33 IGC excursion No 56, August 15 – 22, 2008

33 IGC, The Nordic Countries

# Bjørnøya, an Upper Paleozoic-Triassic window into the Barents Shelf


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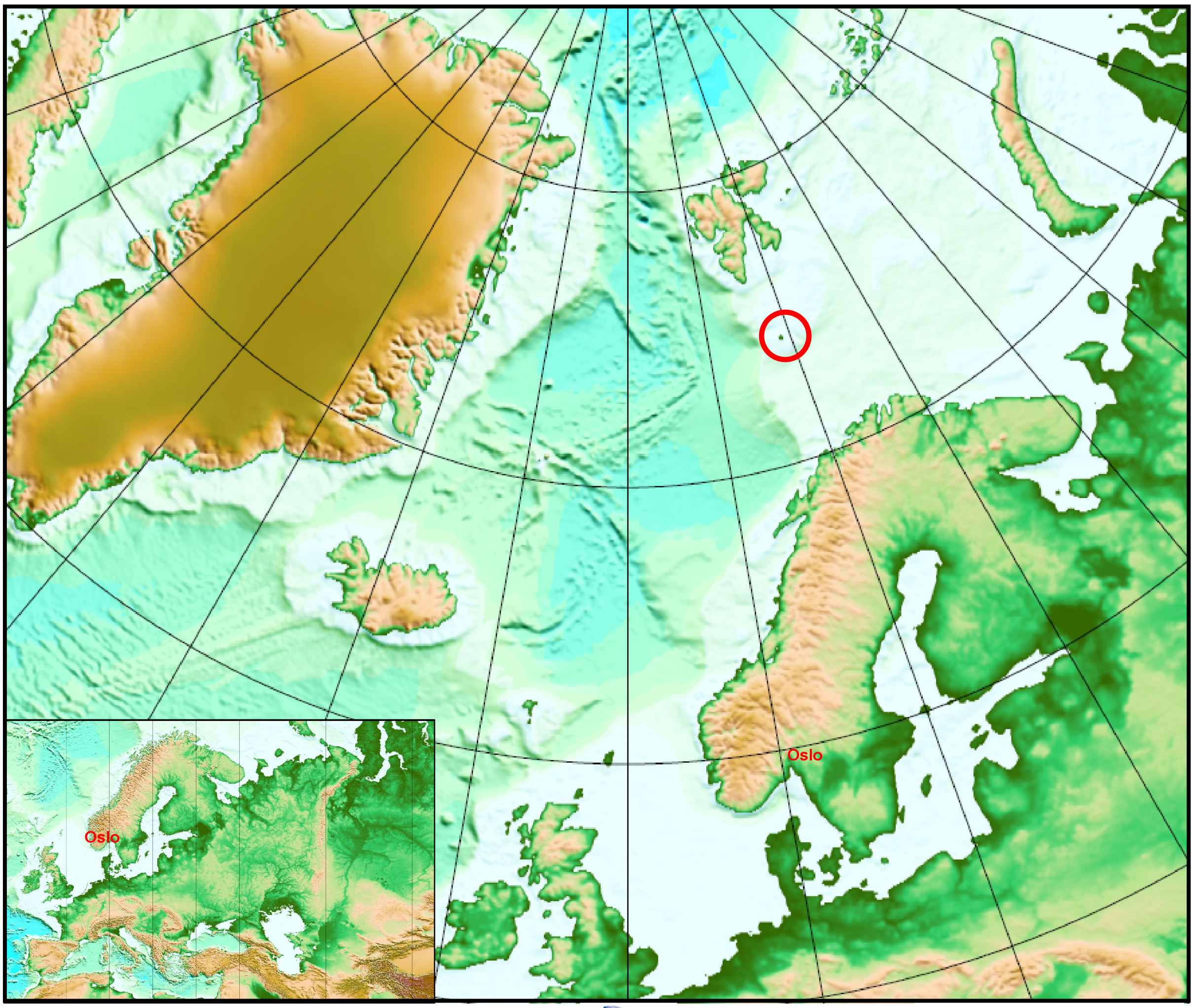


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**Figure 1** **Bjørnøya (red sircle) is located in the middle of the Barents Sea**

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# Abstract

The small island of *Bjørnøya* ("Bear Island"), situated in the Barents Sea almost midway between northern Norway and Spitsbergen (Figure 1), displays a Precambrian to Triassic succession in a continuous series of spectacular cliff exposures. These exposures provide a key not only to the evolution of the Stappen High (on which Bjørnøya rests) but also to a better understanding of the Barents Shelf.

Precambrian to Ordovician dolomites, limestones, quartzites and shales form the basement (Hecla Hoek) on which the Upper Palaeozoic succession of Bjørnøya was deposited. In the latest Devonian and early Carboniferous times a southwestwards downtilted half-graben developed over the present-day island. Some 600 m of sandstones, coals and shales are preserved in two upward coarsening sequences. These represent the repeated progradations of sandy fan systems over floodplains with lakes and northward meandering river channels. Mid-Carboniferous (Serpukhovian) uplift was followed by rifting and the western hinterland shed debris over its faulted eastern margins. A shift from humid to a semi-arid climate is reflected by the predominantly red colouration of the resultant 200 m thick succession of conglomerates, sandstones and shales, with caliche horizons. Penecontemporaneous regional sea level rise resulted in the gradual replacement of the alluvial floodbasin deposits by shallow marine siliciclastics and carbonates of shoreline, tidal flat and shallow shelf origin. Continued transgression through the Moscovian, is indicated by the gradual change to a marine carbonate-dominated succession, with cherty biomicrites reflecting the establishment of an open carbonate shelf over the entire area.

A marked rejuvenation of tectonic activity in the late Moscovian established a different depositional mosaic - faulting affected exposures on the present island along N-S to NE-SW lineaments, with differential subsidence down to the west. This produced erosion of earlier deposits over the eastern part of Bjørnøya and deposition of conglomerates, sandstones, shales and dolomites in alluvial gully, coastal and shallow shelf environments to the west. A 200 m thick succession is preserved in western areas and eroded remnants are also preserved as outliers elsewhere on the island. Conglomerate clasts indicate derivation by successive stripping and redeposition of mid-Carboniferous to uppermost Devonian and then basement strata. By the latest Carboniferous the region had again stabilised and platform carbonate deposition resumed, with the development of paleoaplysinid carbonate build-ups. Early Permian flexuring, uplift and peneplanation followed. The highly condensed mid- to Upper Permian marine succession of mixed siliciclastics and carbonates oversteps all older strata. The Stappen High then remained a positive feature through to the late Triassic, the youngest beds preserved being of Carnian age. The high subsequently subsided significantly during the Mesozoic, but it again became a positive feature as a result of one or more phases of uplift during the Cenozoic.



## Sponsors and contributors

## Excursion Route

**Bjørnøya is an island in the middle of the Barents Sea. We will stay on board the ship (Figure 2) and sail to the actual location for each landing. The localities are spread around the entire island, and proper landing locality will be selected each day based on weather, wind and wave conditions. The guidebook is therefore organised stratigraphically, but the planned landings are suggested in the "Field Plan", in Figure 5 and in the Field activity part of this guidebook.**

## Field plan

Topics to study:

- Devonian - Lower Carboniferous sequences with fluvial deposits and flood plain coal bearing sediments. A visit to the old mining town of Tunheim (1916-1925) is included (E coast, Røedvika Fm)
- Lower Carboniferous porous sandstones (Nordkapp Fm) and Permian limestones (Miseryfjellet Fm) on the N coast
- The continental to marine transitional Landnørdingsvika Fm (Mid-Carboniferous) on the SW coast
- The marginal marine rhythmic sequences and marine carbonates of the Moscovian Kapp Kåre Fm (N and SW coasts)
- Tectonically influenced clastic deposits of the Upper Carboniferous Kapp Hanna Fm (N and W coasts)
- Lower Permian palaeoaplysinid reefs and stacked bioherms of the Kapp Dunér Fm (W coast)
- Mixed carbonates and clastics of the Hambergfjellet Fm, the only land exposure of the Bjarmeland Group (SW cliffs)
- Upper Permian fossil-rich platform carbonates of the Miseryfjellet Fm (N coast and Miseryfjellet)
- The Triassic Urd and Skuld fms forming the highest points of Bjørnøya, top at 536 m above sea level
- Visit the Bjørnøya Meteorological Station (with its amateur museum – N coast).

Which localities to be visited will be decided each day depending on weather conditions.

# Logistics

## Dates and location

***Timing***: **From 15 August to 22 August 2008**
***Start location***: **Tromsø,** morning 15$^{th}$ August.
***End location***: **Tromsø,** return evening 22$^{nd}$ August.

## Travel arrangements

The excursion is ship based, we live and have meals on-board and go ashore using rubber boats for the localities, which are mostly coastal cliffs. Inland exposures include Permian sandstones and limestones and the clastic Triassic succession forming the top of Miseryfjellet mountain at 536 metres above sea level.

## Accommodation

The ship has all facilities (Figure 3); you only need to bring proper field-clothes. Depending on flight schedules you may need hotel accommodation in Tromsø the night before and after the excursion.

## Field logistics

We go on land each day (some days several times) using rubber boats and survival suits for transport between ship and land. You should bring a small rucksack for extra clothes, raincoats and a thermos-flask. Temperature will normally be between 0 and 10 ºC. We will supply all other equipment such as guns for polar bear protection, ropes to prevent sliding, radios for contact with the ship etc.

Weather permitting, one day will include a walk from sea level to the highest peak on the island (to see the Triassic) which is 536 metres above sea level. Participants need to be fit for this walk. The remaining days will consist of easy walks along sea cliffs, but sometimes on rugged and blocky surfaces.

