The tectonic structure of the Devonian Graben (Spitsbergen)

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Abstract

A description is given of the tectonic structure of the Devonian Graben (island of Spitsbergen) and the history of its development. It is stated that the sedimentation within its confines has been controlled by fractures of deep location, and the field of development of Devonian deposits at the period of sedimentation was essentially larger than its present dimensions. Main plicative and disjunctive structures have been recognized, the latter being united into differently aged erathems (groups). The present look of the graben has to a considerable extent been conditioned by vertical movements.

Description

Study of the Devonian Graben of Spitsbergen is all important because of its key position as the extreme north-westernmost projection of Eurasian continental structures, and the variety of its geological formations concentrated within a relatively small and accessible area.

Devonian rocks occur in northern Spitsbergen as a thick variegated molasse sequence with a basaltic conglomerate at the base. The Devonian sequence rests on the Caledonian basement with a sharp unconformity and is of great interest both for correlation of not well known coeval sequences in the Arctic and their implication for the geological history of Spitsbergen before its platform development, starting early in the Carboniferous.

The study of Devonian deposits of Spitsbergen was initiated by Swedish expeditions under the leadership of Nordenskiöld, Nathorst, and De Geer between 1868 and 1899 and has continued up to the present. Studies included the construction of a stratigraphical standard and environmental reconstructions of the Devonian deposits. A synthesis of results may be found in Nathorst (1910), Føyn and Heintz (1943), and Friend (1961).

Since 1964 Spitsbergen expeditions of the Institute for the Geology of the Arctic (Leningrad) have studied the Devonian deposits and carried out geological mapping (generally, at a scale of 1:200 000) in the Liefdefjorden, Bockfjorden, Woodfjorden, Wijdefjorden, and Austfjorden areas, as well as in the regions of Raudfjorden, Mimerdalen, and Hornsund. Almost all of Andrée Land and most of Dickson Land have been mapped.

Fold and fault structures revealed by mapping within the Devonian graben aid the reconstruction of the general history of the area in the postgeosynclinal period and subsequently during the development of its present day form.

The Devonian Graben is exposed in central Spitsbergen to the north of Isfjorden. Its history is closely related to fundamental faulting, particularly with faults bordering the graben to the west and the east. The major displacements seem to have been initiated before or during the early stages of the Caledonian orogeny. Movement along existing fault planes took place later, particularly during the Devonian, influencing the environment of deposition. This reflects in non-depositions, distribution of facies, thicknesses, and lithologies of Devonian deposits. In Upper Devonian and post-Devonian time block movements affected the mode of structure formation. In the Jurassic–Triassic the displacements along major fault planes were accompanied by trappean magmatic activity.

Thus, the history of the Devonian Graben is in fact that of the block movements.

The modern graben is distinctly divided by a north-south trending submeridional fault (Breibogen to Bockfjorden) into two parts: the western inner horst and the eastern deep depression.

The western boundary of the inner horst coincides with the western boundary of the Devonian Graben, probably representing the major fault zone, and occurs along the whole western coast of Spitsbergen. The lowest beds of the Devonian, the Lower Devonian Siktefjellet and Red Bay Groups with a total thickness of the order of 3000 m, rest unconformably on the eroded surface of the Caledonian basement within the inner horst. The deposits consist mainly of rhythmically alternating red sandstones and siltstones of lagoonal and non-marine origin together with a 600 m sequence of coarse conglomerates containing some beds of coarse-grained sandstones at the base of the section. The highest beds of the succession are found in the northern end of the horst in the Raudfjorden area; to the south successively lower horizons of the succession are exposed. Some relics of Red Bay conglomerates reach the latitude of Kongsfjorden. Faults, generally trending north or northwest, divide the inner horst into the blocks of varying size and with vertical uplift from some hundreds of metres to at least one kilometre. Within these blocks the Devonian deposits dip steeply to the west (60–80°) while in the southernmost inner horst (south of 79°N) they dip mainly to the south. In the vicinity of normal and strike-slip faults the Devonian rocks are folded to form local syn- and anti-forms which are steep-limbed, usually with small amplitudes, and near-fault in character. Their axes are generally subparallel with the fault trends. These structures do not usually exceed 300–500 m with amplitudes amounting to

