Seismic mapping of the post-Caledonian strata in Svalbard

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The status of seismic exploration work mapping the post-Caledonian strata in the Svalbard area is presented. Compressional wave velocities are very high throughout the area, around 4 km/s in the Tertiary and Mesozoic layers. In the Permian section velocities exceed 5 km/s, with refraction velocities > 6 km/s in the calcareous rocks of the Gipsdalen Group (early Permian/Late Carboniferous). Apart from correlation with carbonate and chert lithology, high velocities reflect the high degree of consolidation and the low porosities of shales and sandstones in the post-Caledonian strata in Svalbard. In van Mijenfjorden seismic reflection events are observed down to 3–4 km depth and associated with Carboniferous and younger strata. The thickness of the Mesozoic layers in this part of the central Spitsbergen syncline seems to be greater than previously suggested, and there is an apparent eastward divergence between the Jurassic and the Triassic reflectors. In south-western Storfjorden, reflections interpreted to originate from Carboniferous and Permian strata might represent the seaward extension of the central Spitsbergen syncline. In the northern part of Storfjorden, carbonate layers within the Gipsdalen Group are interpreted to lie about one kilometre below the sea floor. A prominent fault zone in this area trends NNW–SSE, like the main structural elements on Spitsbergen. It shows block-faulting, presumably caused by extensional movement in late Devonian–Carboniferous time.

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In spite of the extensive geological research done in Svalbard and several exploration wells there, little seismic work has been done. Part of the reason for this might be the inhospitable environment for land operations, and severe water-layer multiple problems in marine data. On the other hand, absorption of the seismic energy seems to be small due to a high degree of consolidation of the sediments, and permafrost minimizes the need for any weathering-layer correction.

The first reflection measurements in the area were reported by Pozdeev (1965). In a land survey in central Spitsbergen he observed many irregular arrivals down to 1.8 sec two-day travel-time (3.5–4.0 km). No interpretation was published.

In 1979, 1980 and 1984 the University of Bergen carried out small-scale land-seismic surveys. The first field experiment was in Agardhdalen near Storfjorden (Fig. 1). Layers from the Triassic down to the Carboniferous of the sedimentary section were sampled by reflection and refraction profiles (Eiken 1981), and the main results will be summarized here. Later work has focused on the shallow, coal-bearing Tertiary strata at locations near Longyearbyen. These surveys are of limited interest for this paper, but we note that observed velocities in sandstones and shales of Tertiary age are generally 4.0–4.5 km/s (Bruland et al. 1982).

In Storfjorden, east of Spitsbergen, the Norwegian Petroleum Directorate (NPD) shot one reflection line in 1974 and two lines in 1980 as an extension of the denser Barents Sea profile grid (Fig. 1). A geologic model for Storfjorden has not been published, but Rønnevik et al. (1982) and Rønnevik & Jacobsen (1984) extend an isochrone map of a mid-Permian horizon into the area, suggesting that two-way travel-time to this horizon decreases northward to about 1.0 sec at 77°N.

In 1978, Institute Français du Petrole and the University of Oslo conducted a regional survey in the Barents Sea. On the basis of a line into Storfjorden (BAR-2 in Fig. 1) Faleide et al. (1984) suggested two sedimentary basins: the Storfjorden basin and the Edgeøya basin.

Sonobuoy profiles in the southern part of Storfjorden (SB 32/75 to SB 36/75 in Fig. 1) reveal refractors with velocities about 5.6 km/s at depth 1.5 km and refractors with velocities about 6.4 km/s at depths 2.5–3.0 km (Sundvor & Eldholm 1976). These layers have been associated with acoustic basement.

During a marine survey in 1981, the University of Bergen shot about 950 km reflection data and six sonobuoys in Storfjorden, and about 80 km reflection data and one sonobuoy in van Mijenfjorden (Fig. 1). In this paper I present a

