

The Tertiary orogenic belt of West-Spitsbergen: Seismic expressions of the offshore sedimentary basins

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Sedimentary basins west of the exposed part of the West-Spitsbergen orogenic belt have been outlined by seismic reflection data. Narrow, fault-bounded grabens are infilled from both sides, with syndepositional movement and weak compression of the whole sequence. The grabens are probably all of Tertiary age. Sediment thicknesses are up to 4 km and widths are up to 15–20 km. The main graben starts in the north with the Forlandsundet graben and is offset outside Isfjorden and possibly south of Bellsund. We are not able to discriminate between an extensional and a strike-slip model of graben-formation. Based on lateral velocity variations and thickness of post-rift sediments on the outer shelf and slope west of Spitsbergen, we assume 1–2 km of Tertiary sediments have been eroded from the offshore basins and 3 km in central Spitsbergen.

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Svalbard is located at the northwestern corner of the Eurasian plate. A young (Tertiary) fold belt exists along its western margin (Fig. 1). Continuation of this Tertiary orogeny is not seen on the passive margin of the Barents Sea shelf to the south, it terminates somewhere north of Bjørnøya (Faleide et al. 1984a, b; Riis et al. 1985; Steel et al. 1985). To the north, the fold belt terminates at Kongsfjorden (Fig. 1, Birkenmajer 1972; Hjelle & Lauritzen 1982). The fold belt has been interpreted to be a result of dextral transpression between the Eurasian and Greenland plates when seafloor spreading started in the Norwegian–Greenland Sea and in the Arctic Ocean (Harland 1969; Birkenmajer 1972; Lowell 1972).

The outer part of the continental shelf consists of thick sequences of low-velocity sediments, assumed to be deposited after a change in plate motion from shear to oblique rifting in the lower Oligocene (Malnod & Mascle 1975; Schluter & Hinz 1978; Myhre et al. 1982). Basement has not yet been traced below this wedge, and the position of the ocean/continent transition is unknown. The Hornsund Fault Zone, or the Hornsund Lineament, is the eastern limit of the late-Tertiary wedge of sediments. This is expressed on the seismics as an abrupt increase in velocities to the east (Schluter & Hinz 1978; Myhre et al. 1982).

Because of poor quality of the seismic reflection data, little information has been obtained on the

inner part of the shelf. Schluter & Hinz (1978) indicate vaguely some faulting inside the Hornsund Lineament, but Myhre (1984) shows no fault interpretation using the same data.

Holtedal (1936) postulated a N–S trending fault west of Prins Karls Forland on the basis of bathymetric features. Ohta (1982) used detailed bathymetric maps to tentatively draw lineaments on the shelf west of Spitsbergen. In our data we rarely see faulting or steep layering expressed in the bathymetry, and probably late-Tertiary and Quaternary (glacial) sedimentation very much controls these features in the study area.

The Tertiary fold and thrust belt is oriented NNW–SSE between Sørkapp land in the south and Kongsfjorden in the North (among others, Birkenmajer 1972, Lowell 1972, Kellogg 1975). The orogenic belt can be divided into a major thrust zone to the east and a transitional zone to the west (Birkenmajer 1972), or into a southern zone of upthrusting, a central zone of folding between Bellsund and Isfjorden and a northern zone of overthrusting (Kellogg 1975).

Lowell (1972) argued that dextral shear movement was indicated by several anomalous features: a narrow deformation zone with much basement involved, faults that steepen with depth and en echelon folds. In a detailed study in the Bellsund area, however, Craddock et al. (1985) found mainly compressional features.

Within the fold belt Tertiary sediments are exposed in four areas: Ny Ålesund, Forlandsundet, Renarodden and Øylandet. The exposed part of Forlandsundet Graben consists of alluvial-fan deposits in the southwest and east and submarine-fan deposits in the northwest (Atkinson 1962; Steel et al. 1985). The half-graben has been rapidly infilled from both west and east. Rye-Larsen (1982) found a thicker stratigraphic section (5 km) than the true thickness of the graben, and he explained this by depocenter migration.

Birkenmajer (1972) suggested that the basins in Forlandsundet and at Renarodden were parts of the same rift valley (graben) along the western coast of Spitsbergen, formed subsequent to the major deformation. Similar basins were also suggested by Kellogg (1975). Lepvier & Geysant (1985) found evidence in microtectonic data of a two-stage structural development of the western part of Spitsbergen: a first transpressional episode of N-S direction formed the main compressive structures of the fold belt and initiated the basins along the coast by a pull-apart mechanism. A second transtensional episode gave moderate rifting. A similar interpretation has been published by Steel et al. (1985) based on sedimentological data.

In this paper we will discuss the Tertiary grabens in light of some seismic reflection profiles of better quality, especially on the inner shelf.

Seismic data

The seismic reflection profiles used in this study are shown in Fig. 1; most of them were shot by the University of Bergen in 1976, 1977, 1979 and 1981. All the 1981 lines were shot with a 24 channel/1200 m streamer and an airgun array of 1200 in³, while the older data were shot with a 16-18 channel/800-900 m streamer and a single airgun of 200-300 in³. Lines NPD 7700-77 were shot by the Norwegian Petroleum Directorate in 1977 with a stronger source and a 48 channel/2400 m streamer. In spite of these far from optimal acquisition parameters (too long group interval for the uppermost 1-2 km and too short streamer for depth below 1.5-2 km), careful processing makes it possible to see many features in the uppermost 2 seconds of most of the sections. Interpreted depth-sections (line drawings) of the E-W lines are shown in Fig. 2, ordered from

north to south. In Fig. 3 an example of the data (migrated version of line UB 38-81 west of Hornsund) is shown together with an interpreted time section.