**Figure 2 M/V *Kongsøy* used as expedition ship on eastern Svalbard, summer 2007**

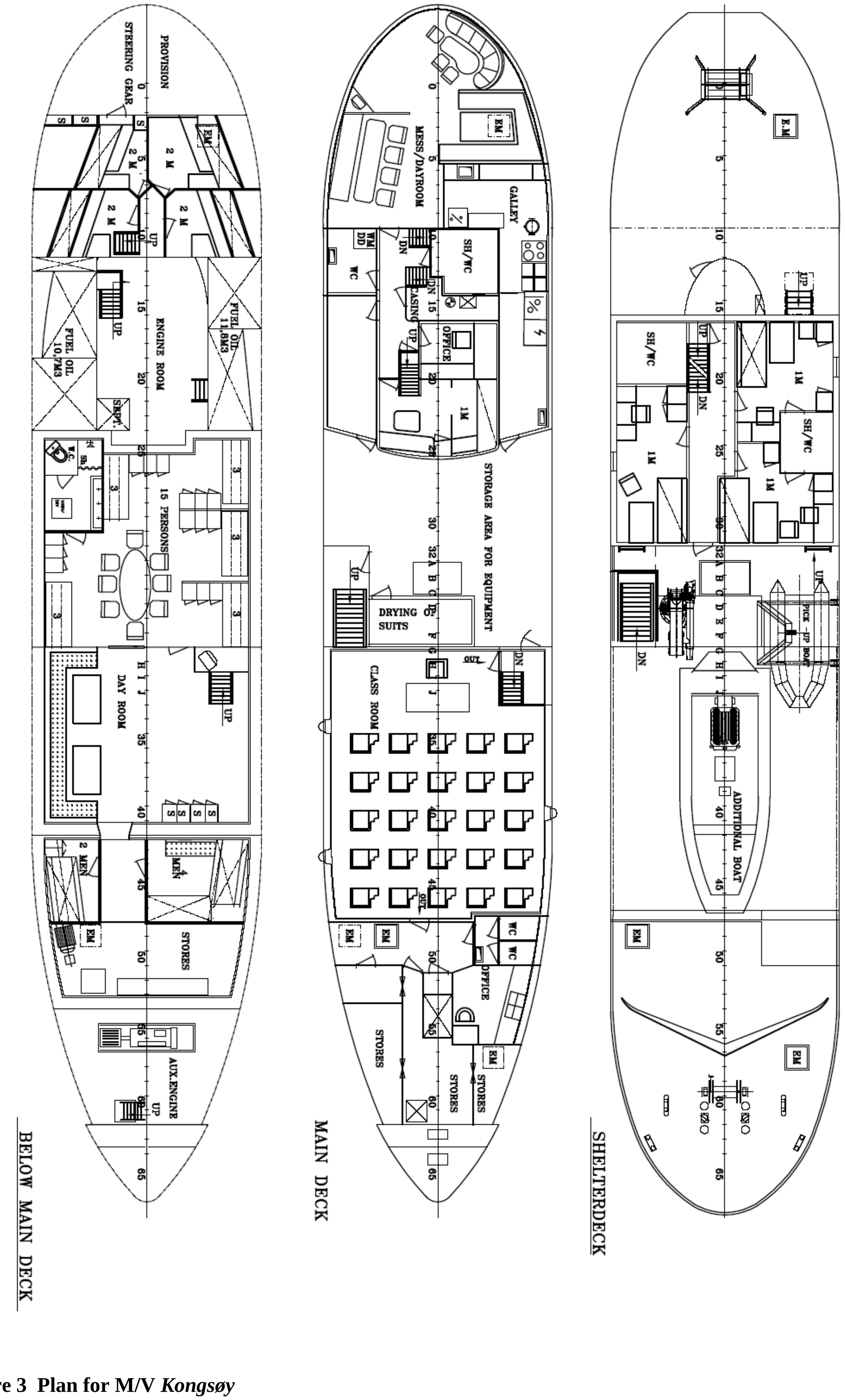



**Figure 3 Plan for M/V *Kongsøy***

## Brief history of Bjørnøya

This short summary of parts of the history of Bjørnøya is mainly based on the account by Horn & Orvin (1928) for the older part. Although Bjørnøya must have been known to the Norsemen who found Svalbard at the turn of the twelfth century, the Dutch expedition in 1596, with Willem Barents as chief pilot, is regarded as the modern discovery of the island. At the island they killed a polar bear, and in this way the island was named, although normally polar bears only sporadically visit the island during the maximum ice period in winter.

In the early sixteenth century Englishmen carried out extensive walrus hunting, while little is known for the latter part of the century. The first wintering, however seems to have taken place in 1700 by the crew of a ship which was wrecked on the island; only half of the crew survived.

Russian trappers wintered often during the eighteenth century, and at this time Norwegians also started to show interest in the island. Examples of the hazardous nature of these expeditions are demonstrated by two accounts from 1820 of a crew which managed to return to Norway in an open boat when their ship was forced ashore in a heavy storm.

Houses were build by Norwegian merchants in the early 1820's and were used for wintering by the hunters. The catch varied considerably from 700 walruses down to only one; few hunters seems to have wintered repeatedly. In the winter 1865-66 skipper Tobiesen raised a house in Nordhamna, at the location of the present radio station. This house was later rebuilt with government money for free use by fishermen and hunters.

In 1827 the geologist B.M. Keilhau visited the island, and he collected fossils and commented on the coals, which he was astonished to find at such high latitudes.

Scientific expeditions became more common on the island from the mid-19th century, and Sweden played a major role. After an initial visit in 1864, Nordenskiöld made a rough sketch of the island, and in 1868 the Swedes for the first time used coals from Bjørnøya for bunkerage. Investigations of fossil plants collected on these expeditions were subsequently published by Heer (1871). In the later part of the century several expeditions visited the island, most of them from Sweden. The resulting first extensive geological accounts from the island were published by Andersson (1900).

### The 20th Century

The "no man land" nature of Bjørnøya prompted different exploitation efforts in the first part of the 20$^{th}$ century, when mineral resources came into focus.

Different German interests proclaimed claims on the island at the turn of the century, the driving force was the journalist Lerner. They also built houses, and some coal was mined for testing purposes. This German company also did some diamond core drilling. Commercial mining, however, was never started, and in 1925 Norway bought the German claims. Some interest in Bjørnøya was also shown by Russia, and minor expeditions were sent to the island in 1899, 1916 and 1921. One area claimed by the Russians was returned to Norway in the 1920s as part of the general agreement over Svalbard. All economic activity, except for the exploration work by the German and Russian interests mentioned above, was carried out by Norwegians.

From 1905 to 1908 a whaling station was run by M.A. Ingebrigtsen at Kvalrossbukta and the catch of 231 whales gave 5790 barrels of oil. This company also claimed the northeastern half of the island for coal and galena exploration.

The major activity on the island was run by the Stavanger company I/S Bjørnøens Kullkompani, later Bjørnøen A/S, which claimed the whole island in 1915 and bought the claims and houses owned by Ingebrigtsen. In the first years the work was concentrated on the coal-bearing formations, and diamond core drilling was carried out north of Miseryfjellet and near Laksvatnet. The building of the mining town Tunheim also started, as well as some mining. A mapping survey of Bjørnøya was undertaken, with the main mapping activity from 1922 to 1931 (the results, including a 1:25 000 scale map were published in 1944 as number 86 in the Norsk Polarinstitutt Skrifter series). Most exploration and construction activity was undertaken during the summer months, while a reduced staff wintered and worked in the mines. A coal-loading system was also established, together with a short railway between the coast and the mines. Altogether 116 095 tons of coal were produced from 1917 to 1925 and the maximum number of men was 260 in 1923. In 1926 75 tons of lead-ore were also shipped.

Following the exploration work in the mining area, geologists were employed to evaluate the possibilities found on the island. In 1918 Olav Holtedahl worked on the island, and he supervised drilling and carried out some general mapping. His main interest, however, was the Hecla Hoek complex, were he concentrated his scientific work (Holtedahl 1920a, b). From 1922 an extensive geological investigation was conducted by the State supported Svalbard Expeditions (later Norsk Polarinstitutt), with G. Horn and A.K. Orvin as responsible geologists. As new maps (1:10 000) were available, geological maping of the whole island was undertaken. As a result of the excellent exposures on the island and using data from shallow cores, a good geological map was produced; this was later published (Horn and Orvin 1928). During this period of exploration a total of 1 505 m of cores were drilled and several pits and trenches were dug.

A drop in coal prices to 1/3 in 1921 and a continuous low price level, and the result of the geological exploration which showed that the coal-seams did not have the necessary thickness or purity, prompted the decision to close down the mines in 1925 - a conclusion confirmed by the evaluation of Horn & Orvin (1928). The claims on Bjørnøya are today owned by the Norwegian coal company in Longyearbyen (Store Norske Spitsbergen Kullkompani, SNSK).

From 1918 a meterological and radio station was operated by the Norwegian authorities, and this was in function until the Second World War. In 1941 this radiostation as well as the whole mining town of Tunheim was shelled by the British to prevent use by the Germans. The Germans however managed to maintain a wireless and meteorological station in the southern part of the island during the war. After the war the new Norwegian meteorological station was built at Herwighamna on the north coast, and this station have been the centre for activity since then.

The detailed geological survey in the 1920s discouraged other geological investigations for a considerable time. Except for a few paleontological works, new fieldwork was not conducted before the 1970s. Some Russian work has been published from this period, notably

Krasilscikov and Livsic (1974) on the tectonics of Bjørnøya, and Pcelina (1972) on the Triassic succession.

A new approach concentrating on sedimentological aspects of the Upper Paleozoic succession was started by Worsley and Edwards (1976), and was followed by work by the Universities of Bergen and Oslo as well as other Norwegian institutions. These studies related the Bjørnøya succession to the geology of the other islands in the Svalbard Archipelago and the adjacent shelf. A synthesis of this new generation of work was published by Worsley and coworkers in 2001.

# Geology

The small island of Bjørnøya ("Bear Island", only 178 $km^2$ in area), situated near the Barents Sea's western margin almost midway between northern Norway and Spitsbergen, shows a Precambrian to Triassic succession (Figure 4) in a continuous series of spectacular cliff exposures. These exposures provide a key not only to the evolution of the Stappen High (on which Bjørnøya rests) but also to the development of the major lineaments that subsequently contributed to the formation of both the Norwegian-Greenland Sea and the Arctic Ocean.

A synthesis of both published and unpublished recent work was presented by Worsley *et al.* (2001) and the present guidebook is based on this and other recent work.

## *Regional Geology*

The Barents Sea covers an extensive shelf area that extends northwards from the arctic coasts of Norway and Russia to the margins of the Arctic Ocean (Figure 1). Bjørnøya is situated on the Stappen High, near the Barents shelf's western margin and approximately midway between mainland Norway and Spitsbergen. This high was a positive Late Palaeozoic feature; it then subsided in the Mesozoic and was again uplifted in the Cenozoic. The sedimentary succession exposed on the island ranges from the Upper Precambrian to the Upper Triassic, with a composite thickness approaching 3 km (Figure 5). Significant unconformities define the boundaries between three main depositional complexes: *viz*. the Pre-Devonian economic basement, the Late Paleozoic basin and the Permo-Triassic platform.

Bjørnøya itself comprises two topographically distinct areas, each directly related to its underlying geology. The extensive northern plain generally undulates between 20 and 50 m above sea level, with a labyrinth of rock fields, marshes and small lakes - all of which make walking and reconnaissance difficult. The few poor inland exposures give little information on the complexity of the underlying Upper Palaeozoic sequence and this succession is best studied in the coastal cliffs. The exposures there are excellent, but fieldwork is often hazardous. The south and southeastern part of the island is a rugged mountainous terrain dominated by basement exposures, and more than 400 m high cliffs rise precipitously from the sea. Mountaintops in this area show almost flat-lying exposures of the Permo-Triassic platform sequence unconformably overlying all older units; Late Paleozoic half-grabens are locally developed, cutting into the basement but predating the platform units (Figure 6). Triassic strata - the youngest pre-Quaternary deposits preserved on the island - are exposed in three conical peaks on the Miseryfjellet massif, with youngest Carnian deposits preserved at 536 m above sea level.