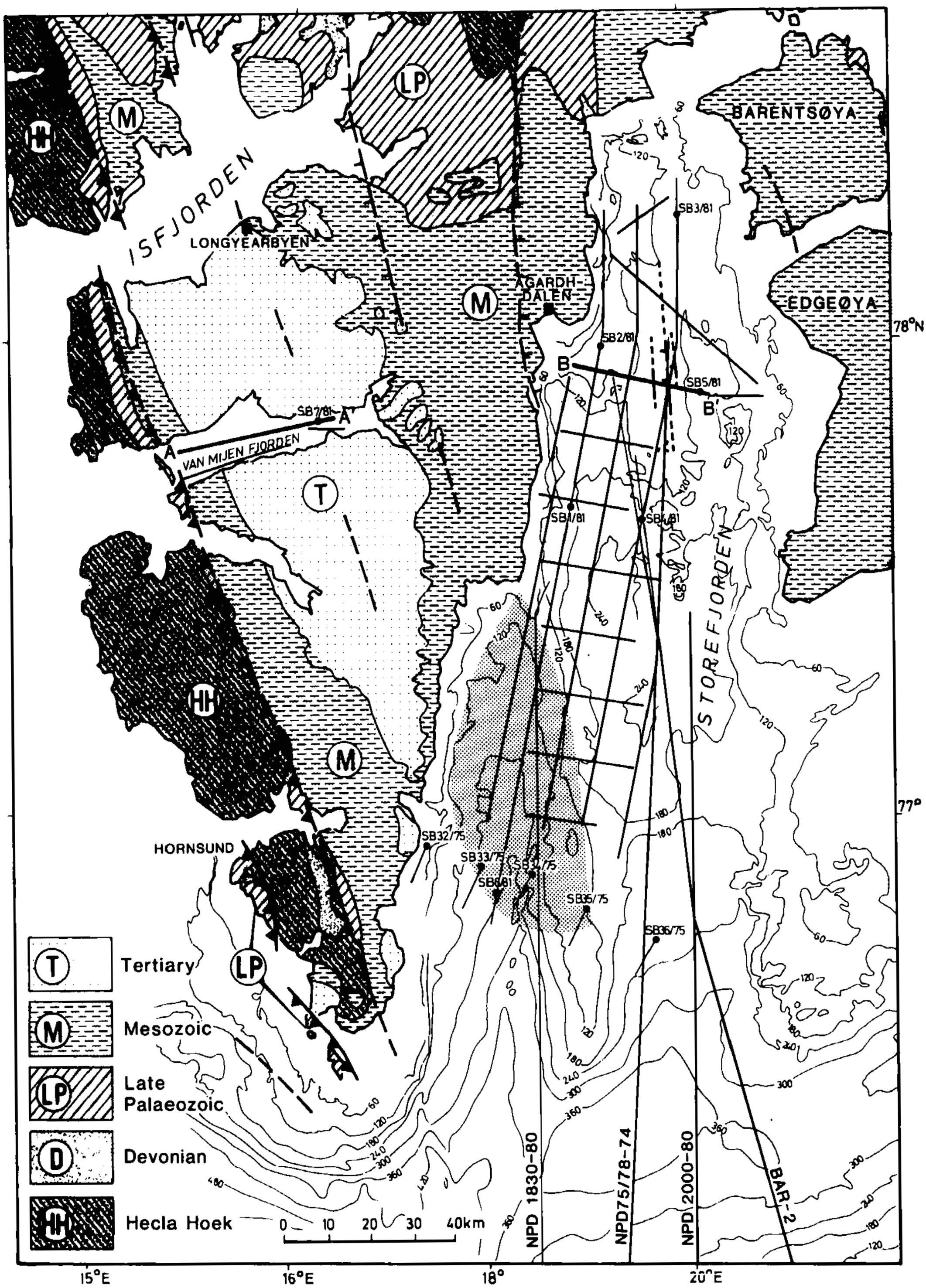

Fig. 1. Map of the survey area with seismic reflection lines in Storfjorden and van Mijenfjorden. Sonobuoys, from Sundvor & Eldholm (1976) and from the 1981 survey, are marked with dots. Simplified geology from Steel & Worsley (1984) and bathymetry from Norsk Polarinstitutt hydrographic surveys. The fault zone in northern Storfjorden is shown, and the shaded area in south-western Storfjorden marks the area of fairly horizontal reflectors of Permian–Carboniferous age at 2–3 km depth.

tentative interpretation of the post-Caledonian structures in the central Spitsbergen syncline and in Storfjorden based on these data and the NPD data. The land-seismic results from Agardhdalen serve as an important velocity check.

Geologic framework

An extensive literature exists on the geology of Svalbard; a key reference to the depositional history of the post-Caledonian strata is Steel & Worsley (1984). The islands are covered by geological maps in scale 1:500,000 (Flood et al. 1971; Winsnes & Worsley 1981; Hjelle & Lauritzen 1982). Only the main lithological units will be recapitulated here.