In the northernmost part of the shelf, west of Magdalenefjorden (Figs. 1 and 2, line 5B-81 and line 5C-81), two prominent NNW-SSE trending horsts can be seen. The horsts are characterized by a flat and strong-reflecting top, probably an erosional surface of the basement. Sediments have filled in between and buried the horsts. The sediments differ from those in the grabens to the south; they have lower velocities, are well stratified, and they onlap the basement blocks. The blocks dip to the north and disappear beneath thick sediments in the complicated area NW of Spitsbergen.

The thickness of sedimentary infill between the blocks decreases quickly to the south because basement is shallowing. On lines UB 15-81 and UB 4-76 (Fig. 2), no signs of sedimentary basins east of the Hornsund Lineament can be seen. The absence of sedimentary grabens on the inner shelf north of Prins Karls Forland may be due to a turn in structural trend of the orogenic belt, as seen in the termination of the exposed part of the belt south of Kongsfjorden and the E-W/NW-SE rather than NNW-SSE trending lineaments at Brøggerhalvøya (Orvin 1940; Challinor 1967; Birkenmajer 1972; Hjelle & Lauritzen 1982).

No seismic reflection data are at present available from Forlandsundet, but Sundvor et al. (1977) found 2-3 km of sediments in the central part, based on sonobuoys. A schematic stratigraphic profile across the southern part of the graben is shown in Fig. 4, taken from Rye-Larsen (1982).

In Isfjordrenna, after reprocessing and reinterpretation of line UB 3-76, a basin east of the Hornsund Lineament can be seen. Some of the reflectors have quite sharp bends near the western end of the basin. This basin is also well seen on the closely spaced line UB 22-81. Although the separation of these two lines across the basin is only a few kilometers, there are differences in the location of the deepest point of the basins. This indicates that lateral changes are also significant in a N-S direction. Possibly an E-W fault in this area causes the dissimilarities between the two lines. A very small basin is visible at the mouth of Isfjorden, on line UB 22-81. Across the fold and thrust belt no reflectors can be seen because of severe seabottom multiples, which are

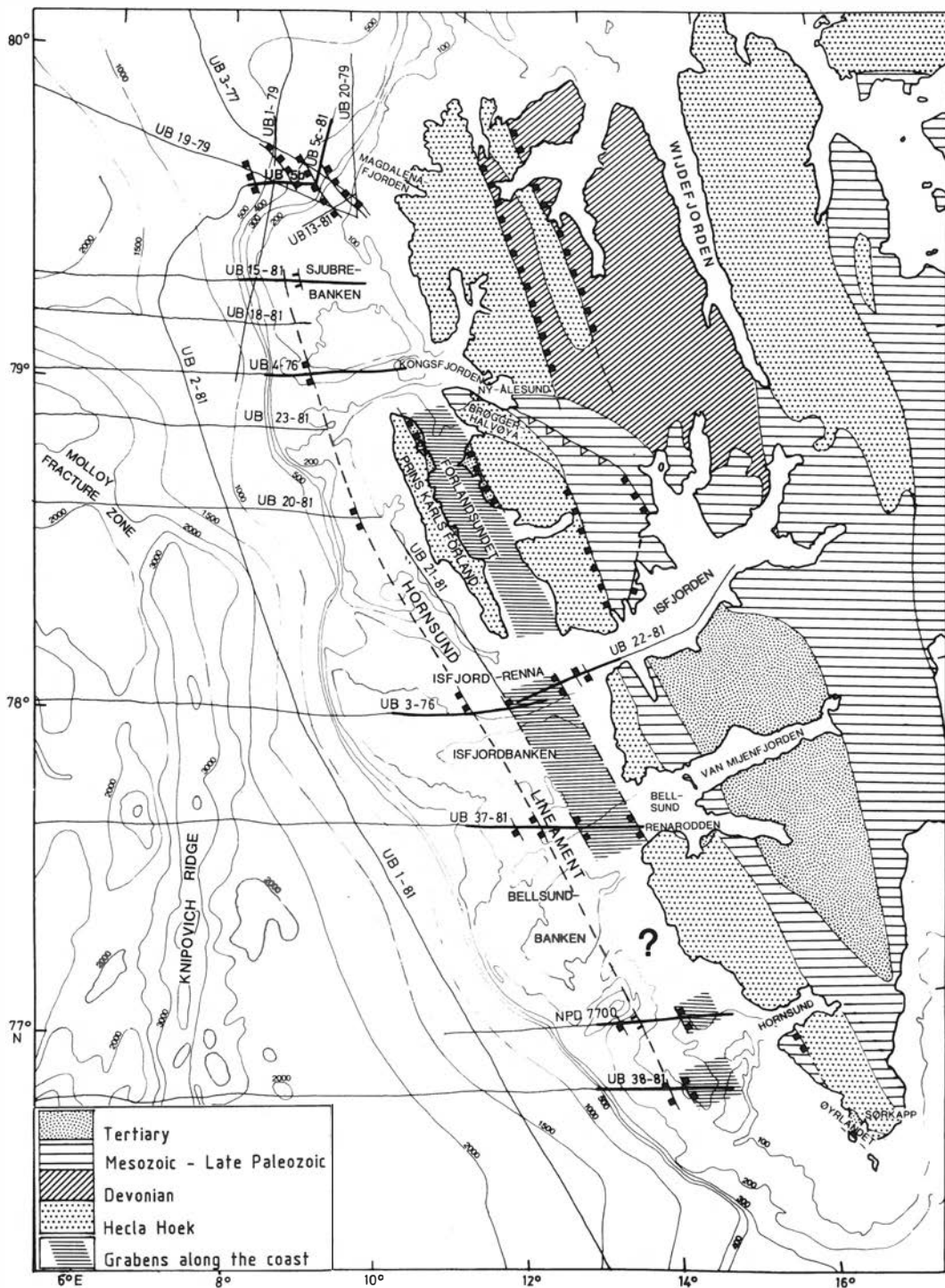


Fig. 1. Map of the western Spitsbergen margin, with schematic land geology, bathymetry, the seismic reflection profiles used in this study and our interpreted structural lineations. Thick lines indicate the locations of the interpretations in Fig. 2. Bathymetry (in meters) was provided by Norsk Polarinstitutt.