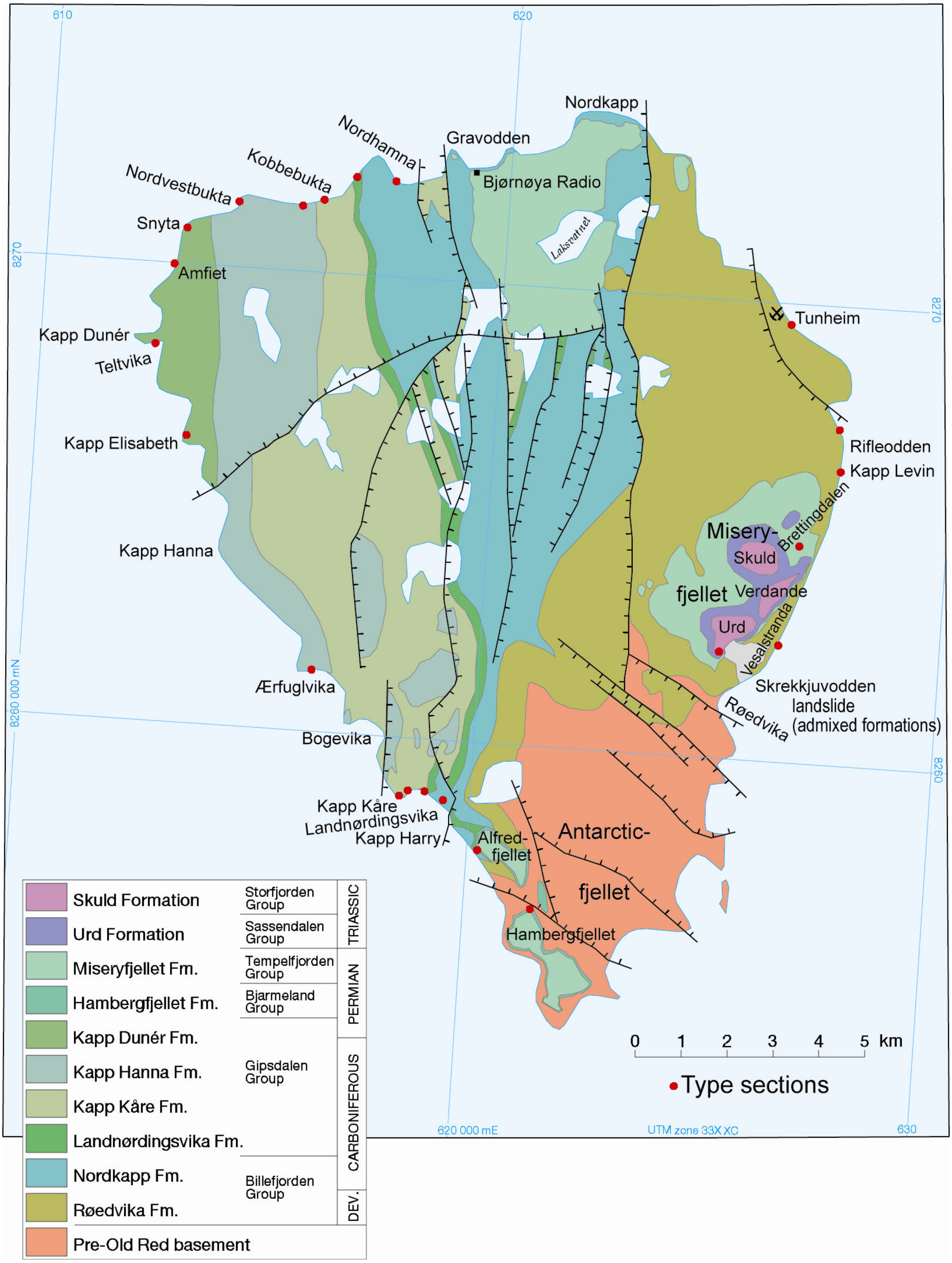



**Figure 4 Geological map of Bjørnøya (from Dallmann 1999).**

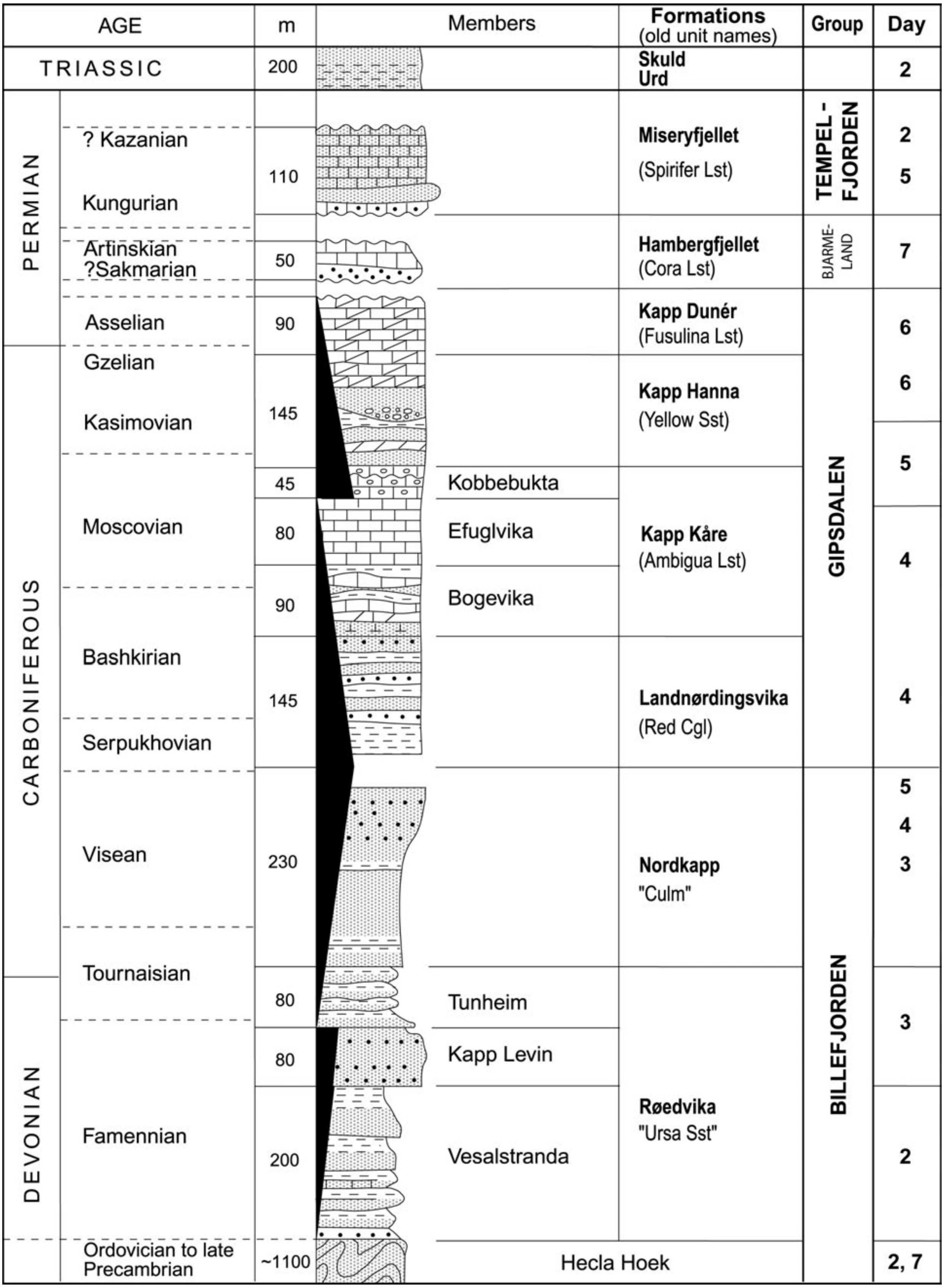



**Figure 5  Stratigraphic column of Bjørnøya, with indications of which part of the succession will be studied each day.**

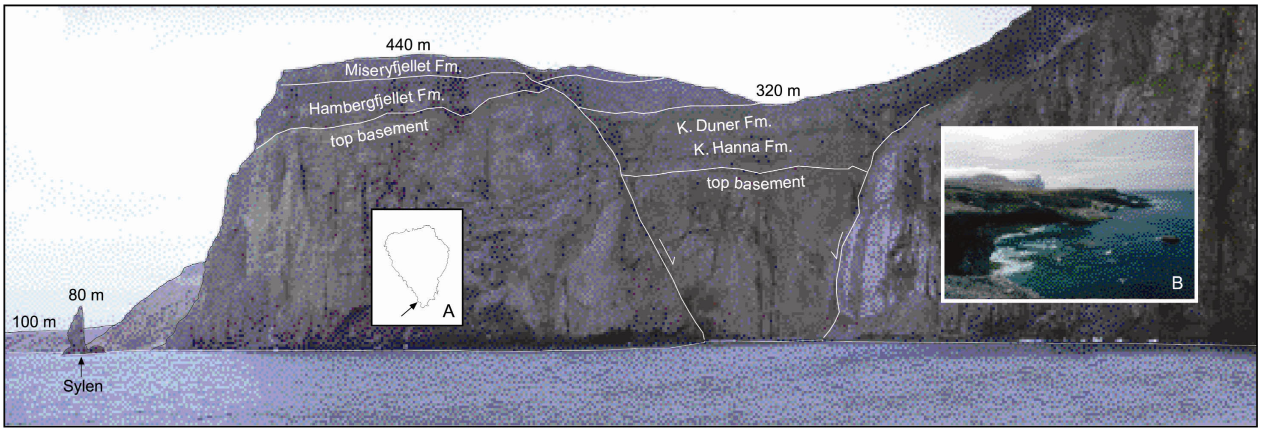



**Figure 6 The cliffs of Hambergfjellet at the SW coast with (Inset A) locality map and (Inset B) view of southern massif from northern coast. Note the 80 m high stack of Sylen (the needle) for scale.**

## *Hecla Hoek Basement*

Precambrian to Ordovician dolomites, limestones, quartzites and shales form the basement on which the Upper Palaeozoic succession of Bjørnøya was deposited. They were first studied by Holtedahl (1920) and defined in their present formational units by Krasilscikov & Livsic (1974)(Table 1). Three distinct basement units, the Russehamna, Sørhamna and Ymerdalen formations, have a total thickness of around 1200 m. The stratigraphically oldest, but structurally highest unit, the Russehamna Formation, consists of grey massive dolomites with a suggested Upper Riphean to Vendian age. Shales and quartzitic sandstones of the Sørhmana Formation are approximately 150 m thick and may correlate to the Late Precambrian, including the Varangian glacial sediments of northern Norway and Spitsbergen. The uppermost stratigraphic unit, the Ymerdalen Formatioon, consists of 640 m thick dolomites and limestones, with a suggested Middle Ordovician age. Although earlier worker, including Krascilsikov and Livsic, have often suggested that this sequence lacks typical Caledonide features (probably based on misleading ship-based views of the southwestern cliffs, with an apparently flatlying basement succession), these rocks are in fact stacked in a WNW-verging thrust pile of Caledonian origin, confirming Holtedahl's original views.

**Table 1 Comparison of the old and new terminology of the "Hecla Hoek basement"**

| Holtedahl (1920) | | Krasilscikov & Livsic (1974) | |
|---|---|---|---|
| **Unit** | **Min. thickness** | **Unit** | **Thickness** |
| Tetradium Limestone Series | > 240 m | Ymerdalen Fm | > 450 m |
| Younger Dolomite Series | > 400 m | | |
| Slate-Quartzite Series | > 175 m | Sørhamna Fm | ca 120 m |
| Older Dolomite Series | > 400 m | Russehamna Fm | > 500 m |

The Hecla Hoek rocks are exposed along the southern rocky mountains and cliffs of Bjørnøya. We will sail past spectacular cliff exposures and study them from the ship. Of especial note are the cliffs of Sørhamna showing thrusting of the late Precambrian Russehamna Formation over the Ordovician Sørhamna Formation, and half-grabens in the southern cliffs which dissect both basement and Late Paleozoic units (Figure 7). We will also see parts of the Hecla Hoek succession when walking to the younger exposures on Miseryfjellet (planned for Day 2).


**Figure 7  Caledonian thrusting of Hecla Hoek rocks in Sørhamna**

Among other special features that we may visit within the Hecla Hoek succession are the small island of Stappen (Figure 8), consisting of lower Ymerdalen Formation grey dolostones, that has given name to the Stappen High on which Bjørnøya rests. Ymerdalen also contains an old led mine (Figure 9) and we may also visit the spectacular Perleporten (Figure 10) that may be navigated in good weather conditions.

