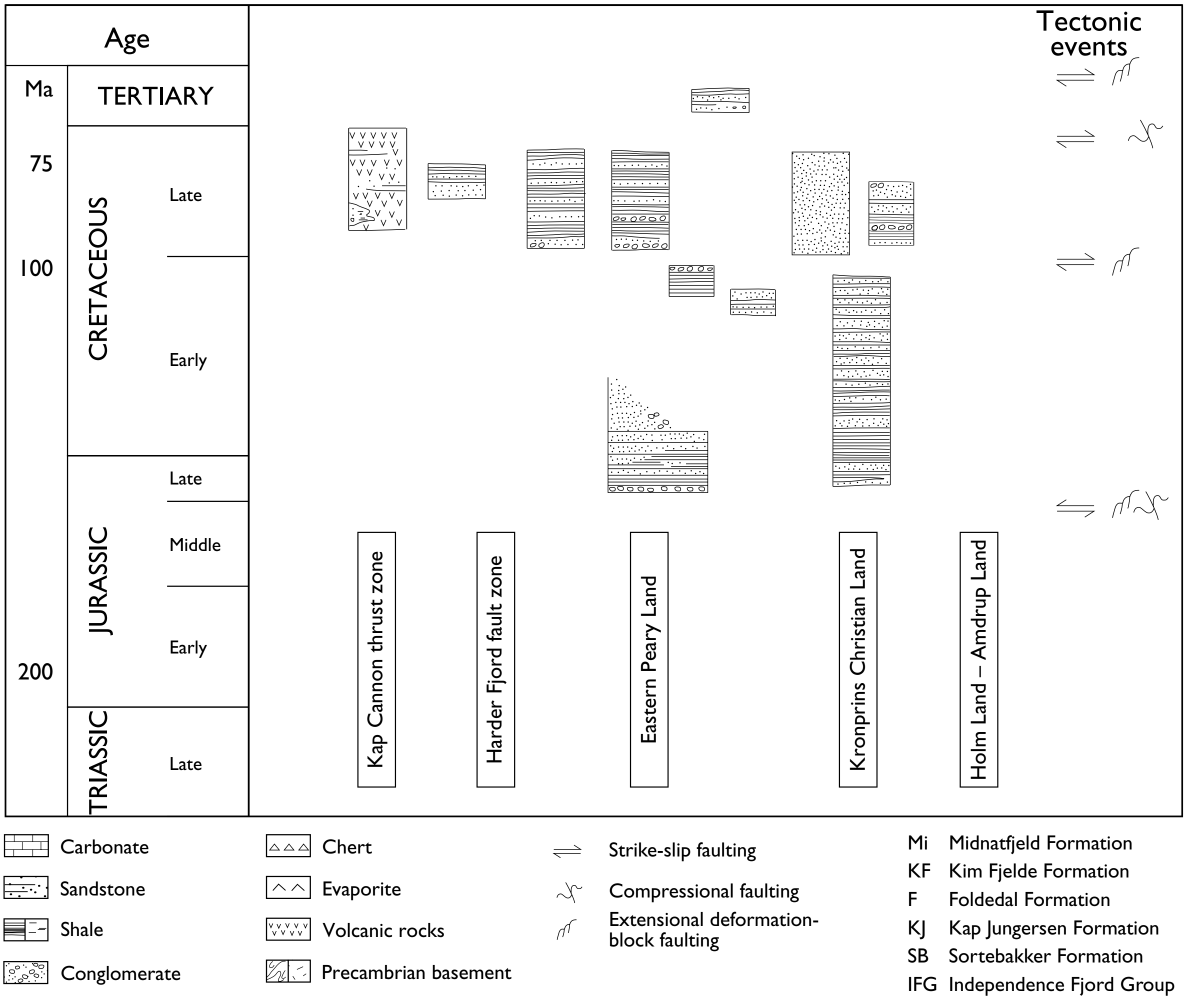


Fig. 1. Simplified geological map of the Wandel Sea Basin with locations mentioned in the text. SF: Sommerterasserne fault, NF: north Amdrup Land fault, PTØ: Prinsesse Thyra Ø, KJ: Kap Jungersen, TLFZ: Trolle Land fault zone. Modified from Stemmerik *et al.* (1994).