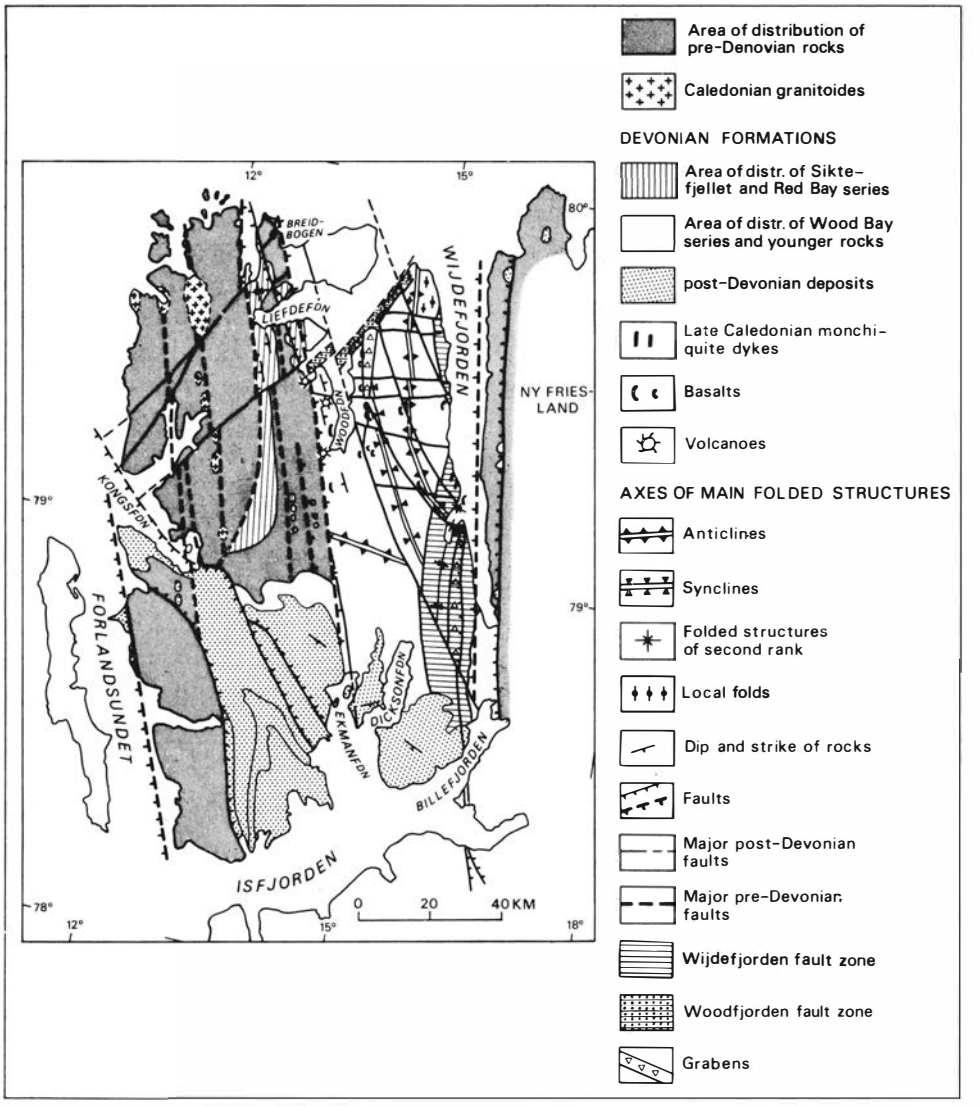

Fig. 1. *Tectonic map.*

some dozens of metres. The most significant one is the synform in the mountain Ben Nevis area between Raudfjorden and Liefdefjorden. This is an asymmetrical fold with its axis trending north-west. The structure attains 4 km in width, and the maximum depth of subsidence is probably not more than 500 m. The eastern limb dips at angles of 25° to 30° while the western limb dips at 15° to 20° although the dip increases westward as the western limb approaches the major submeridional faults bordering the structure. The synform is complicated by a fault pattern with a throw of the order of 400–500 m.