**Figure 8  Stappen the southernmost point on Bjørnøya has given name to the Stappen High where the island rests. "Younger Dolomite" = Ymerdalen Fm.**

**Figure 9  An old galena mine in Hecla Hoek basement rocks within the Ymerdalen Formation at the northern foot of Antarcticfjellet.**

**Figure 10  Perleporten (the pearly gate) is a 170 m long cave through the "Younger Dolomite" =Ymerdalen Fm.**

## *Famennian to Viséan humid clastics*

This sequence has been extensively studied by John Gjelberg, who has contributed this section based on his numerous publications shown in the reference list at the back of the guide.

### Røedvika Formation

The Røedvika Formation (Famennian-Tournaisian) comprises the Vesalstranda (oldest), Kapp Levin and Tunheim members (Figure 11& Figure 12). We will concentrate our attention on the two youngest units as the Vesalstranda Member is exposed in inaccessible and dangerous cliffs on the eastern slopes of Miseryfjellet (Figure 13). The total maximum thickness of the formation is about 360 metres on the eastern coast., thinning towards the S and SW, to about 100 m around Ellasjøen, probably as a result of synsedimentary tectonic activity. The lower and middle parts of the formation form a single coarsening upward motif from the coal-bearing Vesalstranda Member to the coarser braided stream deposits of the Kapp Levin Member. The uppermost Tunheim Member shows a return to mixed fine and coarse lithologies, representing the re-establishment of flood-plain environments in which meandering streams flowed largely towards the northwest.

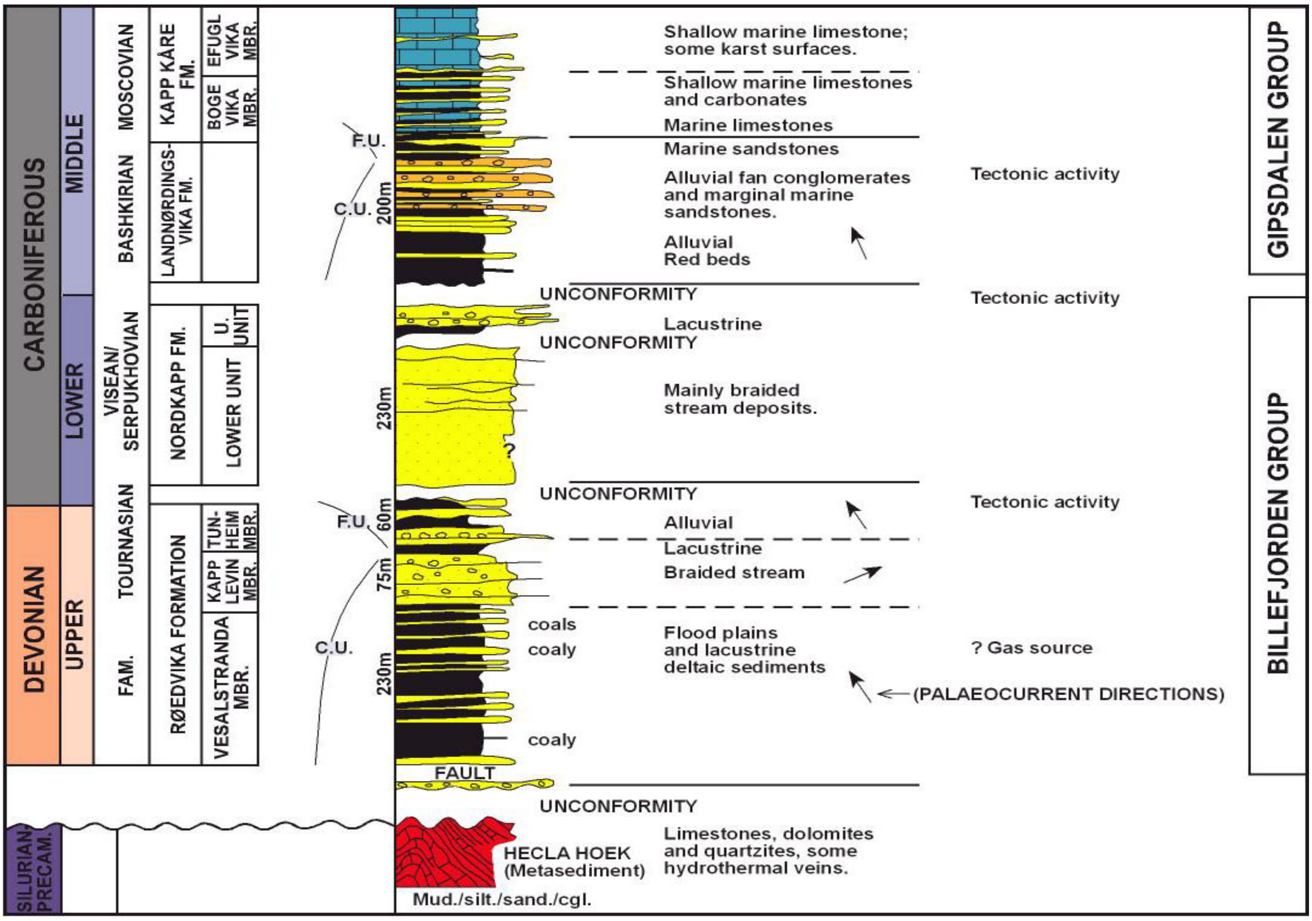



**Figure 11 Lithostratigraphic log through the uppermost Devonian to middle Carboniferous succession on Bjørnøya**

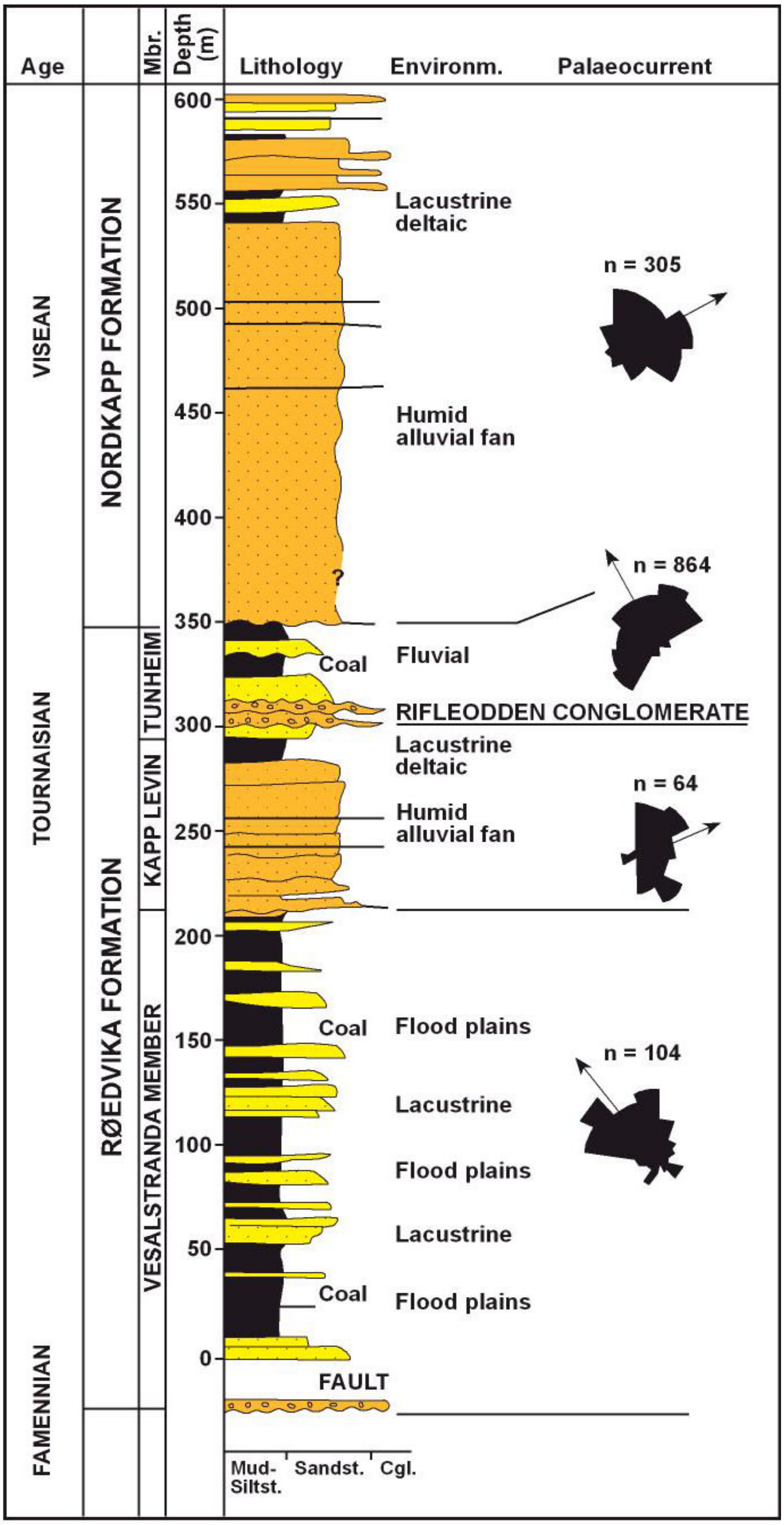



**Figure 12 Simplified stratigraphic log through the uppermost Devonian and Lower Carboniferous succession with palaeocurrent data**

### Vesalstranda Member

The member’s sediments reflect typical continental depositional conditions on low palaeoslopes, while palaeocurrent directions suggest a source area to the south or south-east of Bjørnøya. Two major environments of deposition are recognised:

- Flood-plain environments, with sedimentation in and adjacent to north-westward flowing streams of high sinuosity.

- Lacustrine deltaic environments, with delta lobes prograding into standing water bodies (lakes).

The fluviatile sediments (Figure 14) accumulated in floodplain areas dominated by lakes and high sinuosity meandering streams. Crevasse and distributary channels brought sediments into the lakes and caused a progradational infilling. An overall time trend of sedimentation from lacustrine deltaic in the lower and middle parts to fluvial in the upper part suggests a generally progradational basin filling episode, which culminated in the overlying coarser-grained alluvial Kapp Levin Member.

**Figure 13 The Vesalstranda member occurs below the cliff forming Permian Miseryfjellet Formation and consists of shale and sandstones with thin coal beds.**

**Figure 14 Fluvial sandstones from the upper part of the Vesalstranda Member. Northern foot of Miseryfjellet at Vesalstranda.**

## Kapp Levin Member

The only accessible complete (75 m thick) section through this member is exposed from the north-eastern side of Miseryfjellet and north to Rifleodden. The member's relatively coarse-grained sediments contrast with the underlying fine-grained, coal-bearing deposits. Grey cross-stratified sandstone, conglomeratic sandstone and conglomerate are the dominating lithologies. Drapes of organic-rich mudstone frequently occur between bedding planes. A few lenticular units of shale and interbedded thin sandstones are associated with the coarse sediments which dominate the member.

The lower part of the member is typically composed of erosively based medium and coarse sandstones, with a slight tendency to upwards fining. Scattered intraformational mudstone clasts occur locally in a few basal beds. The most distinctive feature is the occurrence of low angle, very large scale (<4 m set thickness) planar cross-stratification. Such units may be overlain either by low angle sandstone sets (with or without mudstone drapes) or by large-scale, cross-stratified sandstones divided from each other by distinct erosion surfaces. Although the large-scale sets can persist for hundreds of metres laterally, there is usually marked lateral variation, resulting in a complex lenticular stratigraphy. Mudstone and siltstone units of any thickness are rarely found associated with this facies association, and the only few occurrences are laterally impersistent, and often bounded by erosion surfaces. Petrographically the sandstones very much resemble the fluvial sandstones of the Vesalstranda Member, with subangular quartz grains, and rock fragments of quartzitic sandstone as the dominating framework components.