Thick sequences of coarse-grained Devonian sandstones rest on the metamorphic Hecla Hoek unit and are preserved in N–S trending grabens exposed mainly in the north. Carbonate sediments dominate the Gipsdalen Group (early Permian/late Carboniferous), and faulting controls the sedimentation of the lower part of the group. The Tempelfjorden Group (late Permian) consists mainly of cherty sequences. During the Mesozoic, clastic sediments were deposited in a stable platform environment over the entire area. In the Triassic both shales and sandstones are common. Jurassic and early Cretaceous strata consist mainly of shales, except for the sandstones of the Festningen member of early Cretaceous age. The Tertiary section contains alternating strata of shales and sandstones.

Tectonic activity has been concentrated along a series of NNW–SSE lineaments (Fig. 1). Movements have occurred during most of the geological periods, but were most prominent during Devonian, Carboniferous and early Tertiary time. An early Tertiary compressional regime and transform faulting created the fold belt along the west coast of Spitsbergen and the broad asymmetric central Spitsbergen syncline. Van Mijenfjorden is lineated west–east, and layers from the Hecla Hoek through to the Tertiary sequence are exposed here (Fig. 1). Around Storfjorden Mesozoic layers outcrop with a fairly horizontal attitude, and only Triassic layers and some local Permian outcrops are seen on Edgeøya and Barentsøya. Water depths in van Mijenfjorden and in Storfjorden are mostly between 50 m and 200 m.

Generally, the sedimentary rocks in Spitsbergen have low porosities and high densities, Kurinin (1965) measured densities mainly above 2.5 g/cm^3 in post-Caledonian rocks, with highest densities, around 2.8 g/cm^3, in the calcareous rocks of the Gipsdalen Group. A borehole at Grumantbyen in the near-axial part of the central Spitsbergen syncline (Skola et al. 1980) reveals compressional velocities up to 6 km/s in the Permian strata, and around 4.5–5.0 km/s in the Triassic strata. Elverhøi & Grønlie (1981) explained the high seismic velocities and low porosities in the sediments from the Svalbard area in terms of early diagenetic cementation.

Summary of results from land-seismic survey in Agardhdalen

Since the velocity information from the land-seismic data is fairly reliable and can be closely tied to surface geology, it serves as an important link between the known geology and the offshore seismic data.

The range of acceptable P-wave velocity-depth models for the site in Agardhdalen is shown in Fig. 2 together with the geological interpretation (top Triassic is at the surface). Two prominent shallow reflectors, at c. 350 m and c. 600 m, fit well with a possible dolerite intrusion (a still) in the mid-Triassic (Botneheia Formation) and the Permian/Triassic boundary, respectively. This is in correspondence with measured thicknesses of the Triassic in the area (Flood et al. 1971; Nysæther unpubl. data). The Permian/Triassic boundary is a sharp lithological transition from mostly shales above to cherts below, and is observed as a strong reflector all over the Barents Sea (Rønnevik et al. 1982). Velocity analyses of the reflection data give mean velocities in the Triassic section around 4.0–4.3 km/s. We see no clear reflections below the Permian/Triassic boundary in this area.

Refractors with velocities 6.5 km/s and 6.8 km/s lie at a depth of about 1 km. Among sedimentary rocks only limestones, dolomites and anhydrites of very high densities can account for such high velocities (Gardner et al. 1974). We have therefore interpreted the high-velocity refracting horizons as representing carbonates within the Gipshuken and Nordenskiöldbreen Formations of the Gipsdalen Group, because they are the only formations in Svalbard known to include thick beds of such rocks.