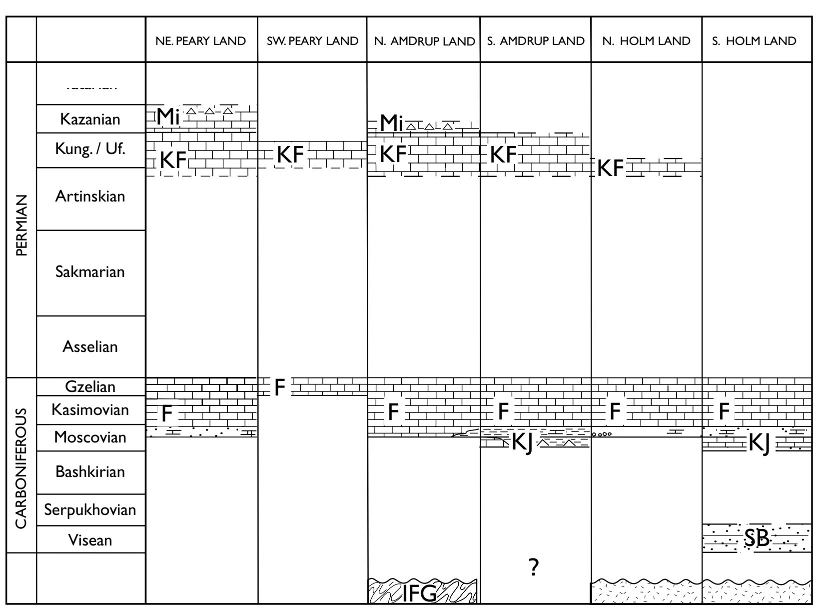


Fig. 2. Simplified stratigraphy of the Wandel Sea Basin. **Above**: Distribution of Mesozoic–Tertiary sediments in the northern part of the basin. **Below**: Scheme showing correlation of the Upper Palaeozoic deposits in the modelled areas.

Greenland, and along the zone of later, Tertiary, continental break-up. The Wandel Sea Basin started to develop during the Carboniferous as a result of extension and rifting between Greenland and Norway, and Greenland and Spitsbergen (Håkansson & Stemmerik 1989), and was an area of accumulation during the Early Carboniferous – Early Tertiary period. Two main epochs of basin evolution have been recognised during previous studies of the basin fill: an early (late Palaeozoic – early Triassic) epoch characterised by a fairly simple system of grabens and half-grabens, and a late (Mesozoic) epoch dominated by strike-slip movements (Håkansson & Stemmerik 1989). The Mesozoic epoch only influenced the northern part of the basin, north of the Trolle Land fault zone (Fig. 1). Thus the northern and southern parts of the basin have very different structural and depositional histories, and accordingly different thermal histories and hydrocarbon potential.

This paper summarises the results of a project supported by Energy Research Program (EFP-94), the purpose of which was to model the Wandel Sea Basin with special emphasis on hydrocarbon potential and late uplift history, and to provide biostratigraphic and sedimentological data that could improve correlation with Svalbard and the Barents Sea. It is mainly based on material collected during field work in Holm Land and Amdrup Land in the south-eastern part of the Wandel Sea Basin during 1993–1995 with additional data from eastern Peary Land (Stemmerik *et al.* 1996). Petroleum related field studies have concentrated on detailed sedimentological and biostratigraphic studies of the Carboniferous–Permian Sortebakker, Kap Jungersen, Foldedal and Kim Fjelde Formations in Holm Land and Amdrup Land (Fig. 2; Døssing 1995; Stemmerik 1996; Stemmerik *et al.* 1997). They were supplemented by a structural study of northern Amdrup Land in order to improve the understanding of the eastward extension of the Trolle Land fault system and possibly predict its influence in the shelf areas (Stemmerik *et al.* 1995a; Larsen 1996). Furthermore, samples for thermal maturity analysis and biostratigraphy were collected from the Mesozoic of Kap Rigsdagen and the Tertiary of Prinsesse Thyra Ø (Fig. 1).