The erosively based sandstone complexes of the Kapp Levin Member show some similarity to the channel sandstones of the Vesalstranda Member. The main differences are shown by the associated and overlying beds. The Vesalstranda channel sandstones are overlain by thick, coal-bearing mudstone overbank deposits, while sandstones of this association are normally repeated in a multistorey manner with little or no fine-grained sediments preserved between. This facies association represents point bars of laterally migrating, low sinuosity channels, where the large scale cross-stratification reflects lateral bar accretion. If the streams were of low-sinuosity, they were not confined in a meander belt by channel-fills and were therefore free to sweep the entire flood plain, resulting in a very low preservation potential for overbank sediments. Alternatively this association may represent the longitudinal or transverse bars of braided river systems. Such bars may produce the sediments found here as they migrate downstream.

The middle part of the member shows a significant change of lithology and sedimentary structures. ). Individual sets of mainly grey, poorly to moderately sorted medium to coarse sandstone and pebbly sandstone with occasional beds of conglomerates are usually bounded by curved erosion surfaces and are often lenticular and of small lateral extent. A wide range of primary structures include, in order of importance: large-scale trough cross-stratification (including scour and fill), low angle, nearly horizontal stratification, medium and small-scale trough cross-stratification and large-scale planar cross-stratification. Relatively thick sets of structureless sandstone and conglomerate are also present. Large troughs often appear as deep scours or channels, filled by cross-stratified sandstone and shales, with occasional concentrations of pebbles at the base. Thin, laterally impersistent drapes of mudstone are present between lenticular sandstone beds. Plant fossils are common and occur as impressions of relatively large trunks or as elongated leaves. Thin zones with concentrations of organic debris occur as drapes of coaly shale.

The frequency of erosional surfaces, cross-stratified channel fill, scarcity of fine-grained sediments and the very rapid lithological and textural changes both vertically and laterally, suggest sedimentation characterized by large discharge fluctuation, rapid channel-filling and abandonment, and transport through considerable surface topography. All these features are typical of braided stream deposits. The very complex large-scale, lenticular bedding reflects multi-story depositional events of complex channel systems, where both lateral and vertical accretion took place. Very low-angle fine-grained sandstone units associated with the troughs probably represent adjacent overbank areas. Mud drapes associated with channel fills reflect periods of slack water conditions with material deposited from suspension. Common mud drapes in one single channel fill reflect composite infilling, with large and sudden changes in water discharge.

Associated heterolithic intervals consist of siltstone and mudstone beds (less than 10 cm thick) interbedded with thin sandstone stringers. These have a limited lateral extent and are often truncated by erosion surfaces. This facies represents vertically accreted sediments deposited mainly from suspension by slowly moving or stagnant waters. Due to their channel-like geometry and the development of a basal lag conglomerate these units are thought to represent some kind of abandoned channel fill, swale fill or slough fill. The sediments have been transported into the «protected» area during high flood stages. Interfingering sandstones represent bedload sediments deposited nearer the active channel, while the more distal, fine-grained silt- and mudstones were deposited from suspension. The siltstones represent the initial stage of deposition from each sediment influx, while the mudstones represent waning or stagnating flow during the falling stage and during periods of slack water between flooding.

In the upper part of the Kapp Levin Member, just below the “Rifleodden Conglomerate”, there is a regionally extensive, thick mudstone unit, capped by sandstone (Figure 12). Plane parallel laminated and blocky, grey and yellowish grey mudstone and siltstone with some ripple laminated intervals dominate this unit, which is overlain by a 5 m thick low-angle cross-stratified, very fine to fine-grained sandstone sequence interbedded with thin mudstone strata and zones of clay-ironstone. Plant fossils are abundant. The association has a relatively large lateral extent, and it is repeated more than 1 km farther to the NW by block faulting. The fine-grained portion of this facies resembles, to some extent, the thick fine grained sequence of the Vesalstranda Member, which represents flood basin or lacustrine deposits. Braided streams, are not characterised by having large flood basin areas, so that the abrupt change in regime may have been caused by a sudden change in river position, for example as a consequence of avulsion or river capture. Alternatively, the fine sediments may be more laterally extensive, representing sedimentation in a more permanent, large water body. The sudden appearance of such a water body may have resulted from tectonic movements along a near-by active fault zone and nearby N-S faults are certainly known to have been active during deposition of later strata. The entire coarsening upwards sedimentary sequence probably reflects deltaic progradation into a standing body of water, with the mudstones as distal lacustrine deposits, the overlying sandstones as delta front sediments and the overlying Rifleodden Conglomerate as the accompanying river channel system responsible for the transport of sediment into the basin.

### *Sedimentary history and palaeogeography*

The Kapp Levin Member’s thick sandstone sequence was deposited by low sinuosity to meandering streams in its lower parts, and by more typical braided river systems in the middle and upper parts. The overall change of depositional environment from the Vesalstranda to the Kapp Levin Member, with a clear influx of coarser sediments through time, is probably a result of increased palaeoslope. The top of the member marks an abrupt change in depositional environment, where a relatively thick sequence of fine-grained sediments accumulated in a standing water body. Palaeocurrent directions obtained from planar cross-strata and trough axes vary considerably, with transport towards all directions but SW. The diagram shown in Figure 12, based upon average palaeocurrent directions within approximately equal intervals of the member, suggests that the upland source area was most likely located towards the W or SW of present exposures.

## The Tunheim Member

The coal bearing (Figure 15 & Figure 6) Tunheim Member (Tournaisian), the uppermost member of the Røedvika Formation (Figure 11), has long been recognised to be of fluvial origin. Its sediments have largely been interpreted as meandering stream deposits, where the complex sandstone sequence below the A-coal represents a multistorey cluster of channel sandstone bodies deposited mainly as point-bars in meandering streams of relative low sinuosity. The sandstone sequence between the A and B coal (Figure 12) has been interpreted as high-sinuosity meandering stream deposits, where the fine-grained, coal-bearing sediments reflect flood basin sedimentation. The drainage direction of the rivers was towards NNW, more or less parallel to the present coastline.

During most of early Carboniferous time, a graben or half graben with an active fault margin existed just west of present-day Bjørnøya. From this western margin fluvially dominated alluvial fans migrated into the basin towards the east, while extensive floodplains occupied the axial tract of the basin. Tectonic activity and climate determined which of the two environments dominated in the basin. The underlying Kapp Levin Member and the overlying Nordkapp Formation represent the alluvial fan systems, while the Tunheim Member generally represents the axial system. Traditionally all the exposures on the north-east coast have been assigned to the Tunheim Member. However, recent investigations suggest that the thick, coarse sandstone unit overlying the B- and C-coal should be assigned to the Nordkapp Formation. This is indicated both by palaeocurrent data and by depositional environments. Palaeocurrent data indicate an easterly transport direction, as in the Nordkapp Formation, and the sediments reflect deposition by sandy braided stream systems (often poorly channelised). The base of this unit, here regarded as the lowermost part of Nordkapp Formation is sharp (Figure 17 & Figure 18), locally with a basal conglomerate. This may represent a minor unconformity: the possibility that the boundary between the Røedvika and the Nordkapp formations could be an unconformity was mentioned by Horn and Orvin already in 1928.

Simple sketches of the coastal exposures in the area between Framneset and Kapp Olsen gives us information about the geometry of lithological units and lateral facies changes (Figure 17 & Figure 18). The lower half of the member consists of a complexly stratified sandstone unit (>30 m thick). The upper half consists mainly of mudstone and shale interbedded with sandstone and coal. Two of the sandstone sequences in this upper part are rather prominent (<10m thick). Two prominent coal seams occur in this upper unit: the A-coal and the B-coals (Horn and Orvin, 1926). Recent investigations show that the traditional correlation of coal seams from the Tunheim area to Kolbukta is wrong. The uppermost coal seam in Kolbukta, traditionally regarded as the A-coal, is in fact the B-coal (Figure 18).

**Figure 15 Entrance to the abandoned coal mine at Tunheim**

**Figure 16 The main coal seam at Kolbukta is approximately 1 metre thick**

***Lower unit*** - (Multistorey channel sandstone). The more than 30 m thick sandstone succession located just below the A-coal in the area around Tunheim is composed of 3 to 5 sandstone sequences, each sequence eroding into one another, separated by undulating erosion surfaces. In areas where mudstone lenses are preserved beneath these erosion surfaces, the underlying sandstone usually grades upwards into the mudstone. This, together with the fact that each sequence has a sharp erosional base, suggests a fining upwards character for individual sequences. However, the grain size in the sandstones varies generally little, and well-defined fining upwards sequences are rare. The sandstone, which is usually of medium grain size is highly silicified, and primary sedimentary structures are not easily seen in vertical exposures. However, bedding planes with trough cross-stratification of varying scale give reliable palaeocurrent data. Gigantic cross stratification, often penetrating individual sequences from bottom to top and dipping from 5 to 10° (Figure 18), is common. Superimposed smaller scale troughs indicate a palaeocurrent direction approximately at right angles to the prograding direction of the giant foresets. Such cross-strata may extend some hundreds of metres and they appear to represent point bar deposits of high-sinuosity streams, where the large, low angle foresets reflect the bars' lateral accretion surfaces (Figure 18, Figure 19 & Figure 20). Well defined fining upwards sequences are rare, but each individual sequence starts with a distinct undulating erosion surface. The character of basal scour surfaces indicates that scouring and filling continued with bar migration. Gigantic cross-stratification or epsilon cross-stratification is common in the sandstones of the Tunheim Member, but as a result of the low-angle and irregular development this may be difficult to recognize. The irregularity which often resembles «reactivation surfaces» may be the result of erosion of parts of the point-bar during long periods of extreme discharge. Abrupt change in the lateral accretion direction for the point-bar may reflect abandonment and reactivation of the channel system with development of a multi-storey channel complex.

The primary geometry of individual point bar sequences within this lower unit is not easily deduced, partly because they often are strongly eroded by the overlying sequence, and partly because of insufficient lateral exposure. The thickness of the units varies considerably, and variation from 2.5 to 10 m over a distance of 150 m has been recorded. Sequences also wedge-out rapidly into shale and mudstone. This explains the great thickness variation of the mudstone sequence located below the A-coal seam. Usually individual sequences are easy to distinguish where the lateral exposures are good, as the extensive erosion surfaces separating each sequence are easy to distinguish from other bedding planes. However, where the lateral control is poor, such erosion surfaces may be difficult to observe, and the multistorey character of the sandstone unit may be overlooked.

***Upper unit*** - (Mudstone shale - sandstone and coal association). Above the complex stratified sandstone unit in the lower part of the Tunheim Member there is a succession of mudstone and shale, interbedded with sandstone, coal and coaly shale (Figure 17 & Figure 18). The thickness and lateral distribution of the different lithological components of this unit is highly variable. Two relatively thick and laterally extensive sandstone sequences occur. The most prominent of these occurs between the A- and the B-coal (Figure 17 & Figure 18). The other one is locally preserved beneath the erosion surface of the overlying Nordkapp Formation.