The eastern part of the inner horst, formed by northward radiating major faults (the Rivieratoppen-Bockfjorden line to the west and the Breibogen–Ekmanfjorden line to the east), represents the most elevated terraine of the

inner horst and has a structurally complex interior. Mainly pre-Devonian rocks are exposed there, but Lower Devonian deposits belonging to the lowest Red Bay Group occur and generally dip to the west at angles of 10° to 35°.

The eastern part of the graben (to the east from the Breibogen–Ekmanfjorden fault) contains younger Devonian groups. These include the Lower Devonian deposits of the Wood Bay Group, with the Kapp Kjeldsen Formation in the Woodfjorden area and the "Austfjorden Sandstone" at the base in eastern Dickson Land. Devonian deposits in the eastern part of the graben are represented by all three groups including variegated and grey-coloured lagoonal — non-marine, coastal — marine and partly non-marine sediments. Upper Devonian deposits of the Mimerdalen Group (Esteriahaugen Formation, Fiskekløfta Formation and Planteryggen Formation) outcrop only in a narrow zone in easternmost Dickson Land. This zone was affected by intensive block faulting in post-Devonian time. The great majority of investigators suggest that the Upper Devonian in the Mimerdalen area rests on the eroded surface of the Lower-Middle Devonian, probably with an angular, unconformity. The total thickness of the Lower-Middle Devonian deposits is evaluated at 4.5 km in the eastern part of the graben, whereas the thickness of the Upper Devonian deposits of Andrée Land and Dickson Land is evaluated at 650 m. Devonian deposits are characterized by cyclic sedimentation on a large formational scale and also by smaller scale rhythms grade as a rule from gravelites or interformational conglomerates, interbedded with coarse-grained sandstones, to sandy siltstones and claystones. In the Lower-Middle Devonian sequence as a whole the grain size as well as the order of cycles, increases south-eastwards from the head of Woodfjorden to the head of Vestfjorden.

The eastern deep depression is sharply divided into two areas by a saddle-shaped elevation not far to the south from the latitude of Vestfjorden. The northern area contains a complex monoclinal structure dipping to the north-east, in the southern area the rocks dip to the south and south-east. The major meridional fault zone associated with Wijdefjorden is a natural boundary for these two areas at the present erosion level. Within this zone the Devonian rocks are strongly deformed and folded by many near-fault diastrophic movements.

The Andrée Land anticline and adjacent syncline to the west are the largest known fold features complicating the northern part of the monoclinal structure. The fold axis of the Andrée Land anticline trends to the north-north-west. The structure can be traced for 70 km from Gråhuken in the north through the head of Purpurdalen to Kapp Petermann to the south, where it "fades" in the zone of strong folding and faulting near Wijdefjorden. The lowest parts of the Wood Bay Group, Kapp Kjeldsen Formation, and Keltiefjellet Formation outcrop near the axis of the structure, whereas the younger Wood Bay Group and Grey Hoek Group are exposed on its limbs. To the north and south of Kartdalen the anticline plunges in north-western and south-eastern directions, respectively. The limb span amounts to not more than 20 km and the vertical uplift of the crest is at least 1000–1200 m. The structure has an asymmetrical form, the eastern limb dipping at angles of 12° to 15° increasing toward Wijdefjorden to 20° and 25°. Angles of dip of the western limb usually

do not exceed 15°. A succession of axis offsets to the west due to a series of east-west trending faults may be observed. A number of north-eastward trending faults extending for tens of kilometres and controlling the basalts in Andrée Land are subparallel with the axis of this structure.