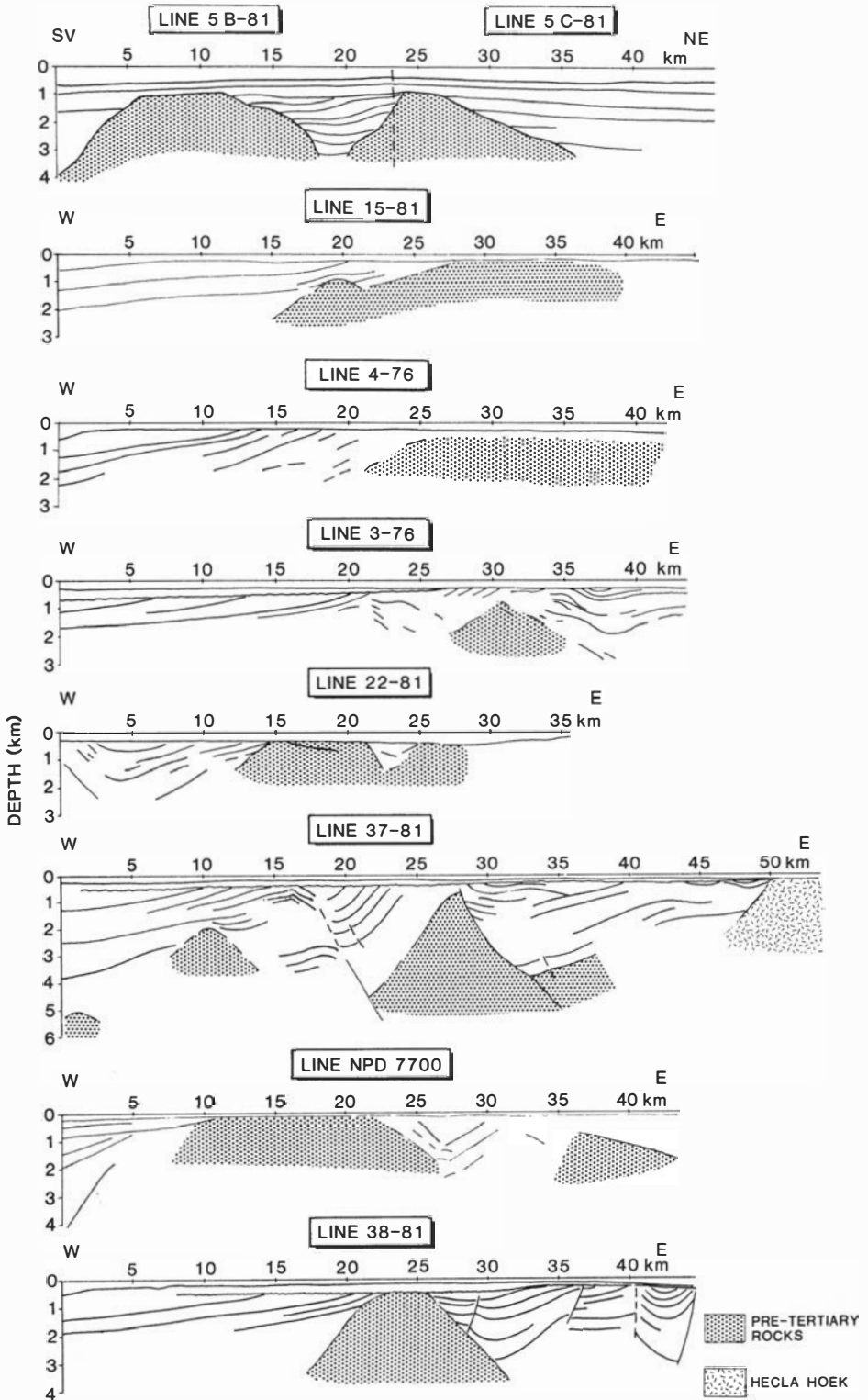


Fig. 2. Interpretations of E-W lines across the inner shelf (thick lines in Fig. 1), ordered from north to south.