Biostratigraphy and correlation

New biostratigraphic data were obtained from the Carboniferous–Permian, Jurassic and Tertiary intervals in the course of this project (Stemmerik *et al.* 1997; J.H. Callomon & I. Nilsson and S. Piasecki & J. Utting, unpublished data). These biostratigraphic data are important, not only as they form the basic framework for the basin modelling, but also because they allow correlation to the adjacent areas with greater confidence.

Early Carboniferous

The Lower Carboniferous Sortebakker Formation (Figs 2, 3) is the oldest unit of the Wandel Sea Basin. It rests directly on crystalline basement rocks affected by the Caledonian orogeny in southern Holm Land. The formation consists of more than 1000 m of fluvial deposits with a poorly preserved macroflora that suggests an Early Carboniferous age for the formation. During this study, a poorly preserved but stratigraphically confined microflora was found in the upper part of the formation (Stemmerik *et al.* 1997); the presence of *Tripartites distinctus, Raistrickia corynoges, Potoniespores delicatus* and *Savitrisporites nux* is indicative of the late Visean NM Zone of the West European system. This means that the upper part of the formation can be correlated with the Nordkapp Formation on Bjørnøya, the upper Billefjorden Group of Spitsbergen and the lower Traill Ø Group of East Greenland (Stemmerik *et al.* 1997). Sediments of this age also occur in the offshore areas of the Finnmark Platform in the southern Barents Sea (Bugge *et al.* 1995).

Late Carboniferous

The Carboniferous Kap Jungersen and Foldedal Formations show marked differences in depositional history and diagenesis between southern Amdrup Land, southern Holm Land and northern Amdrup Land. The succession in Holm Land consists of laterally widespread mixed siliciclastic-limestone cycles whereas at Kap Jungersen the succession consists of more laterally confined cycles that locally form large platforms (Stemmerik & Elvebakk 1994; Stemmerik 1996). The Kap Jungersen Formation is absent in northern Amdrup Land where the Carboniferous succession is much thinner and composed mainly of dolomitised limestones.

The Kap Jungersen Formation has been dated by fusulinids (Dunbar *et al.* 1962; Stemmerik & Håkansson 1989; Nilsson *et al.* 1991; Nilsson 1994; Stemmerik *et al.* 1996). Based on field work in 1993–1995, the zonation of the successions in Holm Land and Amdrup Land has been considerably refined, and it is now possible to correlate on fusulinid zone level both within the basin and with the Barents Sea succession. The oldest marine sediments in Holm Land and Amdrup Land include a fusulinid assemblage dominated by *Profusulinella* spp., *Pseudostaffella* spp., *Eofusulina* aff. *E. triangula* and ?*Aljutovella* sp.. This assemblage shows close similarities to the early Moscovian *Profusulinella* assemblage of Dunbar *et al.* (1962).