This major anticlinal feature is adjacent to the Andrée Land syncline to the west. This syncline has been traced from Jakobsenbukta to the latitude of Høegdalen, over 60 km, and is 7 to 11 km in width. Its axis is subparallel with the axis of the anticline, and similar offsets westward due to sublatitudional faults are developed. The syncline is possibly closed at the head of the Vestfjorddalen, south of which the Devonian rocks plunge stably and gently southwestward. On the western limb of the syncline the dip angles are 8–10° gradually decreasing towards Woodfjorden to 5–6°. Further to the west a monoclinal plunge of Devonian rocks at the angles of 4° to 5° may be demonstrated throughout the Woodfjorden area. The eastern limb dips with angles of 10° to 15°. In the core of the syncline the grey-coloured deposits of Tavlefjellet Formation and Forkdalen Formation outcrop, whereas on the limbs red beds of Keltiefjellet Formation and Stjørdalen Formation occur. The depth of subsidence reaches 1000 m in the Burfjellet area increasing northward as the axis plunges to the north.

The major structures above are in turn complicated by a number of small-scale folds and near-faults. The most important of them are the Prinstoppen graben-anticline (north-western Andrée Land), the Vestfjorden syncline and Gråkammen graben (south-eastern Andrée Land).

The Prinstoppen graben-anticline is formed by two northward radiating faults with a throw of 300–450 metres. The structure extends about 12 kilometres. This graben contains grey-coloured deposits of the Forkdalen Formation which compose an anticlinal feature complicated by small, steep folds and faults with offsets of some tens of metres. The folds are distinct near-fault in character. Their axes trend submeridionally, the limb span varying from 100 to 500 m, and ascending and descending displacements of the limbs being 30–50 m. The folds seem to be limited to the graben. The faults bordering the graben dip at the angles up to 65°.

The Vestfjorden syncline strikes almost meridionally from Krosspynten to the latitude of Høegdalen, for more than 20 km. Morphologically, the syncline is expressed by low relief: Vestfjorden, a bay, and Vestfjorddalen, its south tributary. The structure is 4 to 5 km in width. Its axis coincides with a fault striking meridionally along Vestfjorden. The elongation of the structure (1:4 to 1:5) indicates its genetic association with the faults. Sublatitudinal and northwestern faults successively displace its axis to the west. The beds of the east limb dip more steeply with angles up to 20° and 30°. In the core the "Dicksonfjorden Sandstone" outcrops, whereas on the limbs the "Austfjorden Sandstone" and the lower part of the "Dicksonfjorden Sandstone" are exposed. The depth of subsidence reaches 500 to 600 m.

To the east of the Vestfjorden syncline Gråkammen graben, extending north-south for about 20 km, occurs, its northern end (Kapp Petermann area) and southern end (Høegdalen area) being 1.5 and 4 km in width, respectively.

It is bordered by the major Wijdefjorden fault zone to the east and by the Vestfjorden syncline to the west. It contains red beds and grey-coloured deposits of Wood Bay Group and Grey Hoek Group folded and complicated by faults. The folds are distinctively near-fault in character. Their axes usually have an east-west strike. The limb span ranges from 100 to 500 m and the amplitudes vary from 50 to 100 m. Dips of 10–15° occur on the limbs, increasing up to 25° and 30° in the vicinity of faults.

Many small ups and downs structural features have been observed throughout the region. They are closely associated with major faults. These features are as a rule small steep folds ranging from a few hundred metres to some kilometres in length. Their axes are subparallel with faults situated near the folds. The strike of the axial plane is north-south or north-east-south-west, parallel to the main fault directions in the area. The folding is most intense in the Wijdefjorden fault zone (many folds with limb span of 100 to 300 m and dip angles from 30° to 50°). The intensity of folding decreases westward from this zone.