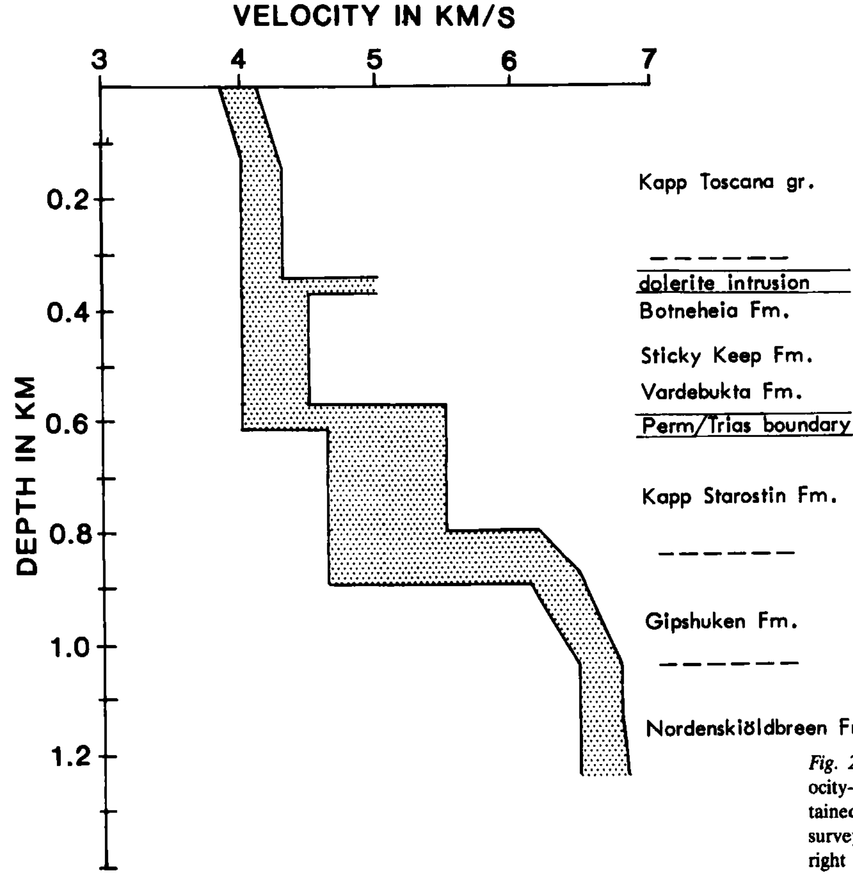

Fig. 2. Range of possible velocity-depth distributions obtained from the land-seismic survey in Agardhdalen. To the right is the geological interpretation of the velocity model.

Velocity measurments from sonobuoys

The sonobuoy data from the 1981 survey have been modelled using travel-time information. I have assumed horizontal or gently dipping homogeneous and isotropic layers – the dip in accordance with the reflection data along the same profile lines. On some of the sonobuoys high-amplitude sea-floor critical reflections can be utilized to obtain sea-floor velocities (Berge & Beskow 1985). These velocities seem to be around 3.0–3.5 km/s, which is slightly below the first-arrival refraction velocities.

Velocity–depth solutions from the five sonobuoys in northern Storfjorden are shown in Fig. 3 together with one of the sonobuoy recordings. The different solutions are very similar: velocities are around 4.0–4.5 km/s at shallow depths and exceed 6.2 km/s about 1 km below sea floor. The velocity functions are also similar to the one obtained from the land-seismic survey in Agardhdalen. On the buoy nearest to this site, the calculated travel-time curves from the velocity–depth model in Fig. 2 fit well when a water layer is added. This makes an extension of the stratigraphic interpretation of the land data reasonably plausible.

At the southernmost buoy (SB6) refractors with velocities above 6 km/s are observed about 2.5 km below the sea floor, with fairly uniform velocities above. This is in good agreement with the interpretation of earlier sonobuoys in the area (Sundvor & Eldholm 1976).

From this we conclude that it is likely the carbonates within the Gipsdalen Group occur about 1 km below the sea floor in northern Storfjorden and about 2.5–3.0 km below the sea floor in southern Storfjorden.