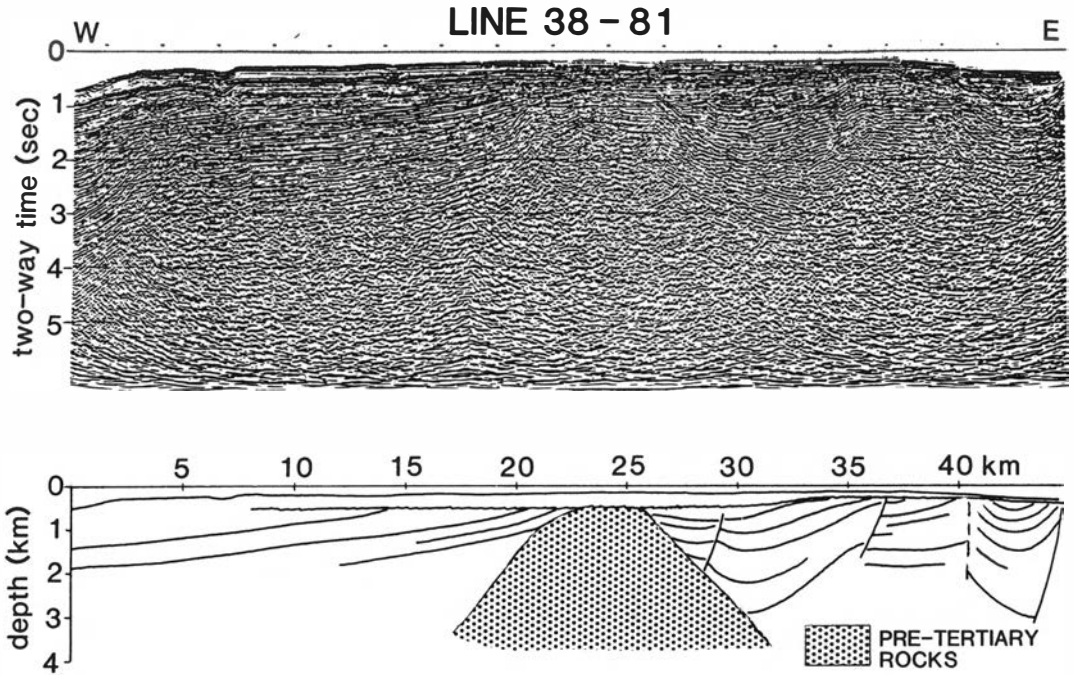


Fig. 3. Example of a seismic line, UB 38-81, migrated section uninterpreted and interpreted.

especially troublesome at water depths as great as in Isfjorden.

Outside Bellsund, on line UB 37-81, the Hornsund Lineament is structurally complex with steeply dipping reflectors. Further east there is a half-graben with signs of syn-sedimentary move-

ments, and with some features that can be interpreted as weak compression of the layers. The basin is approximately 4 km thick (2 sec reflection time) and is bounded to both the east and the west by normal faults. This basin is similar to that seen in Isfjordrenna and to the one proposed in

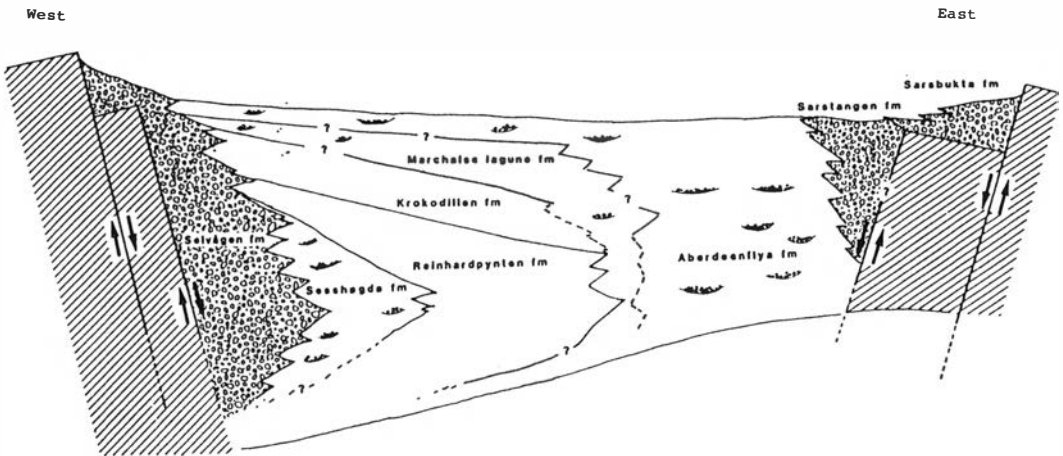


Fig. 4. Schematic cross-section across the southern part of Forlandsundet (from Rye-Larsen 1982).

Forlandsundet (Fig. 4). A simple interpretation of these structures is extensional block faulting. There are some anomalies, however; very steep layers go almost up to the sea floor and there are indications of small folds (not shown on the interpretation). These might be explained by components of compression.

Lines NPD 7700-77 and UB 38-81 are located west of Hornsund. On line NPD 7700-77, two small basins are weakly seen east of the Hornsund Lineament (Fig. 2), elsewhere high-velocity rocks are present near the sea floor. A large positive gravimetric anomaly just landside of the Hornsund Lineament (Faleide et al. 1984) has been explained as a result of a dense body of perioditic rock emplaced in the crust during compressional deformation and an edge effect at the Hornsund Lineament (Aalerud 1986; Aalerud, in press). He further interpreted significant short-

wavelength magnetic anomalies as shallow dyke-swarms intruded along fault planes subparallel to the Hornsund Lineament.

On line UB 38-81, the western side of a prominent horst defines the Hornsund Lineament. The sedimentary basin east of the horst is divided into two lows separated by a high. The basin continues east of the end of the line. There are clearly evidences of differential subsidence in the basin. Both the horst and the graben are truncated by an unconformity, probably caused by glacial erosion. The sequence above the unconformity thins towards zero at the eastern end of the profile.