Devonian deposits outcropping between the "saddle" and the heads of Dickson- and Ekmanfjorden are in general slightly deformed. A constant (monoclinal) plunge to the south and south-west at the angles of 3–4° is typical in this area. Only a few important faults striking north or north-west with displacements of 500 to 700 m have been recognized in this area. These complicate the monocline, and folds are developed in nearby Devonian rocks. Axial planes of the folds are subparallel with the strike of the faults; the dip angles do not exceed 15° to 25° on the limbs. Approaching the Wijdefjorden fault zone, the intensity of folding increases gradually with a simultaneous increase in faulting.

Classification

The Devonian Graben is multiple faulted with a predominance of steep, normal faults. Most investigators suggest that they are connected with the terminal episodes of the Caledonian orogeny. Generally, the fold structures and flexures are related to the faulting. Tectonism also occur in post-Devonian time. The absence of post-Devonian rocks in most of the region hampers a chronological classification of the known faults. However, observations on relationship between faults, data on their orientation, morphological features, position within the graben and facies and thickness analysis may be combined to divide faults into pre- and post-Devonian.

The pre-Devonian faults are represented by the major faults; movements along these planes determined all the general features of the present day block structure of the graben. These faults strike north-south throughout northern Spitsbergen and probably further south where they are buried under younger sequences. During their prolonged evolution the major faults were reactivated both during the Devonian time and in the later epochs. Among these, two major faults, complicating the western part of the graben, may be recognized; the fault along the western coast of Raudfjorden with a vertical amplitude of not less than 1000 m in the Liefdefjorden area and the Breibogen–Ekmanfjorden fault with the amplitude of about 1500 m in the Bockfjorden area. Both

faults are approximately north-south trending and have an axial plane dipping to the east at an angle of 70° to 80°. Shear and mylonization zones associated with these faults are up to 300 m in thickness. Some eastern normal faults and strike-slip faults having a north-eastern strike and belonging to the Wijdefjorden fault zone, may also have originated before the Devonian. The most intense movements associated with these faults and the Breibogen–Ekmanfjorden fault, occurred in the Lower Devonian after the formation of the Red Bay Group within the inner horst.

The steeply dipping faults of post-Devonian origin, widespared within the Devonian Graben, generally have small vertical amplitudes (100 to 500 m) and represent a single set of tectonic deformations related to block movements of the Earth's crust. The main Devonian field is cut up by these faults into many block fragments. The great majority of them formed during the initial stages of platform evolution in this region. The most intense block movements took place during Lower Carboniferous, although along most major faults the movements were reactivated in the later epochs too.

Among the faults of post-Devonian origin, four groups may be recognized (from older to relatively younger): faults trending north-east, submeridional (north-south), sublatitudinal (east-west), and north-west.

A relatively small group of steeply dipping, almost vertical normal faults trending between 30° and 60° NE occur throughout the graben, are 10 to 15 km long, and have variable vertical displacements of 100 to 800 m. They are difficult to see, and only the most important coincide with morphological features such as valley directions. The lack of hydrothermal alteration of the brecciated material is characteristic and the zone of brecciated or intensively fissured rocks hardly exceeds 20 to 30 m. The entire absence of fold structures near the fault zone is also typical.

Normal and strike-slip faults trending from 350° to 20° are grouped as submeridional faults. These displace the north-eastward trending faults, the most significant movements along their planes probably taking place during the Middle Carboniferous (?Bashkirian age). In Andrée Land and Dickson Land the submeridional faults form two major zones related to the eastern coast of Woodfjorden and the western coast of Wijdefjorden and Austfjorden, respectively, the latter being the wider.