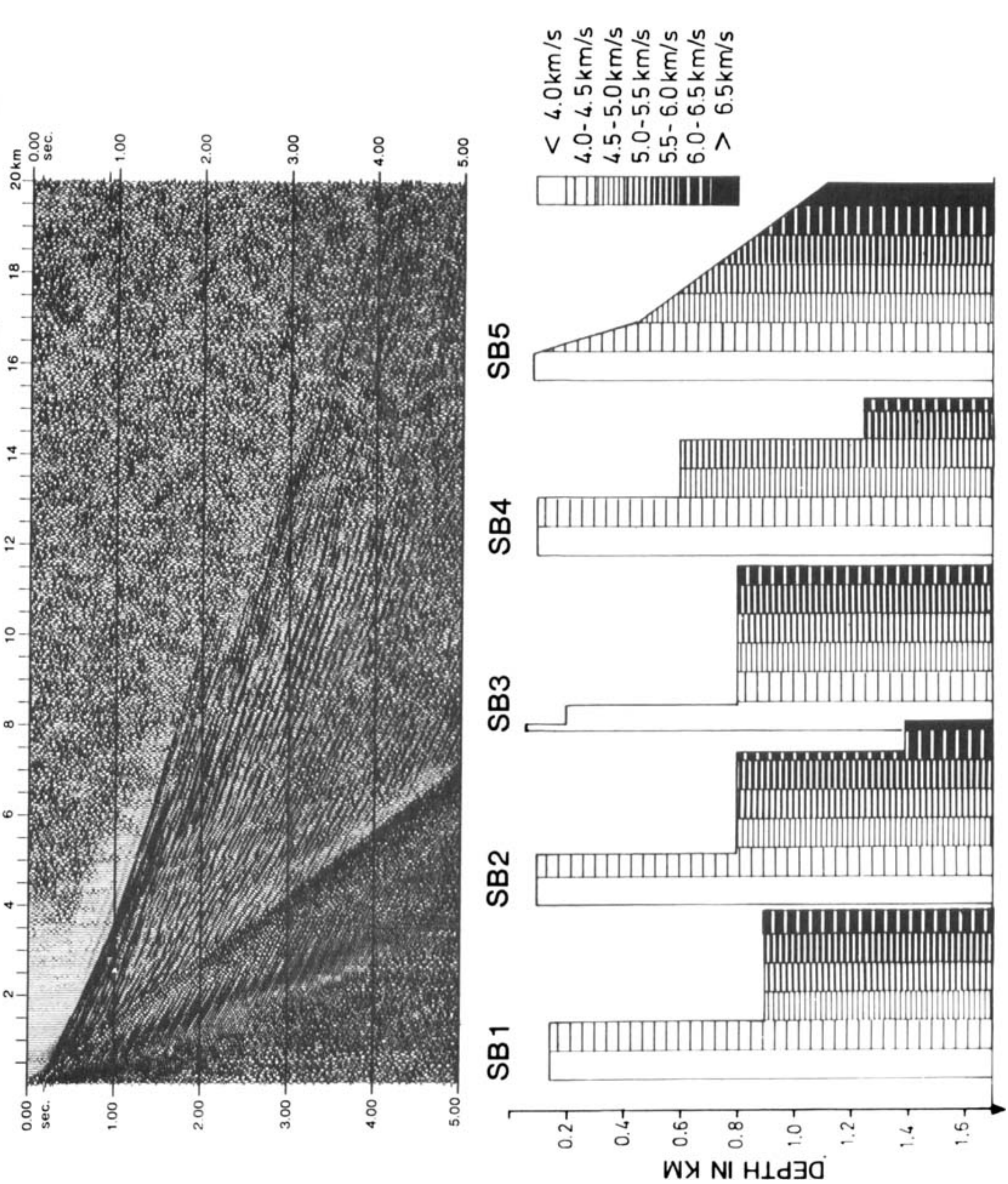

Fig. 3. Above is a sonobouy recording in northern Storfjorden (SB2) and below are velocity-depth solutions from all five sonobuoys in northern Storfjorden.