Prominent sandstone sequences. Both of the prominent sandstone sequences within this upper unit reflect deposition in stream channels of high sinuosity. A sharp erosive base and slightly fining upwards trend (especially in the uppermost part) is typical for such units. These prominent sandstone sequences are usually between 5 and 10 m thick. Trough cross stratification is the dominant sedimentary structure and has been recorded in the lower and middle parts of the sandstone sequences. However, primary sedimentary structures are difficult to detect. Gigantic cross-stratification with an angle of dip ranging between 5° and 12° are common. This type of cross stratification, which also obviously represents lateral accretion surfaces (point bars) usually extends through the sandstone sequences from bottom to top (Figure 18), but they tend to flatten out towards the top of sequences. The dip direction (and hence the growth direction of the point-bars) of the lateral accretion surfaces varies from E to W, through N. Each of these two prominent sandstone bodies appears to be laterally persistent and uniform, usually at the same stratigraphic level with respect to the coal seams over a distance of at least 6 km. Lateral accretion surfaces and palaeocurrent data, show that these sandstones represent a meander belt extending to the N or NW that is composed of a complex system of point-bars (Figure 21), laterally connected, but locally intersected by abandoned channel fills.

*The fine grained association.* The fine-grained succession immediately below the A-coal seam thins from 23 m in the Austvågen area to less than a metre around Tunheim, over a distance less than 2.5 km (probably not more than 1 km). The association consists mainly of grey and rusty red shale, mudstone and siltstone interbedded with thin sandstones. In some cases the fine-grained lithologies occur in an apparently random vertical arrangement, but both fining and coarsening upwards sequences are present. Horizons of clay ironstone (siderite) and well developed underclay were recorded. Pyrite concretions are common just below the A-coal seam, commonly developed in sandstones. Root horizons occur locally below coal seams and may contain a large number of small root imprints, only a few mm thick, or large silicified imprints (30-40 cm thick) penetrating the sediments vertically. The sandstone beds are usually sharply based and often have a sheet-like geometry. They may occur isolated or stacked and vary from a few centimetres to decimetres thick, rarely more than a metre. This association represents sediments deposited in flood basin area (included shallow lakes), abandoned channels, crevasse splays and levees. Sharply based sandstone beds interbedded with mud and siltstone probably represent the product of more severe flooding with active bed-form migration. Coarsening upwards sequences within the fine grained association may represent crevasse splays, prograding infilling of lakes (e.g. abandoned channel infilling) or progradation of levees. Coarsening upwards infilling of abandoned channels is not common in the Tunheim Member, and only two such cases are seen in Austvågen. This type of coarsening upward sequence probably occurs where secondary flows are directed into abandoned channels, causing a pro-gradational infilling. In most situations, however, the abandoned channel sediments become finer upwards, reflecting a gradual decrease in the supply of coarse material. Abandoned channels are common in the thick sequences of fine-grained sediment in Austvågen and Kolbokta and some of these seem to be laterally equivalent to some of the sandstone sequences in the lower unit, occurring just below the A-coal seam, implying that these areas were located beside an active meander belt. This explains the great lateral thickness variation of the fine-grained sequence below the A-coal.

### *Point bar growth directions.*

864 measurements, mainly based on trough axes, show an average palaeocurrent direction towards NW, which means that the elongation of the meander belt was approximately parallel to the present coastline. A total of 20 measurements of epsilon cross-stratification or (in this case) lateral accretion directions along the coastline from Framneset in the south to Kapp Olsen in the north are mostly directed towards the NE. This is somewhat surprising as we should expect a more symmetrical distribution around the mean palaeocurrent resultant vector (NW). Most of the point-bar lateral accretion surfaces are directed normal to the coastline and seawards. Many of the small peninsulas along the NE coast of Bjørnøya are made up of such gigantic crosstratified sandstones. The persistent seawards direction of the cross-strata could be due to preferential preservation rather than an original unidirectional arrangement of point-bar accretion surfaces (dissipation of present-day storm wave erosive power would tend to be maximum where waves break upslope). Point-bar lateral accretion surfaces orientated towards the west would, in most situations, not be preserved as peninsulas because of the erosive power of the waves, and gigantic low angle cross-strata of this type are very difficult to detect in vertical exposures, where dip direction is orientated normal or approximately normal to the

exposure. As most of the data have been measured on the small peninsulas, the mean palaeocurrent resultant vector will not be representative for the mean flow direction of the rivers which deposited the elongated sandstone bodies of the Tunheim Member, and it is suggested here that the average flow direction probably was more northerly. An alternative interpretation is that the exposed point bar deposits mainly represent the eastern margin of the meander belt, where a majority of the point bars tend to migrate towards the margin of the meander belt towards the east. Most of the lateral accretion surfaces have a downstream component, suggesting that an oblique downstream growth of point-bars is the most common pattern in meandering rivers.

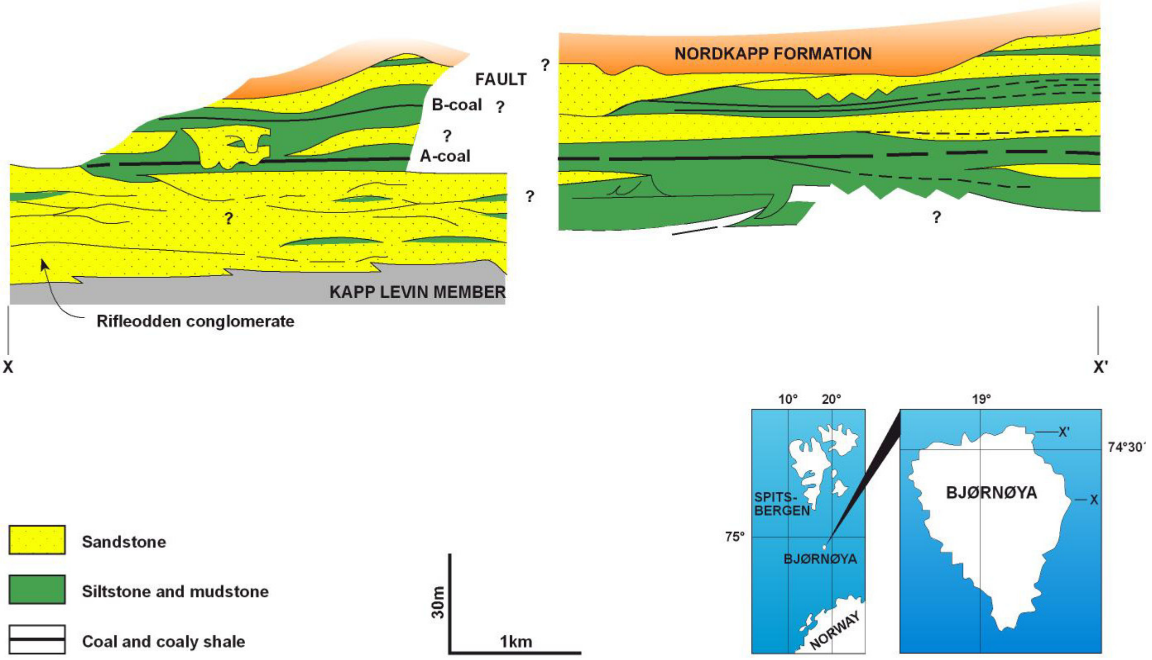



**Figure 17 Development of the Tunheim Member**

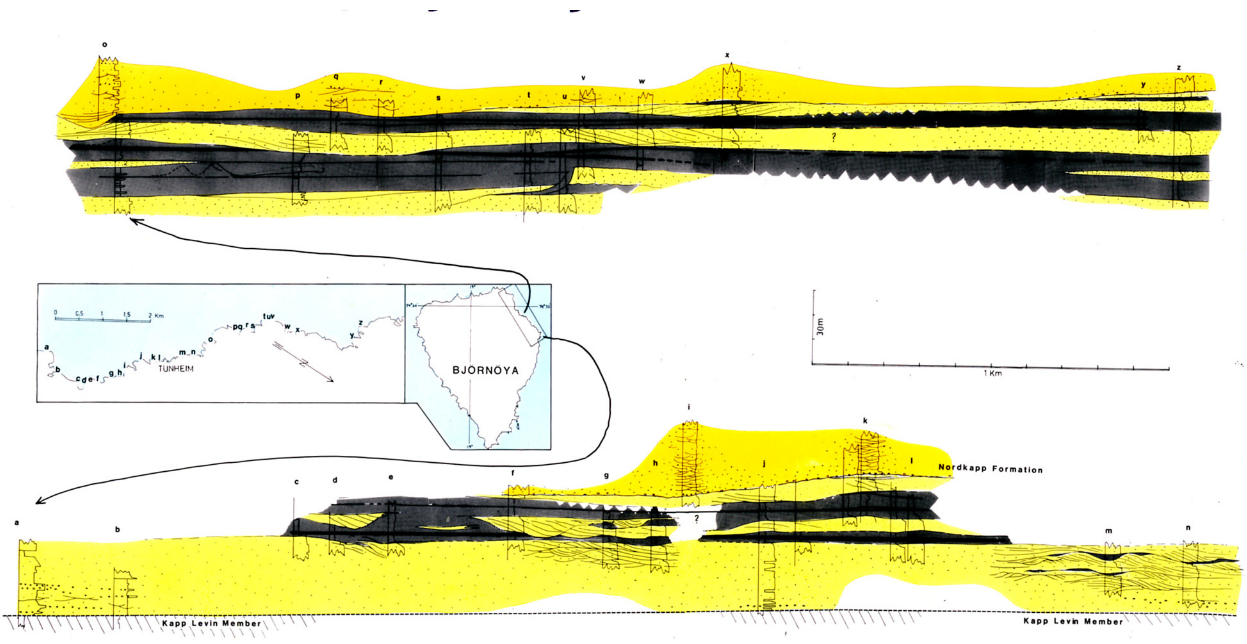



**Figure 18 Some exposures of the Tunheim Member along the north-eastern coast of Bjørnøya**

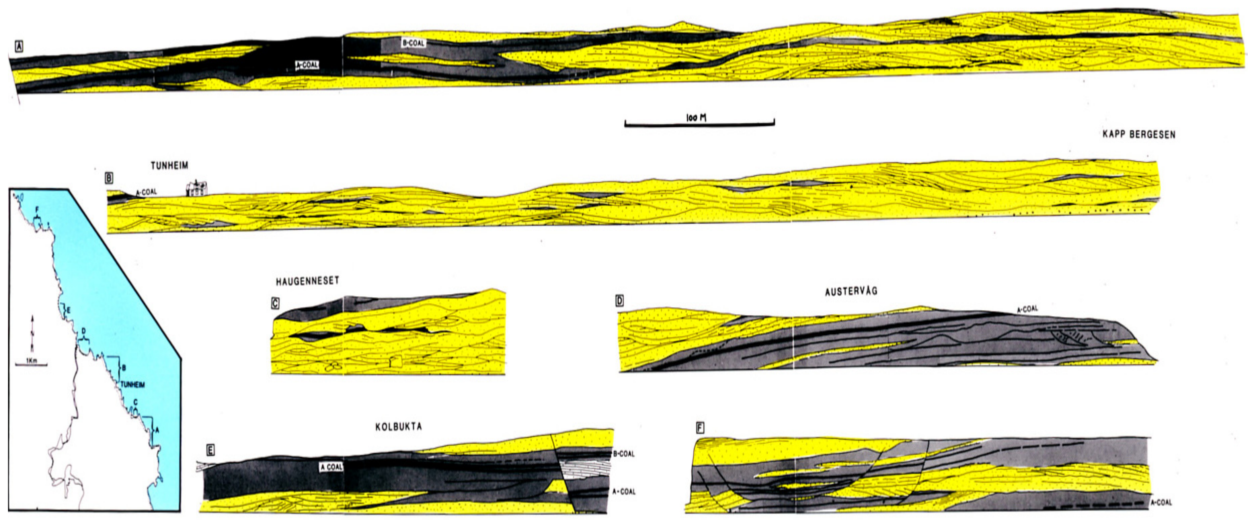
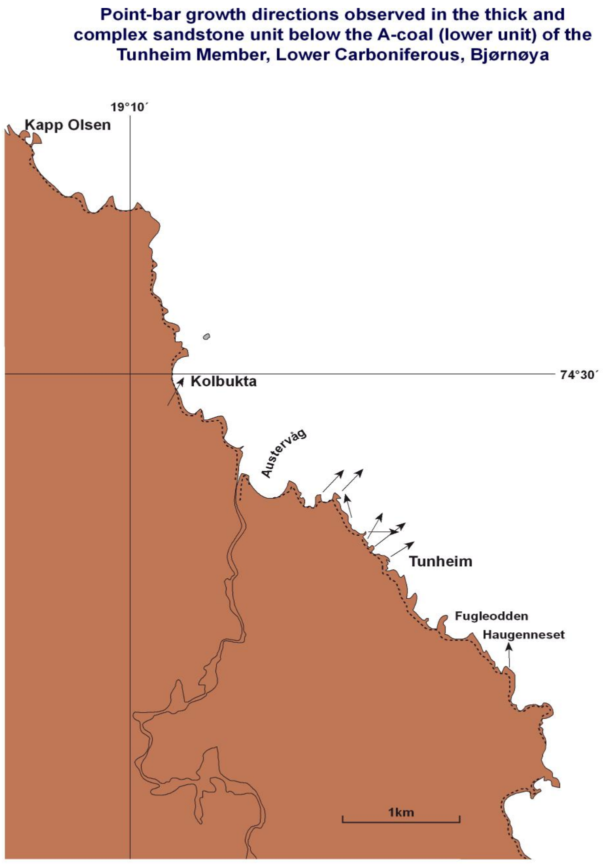