Basement on the seaward side of the horsts which define the Hornsund Lineament is poorly mapped, due to poor penetration of the thick late-Tertiary sequence. Faults with large throws can be seen in the southern part of the area (Fig. 2), and on one line, UB 37-81, deeply buried

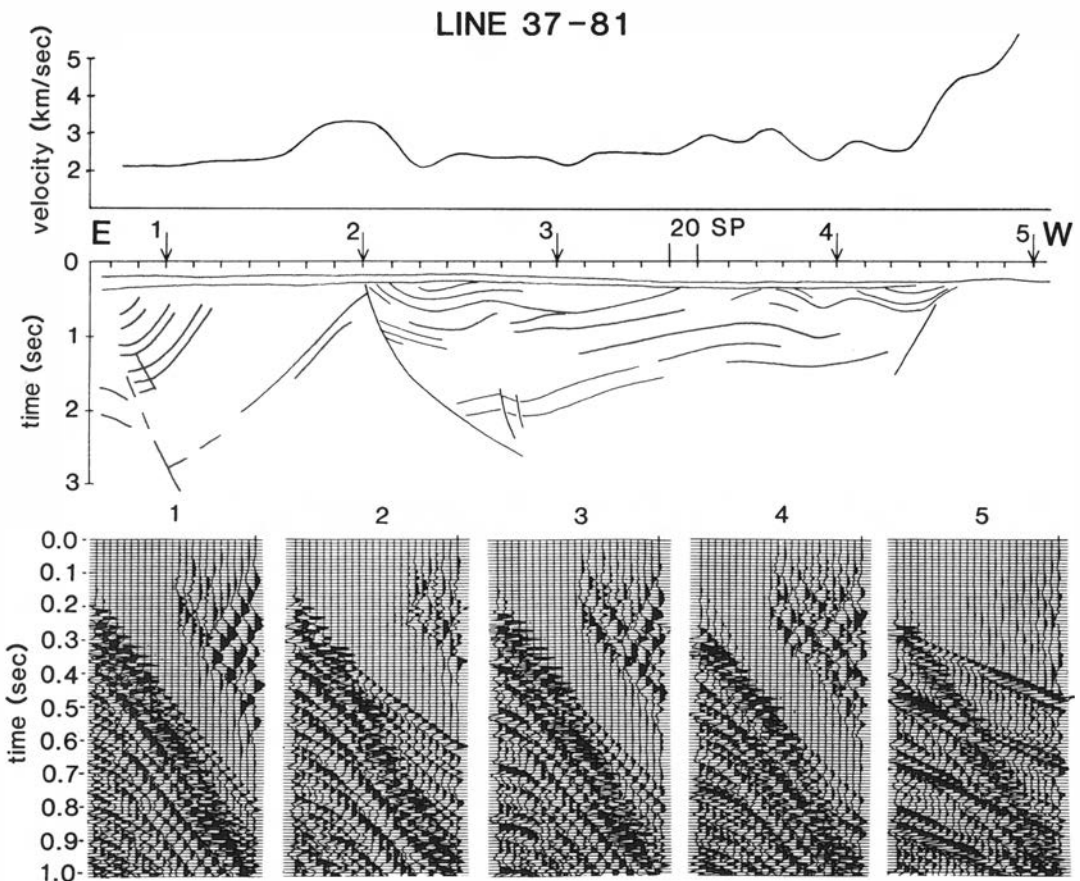


Fig. 5. Shallow refractions recorded on the 1200 m longstreamer (below) and the corresponding velocity profile (above). The interpreted reflection section is shown in the middle. This example is taken from the inner part of line UB 37-81.

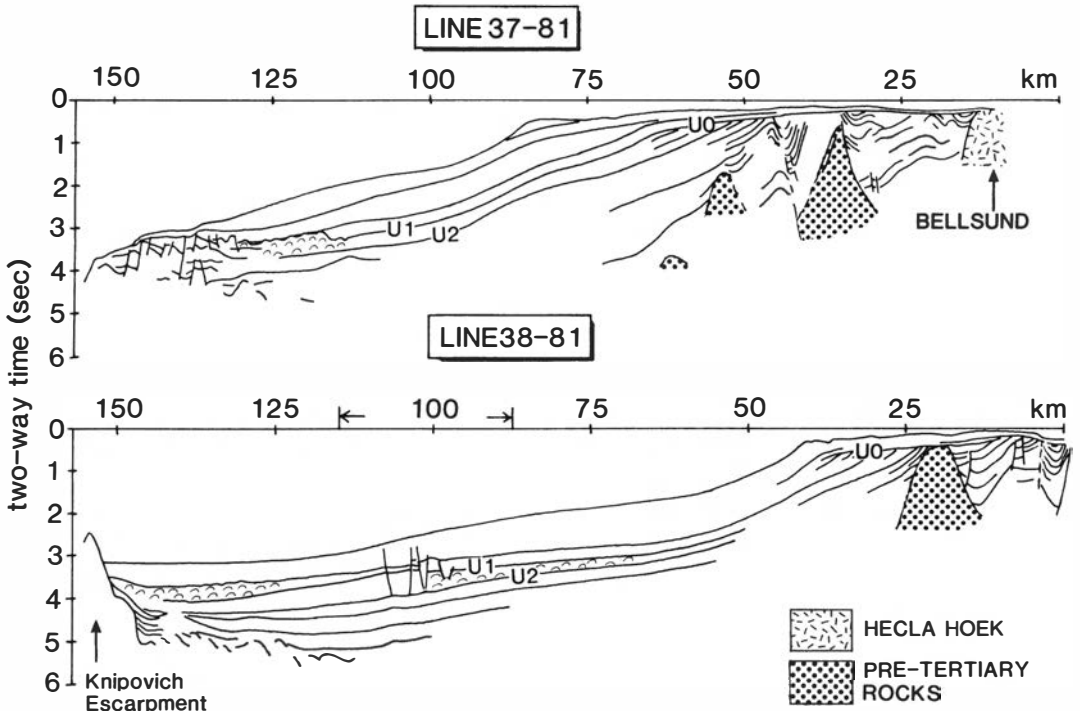


Fig. 6. Interpretations of lines UB 37-81 and UB 38-81, the parts east of the Knipovich Ridge.

fault blocks are seen approx. 20 km west of the shallow expression of the Hornsund Lineament. In this area we have to place the ocean-continent transition some distance west of the Hornsund Lineament. North of Isfjordrenna, evidence of steep faults with large throws is lacking, as diffractions and very steep reflectors are not seen clearly.