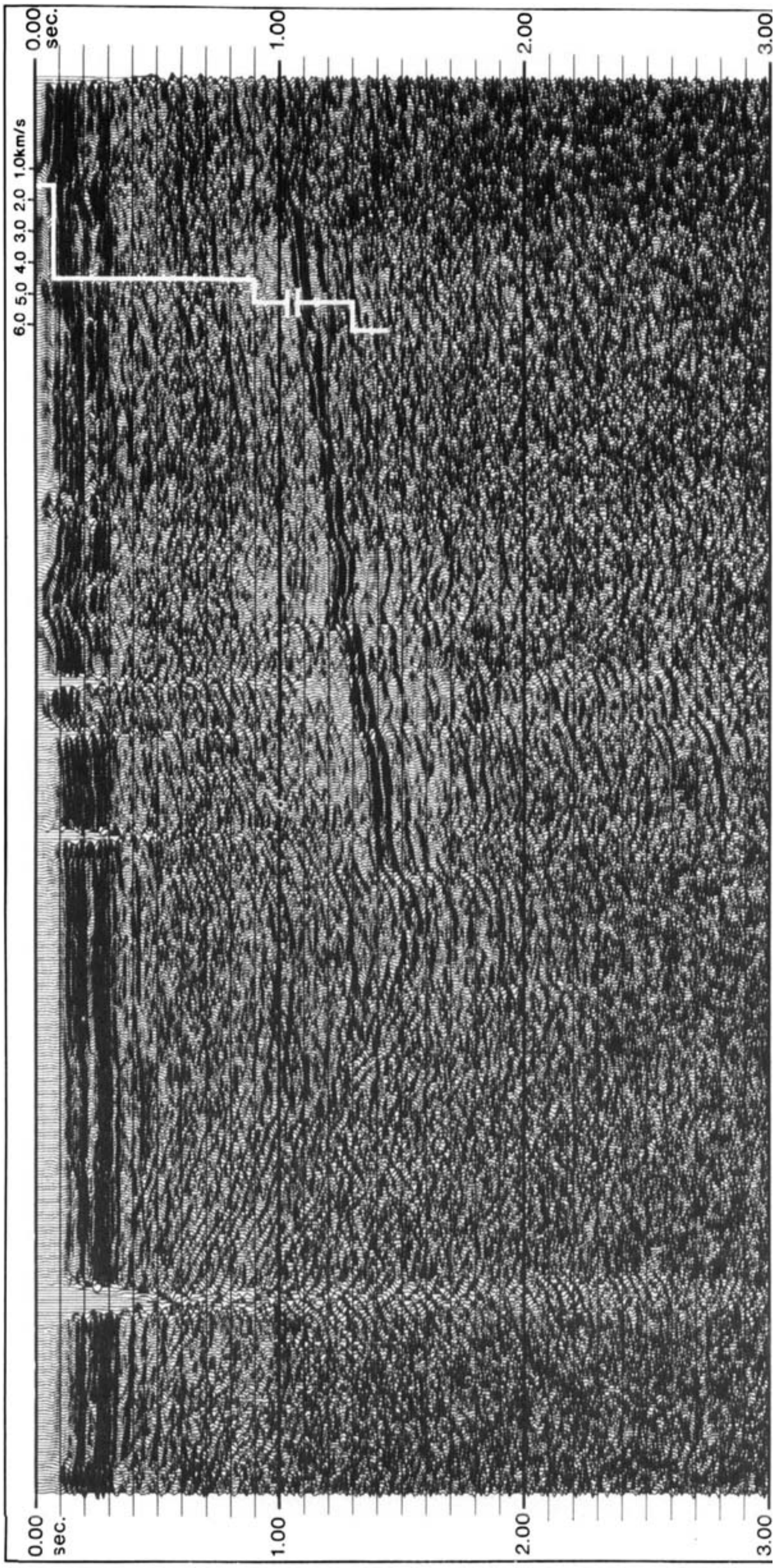

Fig. 4. Seismic section (migrated) along van Mijenfjorden from west to east (A-A' in Fig. 1). A velocity distribution obtained from the sonobuoy is plotted in white on the section. Some dead traces (white areas) on the section are caused by unfired shots.

The only sonobuoy measurement in van Mijenfjorden is of poor quality at great shot-receiver offsets. A possible velocity function is superimposed on the seismic section in Fig. 4. Refracted arrivals seem to be associated with reflections at 0.9 sec and 1.3 sec. A strong reflection at about 1.04 sec does not correspond with refracted arrivals on the sonobuoy measurement. Hence a general velocity increase is not apparent at this reflector. A thin high-velocity layer unable to guide refracted waves could possibly explain this reflection event (see the reflection data analysis later). To satsify the velocity analysis of the reflection data we also have to introduce a low-velocity zone below the shallow 4.5 km/s refractor; this is more likely an effect of anisotropy (transverse isotropy) than a real low velocity zone.

Marine reflection data

In the 1981 survey a point source and a 24 channel/50 m group interval cable was used. The processing sequence includes array generation, a strong mute and predictive deconvolution before and after stack. Processing of the data from Storfjorden has been described in more detail by Eiken (1984). The velocity analysis gives limited information because of the short streamer length and the high velocities. Uncertainty in stacking velocities (and in depth conversions) are estimated to be less than 10%. Interval velocities are generally at least 4 km/s. Although the multiples are attenuated considerably, they generally remain at the same level as the primaries. This makes interpretation of the data difficult. Reflections from the uppermost kilometre are strongly attenuated in the array-simulation, and it is not possible to trace dipping reflectors up to the sea floor. The recording parameters used in the 1981 survey were not optimal; a denser and wider spatial sampling of the data would improve the quality of the processed data, as shown by Eiken (1984).

The NPD lines were recorded with a 48 channel/50 m group interval cable. The 1974 line was shot with point source and has been processed without array generation. The 1980 lines were shot with superlong airgun array and were processed with a simulated receiver array. Due to the longer receiver cable, the processed NPD data are of better quality than the 1981 data for reflectors deeper than about 5 kilometres.

Van Mijenfjorden

Numerous fairly continuous reflections below van Mijenfjorden reveal the broad, asymmetrical central Spitsbergen syncline as shown on the migrated seismic section in Fig. 4. Detailed interpretation in terms of seismic facies analysis would be too speculative on these data, but at least some of the reflectors do have special characteristics.