The overlying Foldedal Formation contains seven Late Carboniferous fusulinid assemblages. The lowest *Beedeina* fusulinid assemblage is characterised by *Beedeina* spp., *Wedekindellina* ex.gr. *uralica*, *Fusulinella* spp., *Neostaffella greenlandica, N. sphaeroidea* and *Taitzeoella* sp. and is considered to be of earliest late Moscovian age, whereas the *Fusulinella* ex.gr. *bocki* assemblage overlies sediments of latest Moscovian age. Next follow sediments with a *Protriticites–Quasifusulinoides* assemblage of possible latest Moscovian to earliest Kasimovian age. A distinct middle Kasimovian assemblage appears to be missing although *Montiparus* is recognised at one level at Antarctic Bugt; this genus first occurs in middle Kasimovian strata of the Russian Platform and disappears close to the base of the Gzelian. Upper Kasimovian strata are characterised by a *Rauserites* ex.gr. *simplex* assemblage with primitive *Rauserites* spp., *Schubertella* spp. and *Pseudofusulinella* spp. This fauna can be correlated with the *Rauserites* ex.gr. *simplex* assemblage of Nilsson (1994). The Gzelian succession can possibly be subdivided into three fusulinid assemblages. The presence of *Rauserites* aff. *R. rossicus* indicates an early to middle Gzelian age whereas a fauna with *Jigulites* sp., *Rauserites* spp. and primitive *Schellwienia* spp. is of possible middle Gzelian age. The youngest fusulinid fauna recorded in Holm Land and Amdrup Land comprises species of *Schellwienia* and ?*Daixinia* and may be of late Gzelian age.

Middle to Late Permian

Sediments belonging to the Upper Permian Midnatfjeld Formation were found to be widespread in a downfaulted area in northern Amdrup Land where they are conformably overlain by > 70 m of fine-grained sandstones and siltstones of Jurassic age (Stemmerik *et al.* 1994, 1995a, b). The Midnatfjeld Formation consists in this area of bioturbated chert-rich limestones and shales and thin, laterally widespread horizons of bioturbated chert, which conformably overlie older Permian limestones of the Kim Fjelde Formation. Middle to Late Permian sediments of the Kim Fjelde and Midnatfjeld Formations (Stemmerik *et al.* 1996) have mainly been dated by palynomorphs with additional information from conodonts, small foraminifers and brachiopods (Dunbar *et al.* 1962; Stemmerik & Håkansson 1989; Stemmerik *et al.* 1996). Based on palynomorphs, the Kim Fjelde Formation at Kap Jungersen is dated as Kungurian. The base of the Midnatfjeld Formation in northern Amdrup Land contains a microflora of Kazanian age (S. Piasecki & J. Utting, personal communication 1997).

Upper Jurassic

A > 70 m thick succession of post-Permian siliciclastic sediments are present locally in northern Amdrup Land. The sediments are preserved in the cores of synforms north of the Sommerterrasserne fault and provide a maximum age for the deformation in northern Amdrup Land. They have been dated as Oxfordian (Late Jurassic) by J.H. Callomon (personal communication 1996) on the basis of two ammonite fragments. The sequence can thus be correlated with the Ladegårdsåen Formation in eastern Peary Land and these sediments record a basin-wide onset of sedimentation following a mid-Triassic – mid-Jurassic hiatus.