Velocity variations across the margin are significant. We have obtained velocities from sonobuoys (reinterpretations of earlier published sonobuoys, Sundvor et al. 1977), from reflection hyperbolas (stacking velocities) and from shallow refractions recorded on the streamer. The last technique proved to be accurate for the uppermost 200-600 metres of the sediments in shallow water. An example of this is shown in Fig. 5, where shot-gathers are shown together with a velocity profile. Velocity variations can be closely related to the structures seen on the reflection section and give more reliable interpretations.

The velocity-depth curves obtained from the sonobuoys are shown in Fig. 8. The curves can be divided into three distinct groups, and correspond to different locations: the outer shelf and slope,

the grabens and central Spitsbergen together with the horsts west of the grabens.

Structural implications

The offshore basins and the main structural elements interpreted from the seismic data are shown in Fig. 1. Between Isfjordrenna and Bellisund there is a graben with geometry very similar to the Forlandsundet Graben; on the map we have interpolated the master faults between lines UB 3-76 and UB 37-81. Outside Hornsund there is another graben, but there are problems in matching the structures between lines UB 38-81 and NPD 7700-77. Holtedal (1936) and Ohta (1982) suggested a graben west of Prins Karls Forland. This is not confirmed in our data, and any basin here must be narrower than the other grabens under discussion.

From the areal distribution these basins seem to be separate features along the coast. There are, however, indications that they are all of the same type as the Forlandsundet Graben: The seismic velocities in the sediments are distinctly

LINE UB 38-81

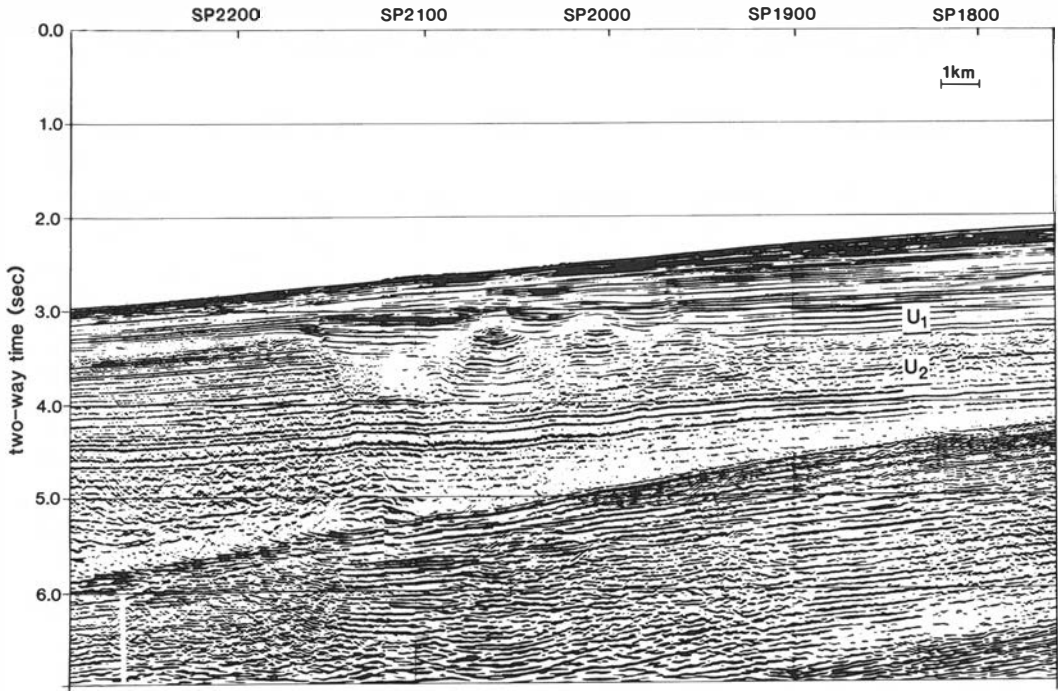


Fig. 7. Detailed part of migrated section of line UB 38-81 at the lower slope (location is shown in Fig. 6).

lower than those of Tertiary, Mesozoic and Paleozoic strata east of the fold belt, but correspond well with what is observed in Forlandsundet (Sundvor et al. 1977) and in the Tertiary outcrop at Øyrlandet (Grønlie 1978).

The half-grabens with infill from both sides, with syn-sedimentary movement and weak deformation of the whole basin, fit observations from Forlandsundet Graben well and also suggested models of graben formation along the coast (e.g. Steel et al. 1985): widened and filled in during an extensional phase after the main compression.

Older sediments may well be present in the deeper parts of the grabens, like Carboniferous sediments found in grabens within the fold belt south of Hornsund and north of Bellsund (Flood et al. 1971; Hjelle et al. 1986). The reflection configuration with lack of major unconformities indicates, however, that the infill has been more or less continuous through the whole sequence, and that older sediments must be situated in the 'basement' beneath this sequence.

The E-W offsets observed between the For-

landsundet Graben and the Isfjordrenna-Bellsundet Graben (magnitude 10-15 km), and probably also present further south, might be due to transfer faults. It is difficult to relate such faults to onshore faults of E-W trends, as the displacement along the transform fault must be considerably larger than observed on land. The SW-NE fault going out into the sea in Ymerbukta on the North side of Isfjorden (Fig. 1, Hjelle & Lauritzen 1982, Ohta 1982, Steel et al. 1985) possibly curves into an E-W fault at the mouth of Isfjorden. Differences in the geology north and south of Hornsund (Flood et al. 1971) suggest an E-W fault in Hornsund.