Most of the faults belonging to the Woodfjorden zone are normal faults. The exposed fault planes are either vertical or they dip westward at an angle of 70° to 80°. The vertical displacement ranges from tens to hundreds of metres, the eastern block as a rule being downthrown. The thickness of the zone of intensively deformed and fissured rocks is 2 to 5 km.

The fault zone related to Wijdefjorden and Austfjorden consists of a basal strike-slip fault subzone 2 to 5 km wide (to the east) and a shearing-linear fold subzone 12 to 15 km wide (to the west). They are separated by a major strike-slip fault which extends along the eastern coast of Andrée Land, through Petermannfjellet and further southwards up to the head of Mimerdalen. To the south of Kapp Petermann the vertical displacement is about 1200 m, the eastern limb being upthrown.

The strike-slip fault subzone is characterized by curved fault planes dipping westward at angles of 50 to 60° and by vertical displacements of one or more kilometres. Zones of quartzitized and calcitized tectonic breccia 30 to 100 m thick are related to these faults. Within this subzone Devonian rocks are strongly deformed and folded. Middle Carboniferous monzonite dykes are associated with these major submeridional faults.

The shearing-linear fold subzone contains many normal faults with vertical displacements of 100 to 300 m. Narrow elongated folds, fault-adjacent in character, are associated with them. The subzone extends from the head of Mimerdalen northward up to Gråhuken, the most significant normal fault extending for 15 to 30 km, the eastern limb usually being downthrown. The shear zones contain quartz-calcite veins 0.5 to 3.0 m thick. On the peninsula between Vestfjorden and Austfjorden the subzones are separated by a meridional graben, the Gråkammen Graben, extending for 20 km and being between 1.5 and 4.0 km wide.

The group of sublatitudinal faults consists of a normal fault series which intersect the Devonian Graben from west to east and displace the other tectonic features except the north-west faults. Many of them coincide with the directions of the widest valleys. Fault planes dip northward at an angle of 65° to 70°, the northern block usually being downthrown. The vertical displacements generally do not exceed 300 to 400 m. The absence of low-temperature mineralization in the fault zone is typical for this group. The most significant faults are the latitudinal Jakobsenbukta fault and those coinciding with the valleys of Verdalen, Stjørdalen, Purpurdalen, and some others.

The north-western fault group contains tectonic displacement trends of 320° to 340° and intersects all the other faults. Most of them are tens of kilometres long and have relatively small vertical displacements (up to 400 m). Faults of this group are known throughout the graben, and are especially widespread in its eastern deep subsidence structure. They complicate the near-crest part of the Andrée Land anticline, and displace the Devonian rocks, forming another major structure of the graben, the Andrée Land syncline. Shear and mylonitization zones, folds, and sharp deviation in dip angles and directions of the rocks are associated with these faults. The zones of brecciated rocks do not usually exceed 20 to 30 m in thickness and as a rule show only slight hydrothermal alternation. The major faults of this group control the distribution of basalt rocks in Andrée Land. The most significant representative of this group is the normal fault extending from the mouth of Junkerdalen in Woodfjorden through the head of Purpurdalen and Kartdalen up to the western coast of Austfjorden. It extends for about 50 km. The fault trends 330° and has a vertical displacement of about 300 m, the north-eastern block being upthrown. Most of the known basalts in Andrée Land run parallel to this fault direction.

Analysis of the data shows that the initial size of a graben-like subsidence may have been significantly larger than the present Devonian Graben. This is indicated by the presence of the same facies of Devonian rocks both in the Kongsfjorden–Hornsund area and in the present-day Devonian Graben. The

western boundary of the graben is probably a northern extention of the western bordering fault zone originating early in the Caledonian orogeny. The position of the eastern boundary of the early graben is not clear. In our opinion this boundary was located to the east of the modern graben boundary, in the Ny Friesland area, or maybe in the Edgeøya and Barentsøya region. This is based on the presence of marine deposits in the Wijde Bay Group in the north-easternmost part of the graben, the zone of their distribution being open eastward. Significant ancient tectonism in the Ny Friesland area is indicated by relics of Lower Carboniferous rocks which occur in the western part of the peninsula. Generally, the presence of Devonian deposits in the area is not to be ruled out.