Fig. 5 shows the structural interpretation of the same line in a tentative depth-converted cross-section. The major reflectors are labelled from A to E and are dated as suggested in the figure text. Reflector D is particularly clear east of the deepest part of the basin. To the west this reflector disappears. We have two different suggestions for the interpretation of reflector D: either the Permian/Triassic boundary or a sill in the middle of the Triassic. The signal shape (very high amplitudes and at least two prominent cycles) favours the sill interpretation with a strong reflecting interface at both the top and the bottom of the sill. Based on the sonobuoy, reflector D is not accompanied by a general velocity increase (Fig. 4). The lateral continuation is at least 20 km. This might be much for a sill, but dolerite intrusions are common in the middle Triassic around Storfjorden and in some places they are continuous and cover great areas. Also in the Grumantbyen borehole south of Isfjorden a 42 m thick dolerite was found within the early Triassic sequence (Skola et al. 1980). The reflector disappears to the west. This could be explained by intense faulting (there are some signs of diffractions on the sections), by erosion of the reflecting interface, or, if it is a sill, simply the termination of the sill. Taking all this into account, we prefer the sill interpretation.

Weaker reflections are visible both above and below this strong reflection, and are generally not very continuous. In the upper part of the sequence we observe a characteristic reflector which may correspond to the stratigraphic level of sandstones of the Festningen Member of early Cretaceous (reflector B). This interpretation is based on geological arguments; there are thick beds of shales with presumably very small velocity contrasts both below and above this sandstone unit (Flood et al. 1971). These beds are not likely to produce significant reflections. If the sill interpretation is valid, we associate reflectors below reflector D with the Permian/Triassic boundary or with the upper part of the Gipsdalen Group. Reflector C

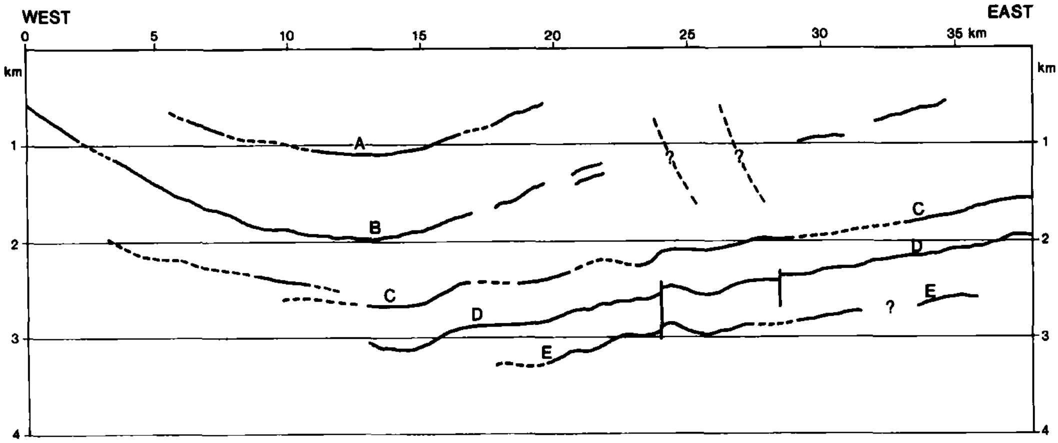

Fig. 5. Depth-converted geoseismic section along van Mijenfjorden from west to east (A-A' in Fig. 1). The following ages of reflectors are suggested: A. near base Tertiary; B. within early Cretaceous, possibly the Festningen Member; C. near top Triassic or in the middle of Triassic; D. a sill in the middle Triassic or at the Triassic/Permian boundary; E. the Triassic/Permian boundary or near the top of the Gipsdalen Group (early Permian).

might represent the sandstones in the late Triassic sequence.

The Thickness of the Jurassic–Cretaceous sequence seems to be about 1500–2000 m, which is considerably more than the 750–900 m suggested by Flood et al. (1971) on their east–west cross-section 30–40 km north of van Mijenfjorden. It corresponds with the thickness of 1350 m measured in the Grumantbyen borehole about 40 km north of van Mijenfjorden (Skola et al. 1980). There are also some signs of an eastward thickening of the Jurassic–Cretaceous sequence. It is possible that faulting is responsible for the poor continuity of the Jurassic–Cretaceous reflections east of the deepest part of the basin.

Storfjorden

In the seismic data from Storfjorden reflectors are generally less clear and less continuous than in van Mijenfjorden. The water-layer multiples are possibly stronger here, but the poor reflections seem to have geological significance too. A shallow sill, for instance, would certainly obscure the deeper reflections.