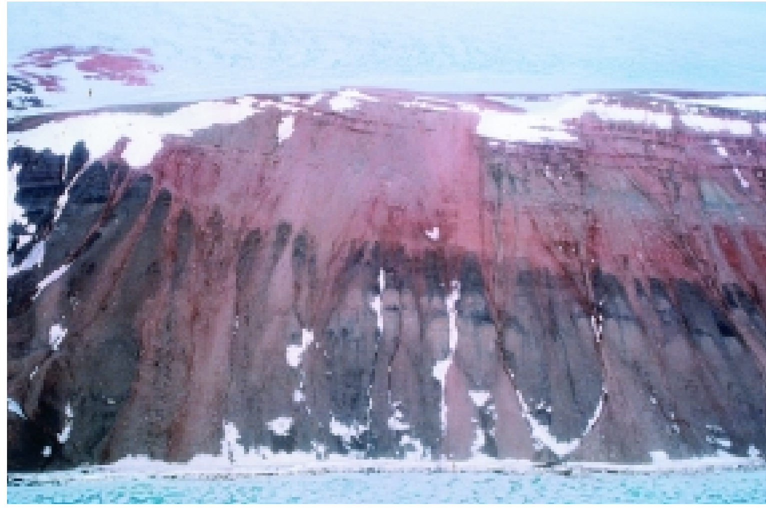
Tertiary

The Paleocene – ?Early Eocene Thyra Ø Formation forms the youngest preserved sediments within the Wandel Sea Basin and precise dating of these deposits is important for basin modelling. The formation was previously tentatively dated as Paleocene on the basis of the macroflora and rare dinoflagellates (Håkansson & Pedersen 1982; Håkansson *et al.* 1991). However, during this study a more diversified microflora containing both spores and pollen, and dinoflagellates was found (Stemmerik *et al.* 1997). The presence of *Cerodinium speciosum* and *Spinidinium pilatum* indicates a Paleocene age whereas *Cerodinium markovae* has a Paleocene–Eocene range and *Spinidinium sagittula* has been reported from sediments of Early Eocene age. Accordingly, the Thyra Ø Formation can be attributed a Late Paleocene to possibly Early Eocene age.

Structural geology

Structural studies of northern Amdrup Land show that the area north of the NW–SE trending Sommerterrasserne fault (Fig. 1) was affected by a compressional event in post-Jurassic time. In the graben area between the Sommerterrasserne fault and the north Amdrup Land fault the Permian and Jurassic strata are folded by gentle, *en echelon,* domal folds with amplitudes of approximately 100 m, wave lengths of 1–1.5 km and a lateral

Fig. 3. Unconformity between faulted fluvial sediments of the Lower Carboniferous Sortebakker Formation and mixed shelf siliciclastics and carbonates of the Upper Carboniferous Kap Jungersen Formation on the 450 m high Depotfjeld, southern Holm Land. Modelling shows that approximately 2000 m of Lower Carbonifeous sediments were removed prior to onset of deposition in the Late Carboniferous.



extent of 4–4.5 km. Fold axes generally strike NW–SE with some local variations. North of the northern Amdrup Land fault, Carboniferous sediments unconformably overlie Proterozoic sedimentary and volcanic rocks affected by Caledonian isoclinal folding. Here the Moscovian sediments are folded in somewhat larger domal folds with a NE–SW trend; a major synform with an amplitude of 250–300 m, a wave length of 3.5 km and a lateral extent of 7.3 km exposes Carboniferous, Permian and Jurassic sediments near Dværgfjorden (Larsen 1996).

The deformation of the Wandel Sea Basin deposits in Amdrup Land took place after deposition of the Upper Jurassic sediments, and should therefore be correlated with either the Middle Cretaceous Kilen event or the end of the Cretaceous strike-slip event of Pedersen (1988).

Basin modelling

Basin modelling of the Wandel Sea Basin is based on stratigraphic analysis of outcrop data and use of the Yükler 1D basin model concept (Mathiesen *et al.* 1997). The Yükler model is a forward deterministic model which quantifies the geological evolution of a sedimentary basin by calculating compaction, pressure, temperature, thermal maturity and hydrocarbon generation, as a function of time and space. Geological information and input data for the model include thickness, age, lithology, porosity, palaeotemperature, heat flow and palaeo-water depth. These data are synthesised into model events in such a way that the model can handle deposition, non-deposition (hiati) and erosion.

A total of 34 model events, each in excess of 1.0 Ma have been used to describe the evolution of the Wandel Sea Basin (Fig. 4). The lithology was based on published or unpublished sources on depositional facies variation. Data on thickness were taken from outcrop-based measurements (Håkansson 1979, 1994; Stemmerik & Håkansson 1989; Stemmerik *et al.* 1994, 1995b, 1996). The surface palaeotemperature was estimated from palaeoclimatic models and palaeolatitude. The variations in heat flow with time were estimated from the basin history, with higher values during periods of rifting and volcanic activity, and lower (and generally decreasing) values in tectonically stable periods with slow and uniform subsidence. The same heat flow history has been used for the whole area, except for a heating event around 65 Ma where the heat flow was increased to 1.35 heat flow units for the Peary Land and northern Amdrup Land area.