**Figure 19 Some exposures of the Tunheim Member along the north-eastern coast of Bjørnøya**



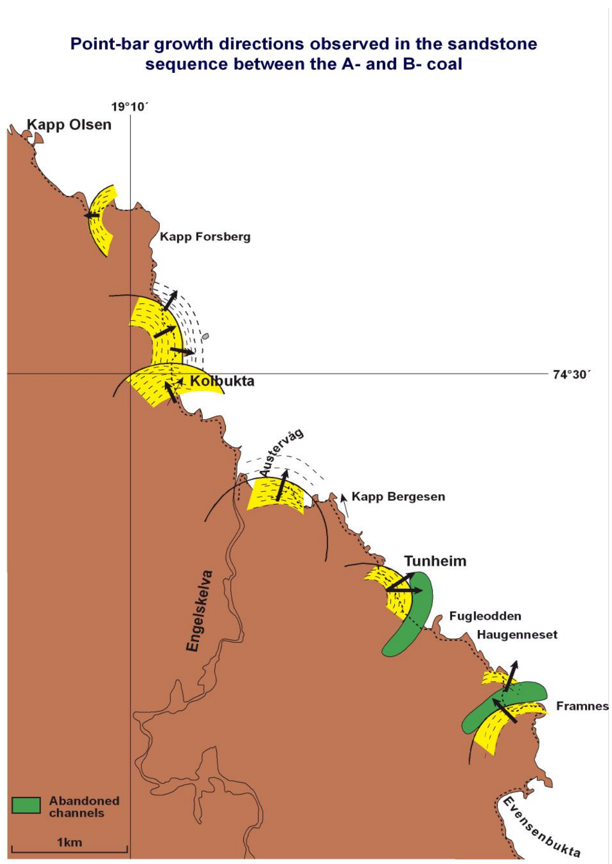




**Figure 20 Point bar growth directions observed in the thick and complex sandstone unit below the A-coal of the Tunheim Member**

**Figure 21 Point-bar growth directions observed in the sandstone succession between the A- and B- coal.**

## The Nordkapp Formation

The best exposures of the Nordkapp Formation occur in Landnørdingsvika on the SW coast of Bjørnøya (Figure 22 & Figure 23), where a continuous sequence of the uppermost 120 m of the formation is exposed. Although the base of the formation is not seen here, the section is referred to as the type profile. Exposures along the north coast are locally good and accessible, but abundant faults make it very difficult to construct a continuous vertical log in that area. The base of the Nordkapp Formation is only exposed in the coastal cliffs near Tunheim. The contact between the Nordkapp Formation and the overlying Landnørdingsvika Formation is exposed both in Landnørdingsvika and in Kobbebukta on the north coast. In Landnørdingsvika, Worsley and Edwards (1976) placed the boundary between the two formations at the appearance of red mudstones characteristic of the overlying Landnørdingsvika Formation. Here there is a sharp contrast between the two formations, suggesting to them an appreciable break in deposition. However, sedimentological studies from the north coast and borehole data suggest that the transition is more gradual, without any clear break in sedimentation. The formation thickens northwards, from 110-120 m around Ellasjøen to more than 230 m in a borehole at the south end of Hausvatnet (Horn and Orvin 1928).

**Figure 22 Coarse conglomerates of the Nordkapp Formation on the SW coast**

**Figure 23 A small "harbour" within fluvial sandstones of the Nordkapp Formation in Båtvika at the SW coast**

Microfloras from the formation's exposures at Nordkapp contain elements of the aurita assemblage of Spitsbergen, now generally thought to be Visèan in age (Playford 1962, Kayser 1970). The lower part of the formation may span the Tournaisian/Visèan boundary: a coal seam of late Tournaisian age, which outcrops south of Ellasjøen, probably belongs to this formation and not (as suggested by Kaiser, 1970) to the Røedvika Formation.

Because the uppermost part of the formation contains much more conglomerate and mudstone than its lower parts, it has been found convenient to define the lower Kapp Harry Member and the upper Nordhamna Member (Dallmann et al. 1999).

Composition of the sandstones does not differ dramatically between the two units, as quartz grains and rock fragments of quartzite are the dominant components in both and account for more than 90% of the rock. Chert, as very small clasts, is much more common than in the underlying Røedvika Formation, and in some conglomerate beds (debris flow and streamflood conglomerates) it constitutes more than 30% of the clasts. Aggregates of clay minerals (mainly illite and kaolinite) are common in conglomerates and sandstones in certain zones in both units. These probably represent the weathered remains of relatively unstable minerals such as feldspar. Plant fossils are common in exposures on the north coast, where they occur mainly as impressions of tree trunks. Otherwise, most of the lithofacies associations in the formation are basically similar to facies associations already described from the Røedvika Formation.

### Kapp Harry Member

This unit is exposed in Landnørdingsvika on the south-west coast and on the north coast around Nordkapp, Herwighamna, Gravodden and Kapp Kjellstrøm. As indicated above this part of the formation consists mainly of uniformly developed sandstone with occasional beds of pebbly sandstone and thin conglomerate and only rare interbeds of mudstone and siltstone. Beds are usually lenticular and often bounded by curved erosion surfaces. Large-scale, high angle planar cross-stratification dominates and sets are usually regularly developed and laterally extensive. Trough cross-stratification and low angle, nearly horizontal stratification is also common. Ripple laminated intervals are present locally. Soft sediment deformation structures occur frequently, some of which may be of considerable size.

The sediments of this member generally represent the same lithofacies as those seen in the middle part of the Kapp Levin Member. The following differences are important here, however:

- The sandstone/conglomerate ratio is much higher here.
- Planar cross-stratification is much more common here than in the Kapp Levin Member, where large-scale trough cross-stratification and channel scour and fill dominate.

The vertical development of sedimentary sequences, grain size and sedimentary structures suggest that most of the member’s sediments represent Miall's (1977) Platte type braided stream system. Because of the abundance of planar cross-stratification in this member more than 300 palaeocurrent measurements have been recorded from various localities. Measurements at all localities a north-eastern transport direction (Figure 12), with a mean vector azimuth of 63° towards E. This suggests that there was an elevated area in the west which acted as an upland area for a persistent, eastward flowing braided stream system.

### Nordhamna Member

A 65 metres thick sequence of this unit is exposed in Landnørdingsvika, while it is about 40 metres thick in Nordhamna, and less than 20 metres in Kobbebukta (probably incompletely exposed because of faults). Sedimentary sequences similar to those described from the middle part of the Kapp Levin Member are most commonly developed in this unit. A very complex and lenticular bedding type dominates. Large-scale trough cross-stratification, channel scour and fill, low angle, nearly horizontal stratification and large-scale planar cross-stratification are the dominating elements. Sandstone, conglomerates and siltstone/mudstone are the dominating lithologies and in Landnørdingsvika conglomerates and siltstone/mudstone account for 24% and 19% of the succession respectively. The siltstone/mudstone horizons locally contain a lot of organic material and thin coals and coaly shale are developed locally.

The sandstones and conglomerates of this unit most likely represent braided river channel systems with sedimentation at different topographic levels within the channel system, or successive events of vertical aggradation followed by channel switching. The lenticular fine-grained mudstone/siltstone units associated with the coarse-grained sediments may represent deposits similar to those described from the Kapp Levin Member, such as abandoned channel fill, swale fill or slough fill sediments deposited from suspension. However, these sediments may also represent distal flood basin environments with good conditions for the accumulation of plant debris and peat.

At Landnørdingsvika the boundary between the upper and lower members may be placed at a distinct 10 m thick sequence of fine-grained sediments, sharply overlying the uniformly developed sandstone succession of the lower unit. This sequence consists of fine-grained, trough cross-stratified sandstone interbedded with thin mudstone strata in its lower part, grading upward into flat stratified sandstone interbedded with siltstone and mudstone. Plane parallel lamination is common in the upper part, and plant fossils are present as elongated leaves between laminae. A 7 m thick sandstone overlying this fine grained unit coarsens upwards in its lower parts before fining upwards uppermost. Somewhat similar developments to those found in Landnørdingsvika are also seen in borehole sections from various localities in the interior of the island and it is probable that these represent lateral equivalents. In this case the unit is laterally persistent (more than 10 km) and it is likely that this transition from the lower to upper members reflects a rather dramatic change in depositional regimes. This suggestion is supported by the very distinct boundary between the two units exposed on the west side of Kapp Kjellstrøm and it may well reflect a hiatus. Sediments deposited from suspension with intercalations of bedload sediments (ripple lamination and plane lamination of lower flow regime) dominate in the upper part of the sequence. In the lower part, bedload sediments dominate. This unit probably represents the vertical accretion of fluvial sediments developed laterally to active stream channels, probably in a flood basin or a lake. Most of the bedload sediments were probably brought into the basin during flood events. The interbedded mudstone and siltstonewould then have been deposited from suspension during periods of slack water conditions.

The prominent conglomerate sequences of this unit in Landnørdingsvika differ considerably from the conglomerates described in previous sections. These sequences are characterized by sheet like sets of internally structureless, unsorted conglomerates, mainly matrix-supported, but with well-sorted, almost matrix-free intervals. Some sets of large-scale, very low angle planar cross-stratification are seen. Individual conglomerate sets are often overlain by thin sheet-like, cross-stratified and massive sandstone sets. However, superimposed conglomerate sets, without intercalated sandstones, are also common. The matrix of these conglomerate is very poorly sorted, with all grain sizes from mud to granules. Clasts of bright quartzite, red and grey quartzitic sandstone and chert dominate. No carbonate clasts are seen and this differs considerably from the composition of the conglomerates of the overlying Landnørdingsvika Formation. Many of the beds show the basic characteristics of both ancient and recent debris-flows, while other beds seem to represent streamflood conglomerates. Palaeocurrent data indicate a transport direction between N and NE.