Most previous works seem to favour models of basin formation with a considerable strike-slip component (Lowell 1972; Lepvier & Geysant 1985; Steel et al. 1985). From our data we are unable to discriminate between extension and strike-slip as the main regime creating the basins. Right-stepping of the boundary faults may give pull-apart basins in a dextral strike-slip regime (Lepvier & Geysant 1985). On the other hand, if the en echelon arrangement was created by

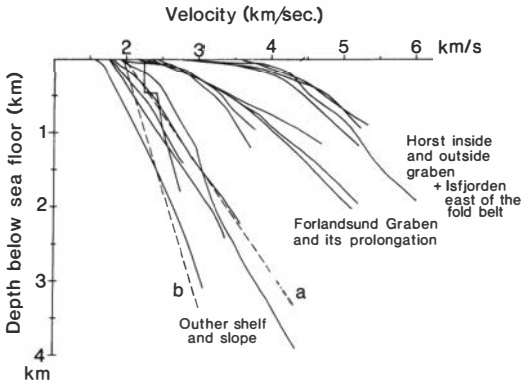


Fig. 8. Sonobuoy velocities grouped into three different provinces. Myhre & Eldholm's (1981) gradient for the shelf 74.5–80 N (a) and for other shelves around the Norwegian–Greenland Sea (b) are shown.

strike-slip movement, it must have been sinistral. Transfer faults may well be an integral part of an extensional system, however (Harding & Lowell 1979).

Post-rift sedimentation

Maximum sediment thicknesses are estimated to about 6 km, mainly based on sonobuoys. Little is known about the oldest sediments because of lack of penetration. Schluter & Hinz (1978) and Myhre

(1984) divided the whole sequence into three units, separated by two unconformities, U1 and U2 (Fig. 6). Depocentres of the youngest sequence, above U1, are at the shelf edge west of Isfjorden and between Bellsund and Horsund. U1 and the chaotic reflection pattern between U1 and U2 have been attributed to slumping (Schluter & Hinz 1978). These features are not seen on the upper slope, they are areally restricted to the lower slope. In some places, as in the example shown in Fig. 7, structural disturbances are seen well above U1. We suggest overpressure and density inversions as an alternative explanation of these features.

The most prominent unconformity in our data, U0— not described earlier, is limited to the shelf areas, and is shallower than 500 m below the sea floor (Fig. 6). Near the shelf edge it becomes conformable. This unconformity might be caused by glacial erosion, as is seen on most of the Norwegian continental shelf. The sediment thickness above this level decreases and the angular unconformity becomes more prominent towards land. This can be explained by differential uplift/erosion, probably with some uplift even west of the Hornsund Lineament.

The velocity variations with depth in these sediments are shown in Fig. 8. Myhre & Eldholm (1981) found a high velocity gradient in the north-eastern Greenland Sea compared to what is typical for the shelves around the Norwegian–

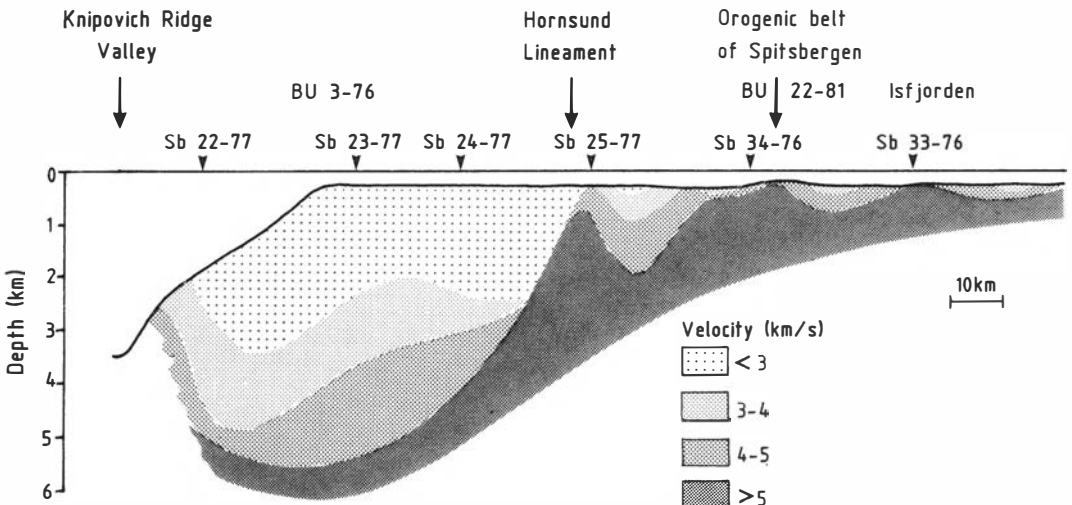


Fig. 9. E–W velocity profile from Knipovich Ridge to Isfjorden, taken from lines UB 3–76 and UB 22–81, from nearby sonobuoys (locations shown) and from streamer-recorded refractions.

Greenland Sea. Their two average curves are shown in Fig. 8 for comparison with the outer shelf area; our velocities are generally lower than theirs in the same area.

The similarity within and the separation between the velocity-depth curves of the three different Tertiary provinces is remarkable, since the rocks are probably close to each other in age and composition. We consider the previous depth of burial as the main factor contributing to these differences. If depth of burial is the only cause of

variations, 1–2 km of sediments must have been eroded in the grabens and as much as 3 km in central Spitsbergen. High pressure in the sediments close to the orogenic belt during the compression would also increase the velocities, but no such E–W variations are observed in the Tertiary and Mesozoic rocks in Spitsbergen and in Storfjorden (Eiken 1985). In Fig. 9 we have shown the velocity-distribution along the lines UB 3–76 and UB 22–81.