In the south-west, reflectors at depths 1.0–1.5 sec two-way travel-time (2–3 km below surface) are horizontal or dip slightly to the south and the west. In Fig. 1 the areas where these reflectors are visible have been shaded; to the north and east the reflections become masked in a long sequence of multiples. The sonobuoy measurements in the area show refractors with velocities above 6 km/s at the same depths (2–3 km), and I therefore associate the above referred reflections with Carboniferous–Permian strata. This area is adjacent to the central Spitsbergen syncline and the reflectors might show the south-east seaward extension of this.

A very prominent fault zone occurs 30–40 km east of Agardhbukta (Fig. 1) with more than 1 km of vertical displacements. We suggest the name Storfjorden Fault Zone for this feature. The flexuring and faulting has a NNW–SSE direction, like the major structural lineaments on Spitsbergen. This appears to be another lineament of regional importance. A geoseismic section across the fault zone from west to east is shown in Fig. 6. The structural pattern is rather complex with block faulting indicating extentional movement. Reflecting interfaces above the blocks are only slightly affected by the faulting. Dating of the reflectors is a bit uncertain. From the sonobuoys we have interpreted refractors within the Gipsdalen Group to lie about 1 km below the sea floor in most of the area. This suggests that the blocks are of early Permian age or older. Major faulting and graben development were important in the late Devonian–late Carboniferous (Steel & Worsley 1984) and we associate the faulting with these movements.

Some very deep reflections, at 4–6 sec two-way travel-time (8–15 km), are visible on some of the

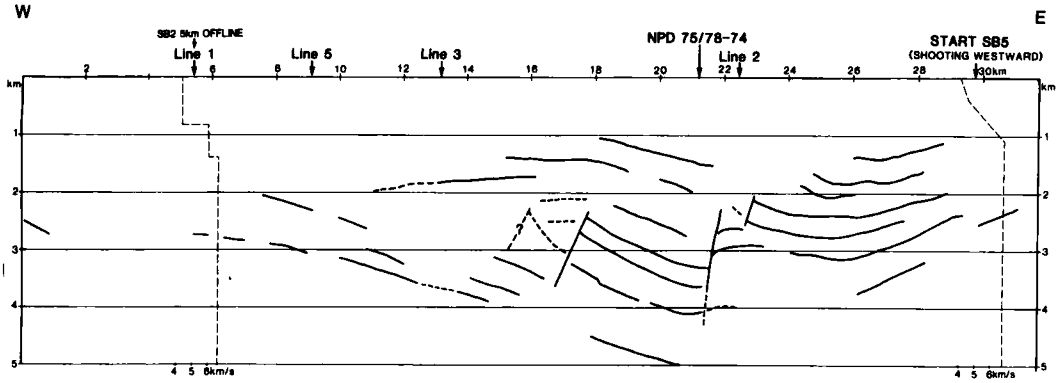

Fig. 6. Depth-converted geoseismic section across the fault zone in northern Storfjorden from west to east (B-B′ in Fig. 1). Velocity-depth solutions of adjacent sonobuoy measurements projected onto line (locations in Fig. 1).

NPD data, mainly in the south-east. These reflections usually have quite steep dips, up to 15°. A systematic trend in the dips is hard to obtain, and it is doubtful that they are associated with sedimentary basin development. These reflections are possibly from layers within the metamorphic Hecla Hoek sequence.

Locally we see shallow reflections (<3 km deep) and minor fault zones in other parts of the area too. The geometrical picture is complex. The absence of prominent reflections in most of the area suggests that pre-middle Carboniferous sediments are of modest thickness, except in the Storfjorden fault zone. Carbonate rocks of Permian–Carboniferous age are likely to be present at shallow depths all over the area as documented by high-velocity refractions.

Summary and conclusions

The thickness of the Jurassic–Cretaceous sequence in the van Mijenfjorden area of the central Spitsbergen syncline seems to be greater than inferred from earlier projections of surface geology. A middle Triassic dolerite intrusion at depth possibly covers most of van Mijenfjorden east of 16°E, and Jurassic and Triassic reflectors diverge to the east of the central part of the syncline.

In south-western Storfjorden, reflectors associated with Permian/Carboniferous rocks at 2–3 km depth dip slightly to the south and the west. This might represent the south-east seaward extension of the Spitsbergen syncline. Further north and east, the quality of the seismic sections is poorer and this might have geological significance. A prominent NNW–SSE oriented fault zone with block faulting in northern Storfjorden, interpreted to be of late Devonian–late Carboniferous age, shows great similarities with the major structural lineaments on Spitsbergen.

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