The model concept has been used to construct seven pseudowells in eastern Peary Land, Amdrup Land and Holm Land, in order to constrain basin history by optimising the subsidence, uplift and thermal history of the different parts of the basin using sensitive surface data (Mathiesen *et al.* 1997). Input data for each pseudowell are accumulated from a large area (often > 100 km^2), and the modelled pseudowells do not therefore correspond to real wells.

The seven pseudowells describe different geological scenarios within the basin. All pseudowells suggest limited Tertiary uplift of the onshore areas – in contrast to the Barents Shelf where more than 1 km of latest

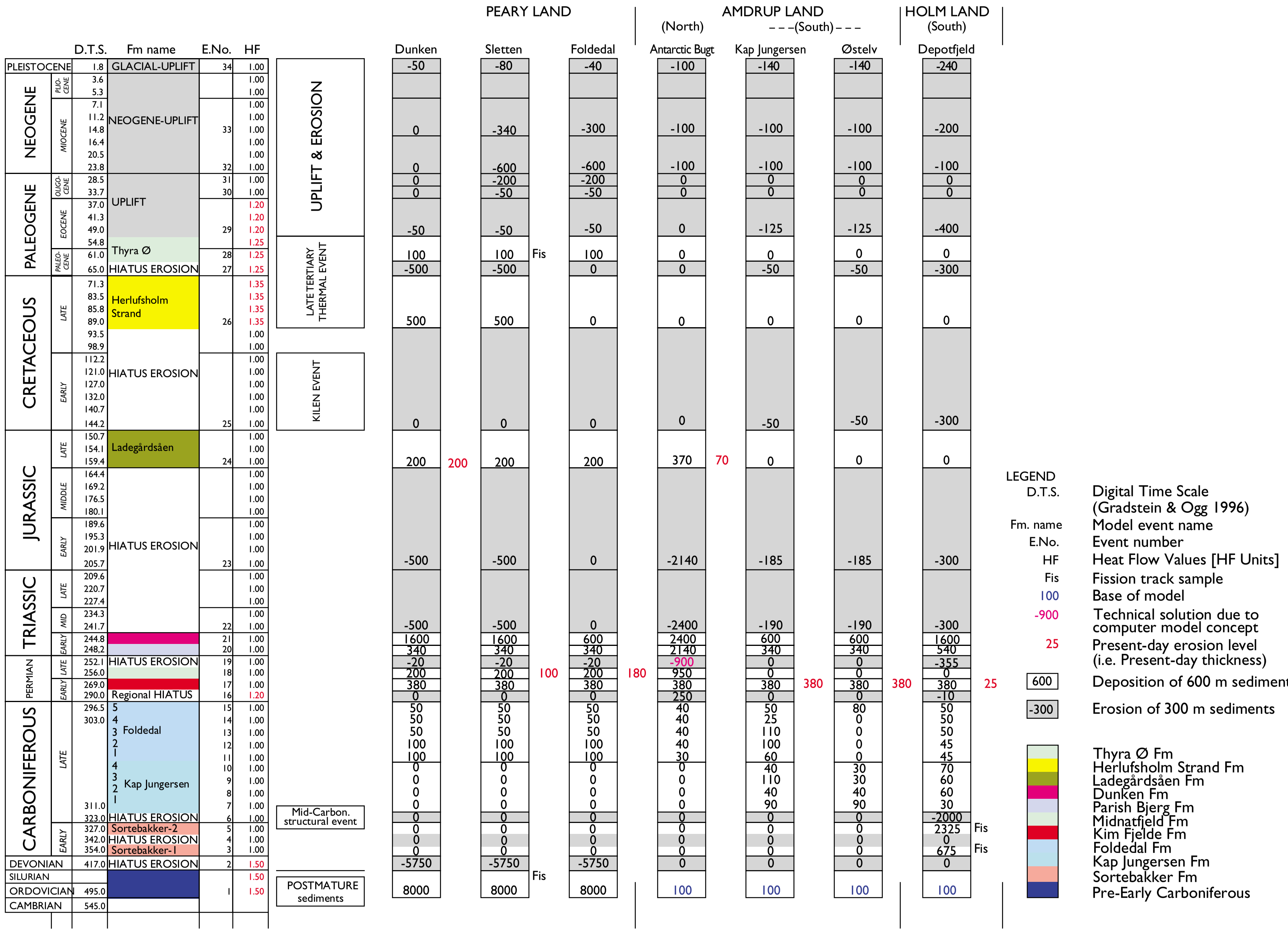


Fig. 4. Pseudowells in eastern Peary Land, Amdrup Land and Holm Land based on the basin modelling concepts applied to the Wandel Sea Basin by Mathiesen *et al.* (1997).

Tertiary to Recent uplift is proposed (Løseth *et al.* 1992). The Holm Land pseudowell puts constrains on the mid-Carboniferous structural event separating the Sortebakker and Kap Jungersen Formations (Figs 3, 4). According to the model at least 2000 m of Lower Carboniferous sediments have been removed during this event to explain the contrasting thermal maturity of the Lower and Upper Carboniferous sediments. Similarly, the Antarctic Bugt pseudowell shows that up to five kilometres of Upper Permian and Triassic sediments are likely to have been deposited in this area, and subsequently eroded away, to explain the contrasting thermal maturity of the Permian and Upper Jurassic sediments (Fig. 4).

Summary and conclusions

The results arising from the project form a major step forward in the understanding of the Wandel Sea Basin. The biostratigraphic resolution of the Upper Palaeozoic succession has been improved considerably and the basin modelling has provided the first quantitative constrains on the subsidence and uplift history of the basin. The most important new results are given below.

1. The finds of the first age diagnostic fossils from the Lower Carboniferous Sortebakker Formation which date the upper part of the formation as Visean.

2. Detailed sampling of fusulinids which allows recognition of eight Upper Carboniferous fusulinid assemblages and dating of all the main outcrops in Holm Land and Amdrup Land.