Geological History

A geological history of the Devonian Graben may be reconstructed from the data. Block movements along faults and orogenesis gave rise to a grabenlike subsidence structure trending north-east, which was superimposed on the Caledonian structures. This subsidence structure was situated between the Spitsbergen west coast high and the Nordaustlandet high (or anticlinoria) and may have extended southwards to Barentsøya and Edgeøya. Its original extent is unknown, but it is possible that it was bordered by the Bjørnøya–Hopen high to the south.

The initial subsidence structure differs from its present form. The western region (to the west of the Breibogen–Ekmanfjorden fault) was deepest, and during Gedinnian, the Siktefjellet and Red Bay Groups were deposited there. Block faulting with slight folding occurred later in this area. The eastern part of the structure was not prominent during the Gedinnian, and sedimentation was slow or absent. Late in the Gedinnian block faulting along the Breibogen–Ekmanfjorden fault and partly along the Wijdefjorden fault zone within the initial graben gave rise to the formation of a vast, deep trough which may have extended eastward to Nordaustlandet. The southern part of Andrée Land and Ny Friesland may represent an area of lower subsidence in the newly formed trough. This is reflected in progressive psammitization of the Wood Bay Group in a south-eastern direction. Steady subsidence with a centre in the eastern part of Wijdefjorden, may have continued to Lower Carboniferous. During that time the trough was filled up by a thick sequence including Lower, Middle, and Upper Devonian formations of lagoonal-non-marine, coastal-marine, and non-marine facies. During the final stage of orogenesis ("Svalbard phase of folding") movement along fault planes was renewed, giving rise to most of the existing faults and producing the block structure of the graben in its present form. The eastern termination was caused by later uplift of the Ny Friesland horst where Devonian deposits were eroded. The Andrée Land anticline formed, together with an adjacent syncline in the west and possibly in the east, along the graben axis and the bordering fault planes.

The platform development of the area was characterized by predominantly continental sedimentation. In the Middle Carboniferous (?Bashkirian) intense block faulting occurred along the ancient Wijdefjorden–Kvalvågen

tectonic lineament together with the formation of most of the submeridional faults. Monchikite dykes dated at 309±5 m.y. (K-Ar age) are associated with these faults.

General uplift and block movements continued to and into the Early Cretaceous, but short-term subsidence may have occurred intermittently. Around Early Cretaceous, the sublatitudinal fault system formed, and the region of Andrée Land may represent a mountainous area with rough topography. In the Late Cretaceous, tectonic movements steadied, and the territory was intensively eroded, eventually giving rise to a vast (?Late Cretaceous) peneplain.

At the Late Cretaceous–Paleogene, boundary block movements along the graben border faults were renewed, which formed a north-eastern fault system parallel to the former and controlling the basalt distribution in Andrée Land. The basalts flooded over a smooth surface dipping gently to the north and mostly submerged below sea level.

It is probable that during Paleogene and early Neogene the region was peneplained. Only in the Pliocene were the intensive tectonic movements initiated in Spitsbergen. North Spitsbergen may have been lifted uniformly considering the hypsometric uniformity of the raised peneplain surface. Reactivation of the bordering faults especially conspicuous in Central Spitsbergen, occurred simultaneously.

The final tectonic episode was characterized by uplift complicated by displacements along rejuvenated faults, with associated volcanic activity. Short-term subsidence intervened.

Glacial isostatic rebound caused an uplift of 45 to 50 m over the last 5000 years.

Thus, the present boundaries of the Devonian Graben have been determined by vertical displacements along rejuvenated faults both of Devonian origin and of post-Devonian age. The most important were the submeridional faults (graben-bordering faults) and the Pretender fault zone with a NW strike.

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