Manum & Throndsen (1978) suggested, based

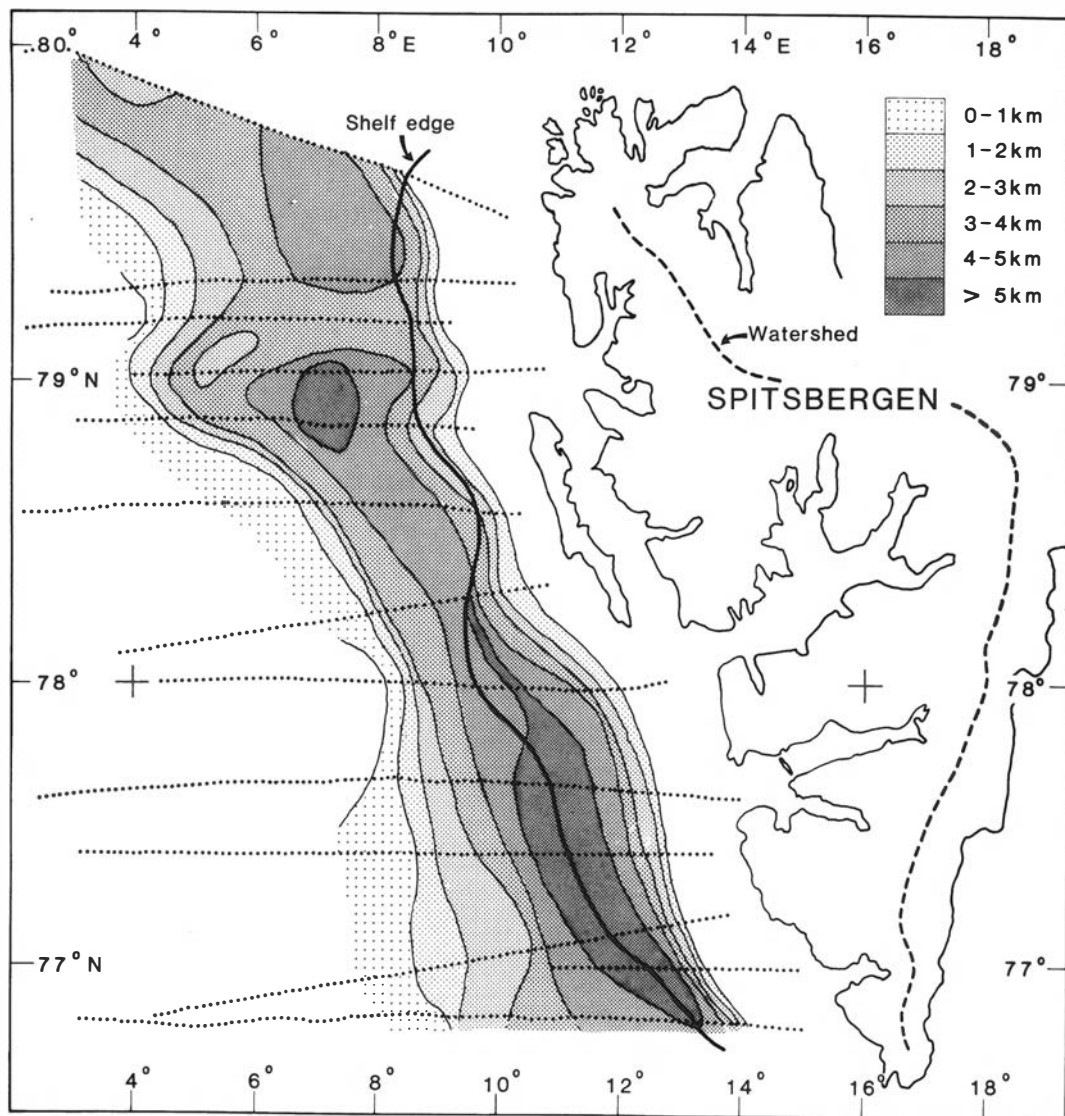


Fig. 10. Isopach-map of total sediment thickness west of the Hornsund Lineament.

on vitrinite reflectance, that 1.7 km of sediments were missing above the youngest sediments in the Tertiary central Spitsbergen basin. For the rocks at sea level, another kilometer of overburden must be added, and then their results are in reasonable agreement with ours.

The rapid uplift and erosion of the source area resulted in rapid sedimentation along the margin. The total sediment thickness between the Hornsund Lineament and the Knipovich Ridge is shown in Fig. 10, based on sonobuoys in the deepest part of the basin. If we limit the source area to the present watershed (shown in Fig. 10) and assume no influx from or transportation to the outside, this gives an average erosion of 3 km east of the Hornsund Lineament. This is in good agreement with the results above. It also indicates that Storfjorden and the area further east has been drained through Storfjordrenna most of the time since Oligocene.

Conclusions

The described grabens are relatively small and deep basins, and they are probably all of Tertiary age. The system of grabens terminates north of Prins Karls Forland, whereas the southern termination is unknown. Complex horst blocks west of the grabens and poor penetration of the post-rift sediments further west gives little information about the continental breakup. We are unable to prove any strike-slip movement, and a simple extension model can explain the grabens as seen in our data. 1–2 km of sediments have eroded from the organic belt and 3 km from central Spitsbergen during the uplift since early-middle Tertiary.

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