3. Discovery of new outcrops of Mesozoic sediments on Amdrup Land which have been dated as Late Jurassic based on ammonites.

4. Structural studies which show that the Trolle Land fault zone extends eastwards across northern Amdrup Land and also affected the northern part of the East Greenland Shelf.

In addition to the above observations basin modelling indicates that:

5. The mid-Carboniferous structural event separating the Sortebakker and Kap Jungersen Formations involved removal of at least 2000 m of Lower Carboniferous sediments before deposition of the Kap Jungersen Formation.

6. Up to 5 km of Upper Permian and Triassic sediments are likely to have been deposited in northern Amdrup Land, and subsequently eroded away, to explain the contrasting thermal maturity of the Permian and Upper Jurassic sediments.

7. Cretaceous sedimentation was very localised and no substantial post-Jurassic cover was present in Amdrup Land and the southern parts of eastern Peary Land.

8. Tertiary uplift of the basin was very limited.

The results imply that the shelf areas east of Holm Land and Amdrup Land have very different hydrocarbon potential. Immediately north of the Trolle Land fault zone it is suggested that mature Upper Palaeozoic sediments are folded in broad domal structures. Further to the north, the shelf area was most likely affected by a late Tertiary thermal event and the sediments are considered post-mature. South of the Trolle Land fault zone, the most prominent feature on the shelf is a north–south trending salt basin (Escher & Pulvertaft 1995). The outcrop studies and the basin modelling have only limited significance for evaluation of this area although sedimentological and diagenetic studies of the Upper Carboniferous carbonates may provide reservoir models for this region. Therefore the next phase of the investigation will focus on the relationships between Upper Carboniferous sedimentary facies and diagenesis, and the structural history of fault blocks. This study will compare the successions on southern Holm Land and southern Amdrup Land and will hopefully lead to a better understanding of the reservoir development in the offshore areas.

Acknowledgement

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