### *Environment of deposition*

The Kapp Harry Member represents a braided river system somewhat similar to that suggested for the Kapp Levin Member. Flow direction probably was towards N or NE (see Figure 12). The sediments of this unit probably represent the distal parts of a more complex alluvial fan system, with a source area in the S or SW. The Nordhamna Member also represents alluvial fan systems, but these differ from the underlying beds by a much higher content of mudstone and conglomerate with deposited by debris flow processes. Some of the mudstones show red/drab colours, indicative of well oxygenated conditions. The interfingering of debris flow sediments reflects more extensive lateral migration of these lithofacies, probably as a result of increased topography (tectonic movements?), or a change in climatic conditions to a more arid climate.

The frequent occurrence of primary deformation structures (probably as a result of liquefaction caused by seismic shocks) suggests that a near-by active fault or fault zone influenced sedimentation through time. This tectonic activity may have produced an elevated source area to the west and southwest and this is consistent with the sedimentological evolution of the overlying Landnørdingsvika Formation. Climatic change to more arid conditions also was an important cause for the observed differences between the two members and we see that arid climates prevailed during deposition of the andnørdingsvika Formation dominated. This climatic shift  from the equatorial humid to northern arid zone through the Lower to Middle Carboniferous is well known throughout the region and has been discussed by several authors.

## Depositional history of the Røedvika and Nordkapp formations

The development of this succession on Bjørnøya was strongly controlled by a sediment source located to the W or SW (Figure 24). The interplay between marginal and axial drainage systems was a central theme in the area's stratigraphic evolution (Figure 25). Tectonic activity along a western marginal fault together with climatic variations are thought to be the main factors deciding which of the two depositional systems dominated in the basin at any point in time. During deposition of the Vesalstranda Member the axial system dominated, with extensive floodplains and meandering channels draining to the NW. Extensive flood basins and lakes developed along the basin margin, whereas well vegetated floodplains gave good conditions for swamp and later coal development.  During deposition of the Kapp Levin Member the marginal system took over, and extensive alluvial fans with braided streams draining towards the NE dominated. The reason for an eastward progradation of the marginal depositional system was probably increased tectonic activity and tectonic uplift of the source area, possibly in combination with climatic changes. During deposition of the Tunheim Member the axial system again took over, and extensive floodplains with meandering channels draining to the NW dominated once more. Prior to the development of the Tunheim Member an extensive lake developed, possibly as a result of tectonic activity along the basin margin. Extensive well vegetated floodplains again gave good conditions for swamp and later coal development. During deposition of the Nordkapp Formation the marginal drainage system took over yet again and extensive humid alluvial fan systems draining to the NE dominated. The upper parts of the Nordkapp Formation show indications of a change to more arid climates, probably precursing the arid conditions that dominated during deposition of the overlying units.

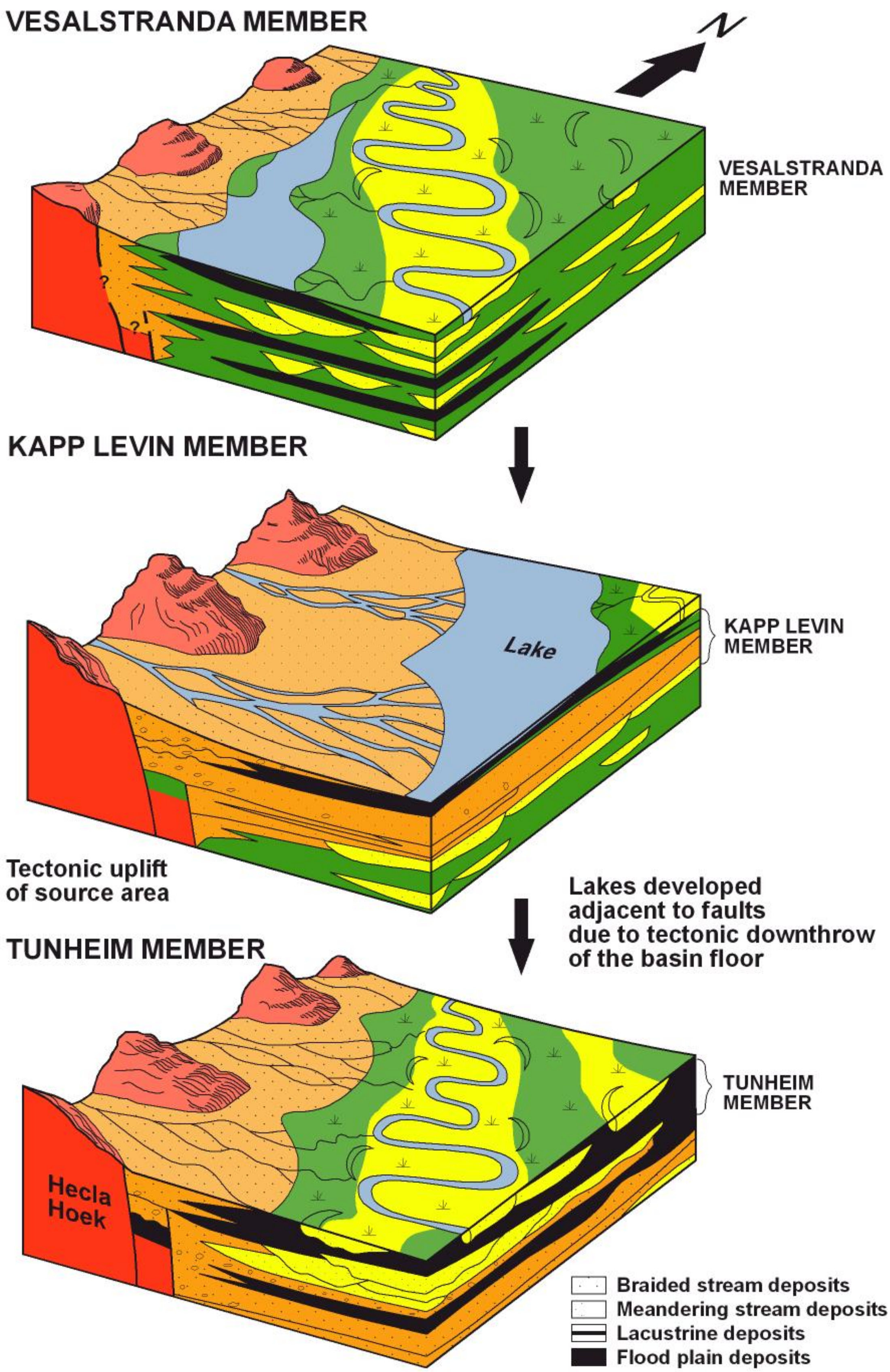



**Figure 24 Block diagram illustrating the development of the Røedvika and Nordkapp formations (From Gjelberg, 1987)**

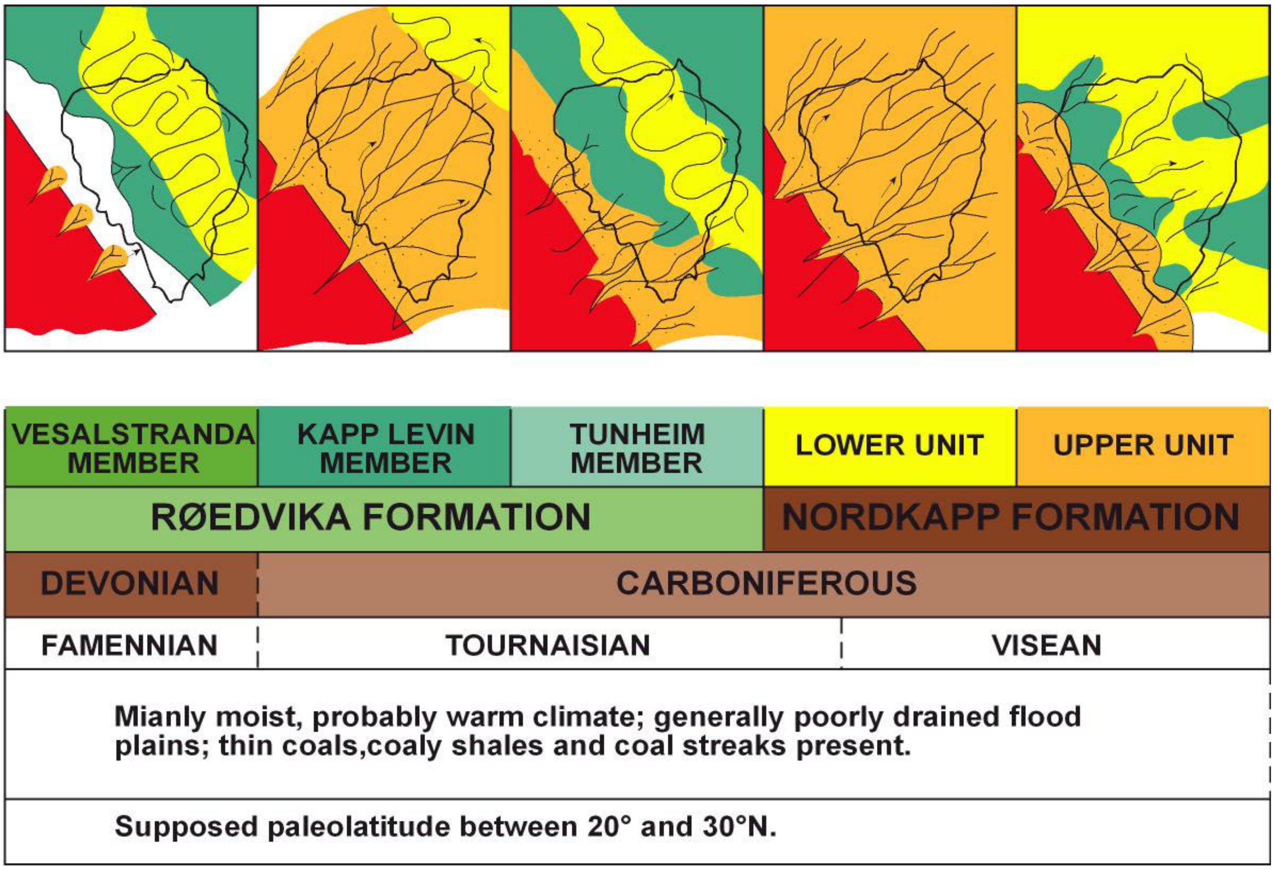



**Figure 25 Palaeogeographic maps illustrating the development of the Røedvika and Nordkapp formations**

## *Mid Carboniferous climatic shift to Landnørdingsvika redbeds*

The transition between the Nordkapp and Landnørdingsvika formations definitively marks the dramatic shift to semi-arid or arid climatic conditions. Palynology indicates a Viséan age for the upper Nordkapp Formation and a youngest Serpukhovian to Bashkirian age for the overlying red beds. The Landnørdingsvika Formation (Figure 26 & Figure 27) consists of interbedded red mudstones, drab yellow-brown sandstones and red conglomerates that together represent an intricate interfingering of flood-plain, alluvial fan and marginal marine sediments. The presence of calcrete paleosol horizons in the mudstones contrasts with the development of coals in the underlying units. Floodplain and coastal plain deposits dominate the lower parts of the unit, but these pass up first into alluvial fanglomerates and then into interbedded marginal marine clastics and carbonates, the latter becoming increasingly common upwards.

The formation's development suggests a complex interplay between axial drainage systems (flood plain/coastal plain deposits) dominating its lower parts and marginal systems, dominated by several events of debris flow conglomerates, in the middle part. This development is interrupted by the gradually increasing influx of marine and marginal marine sediments in a rhythmic development. This complex interplay between coarse clastic input from the west and abrupt but increasingly common marine incursions, may reflect periodic tectonic activity along the western marginal fault of the basin combined with ongoing regional sea-level rise.

Weather permitting these beds will be studied in Landnørdingsvika in shoreline cliffs (Figure 26).

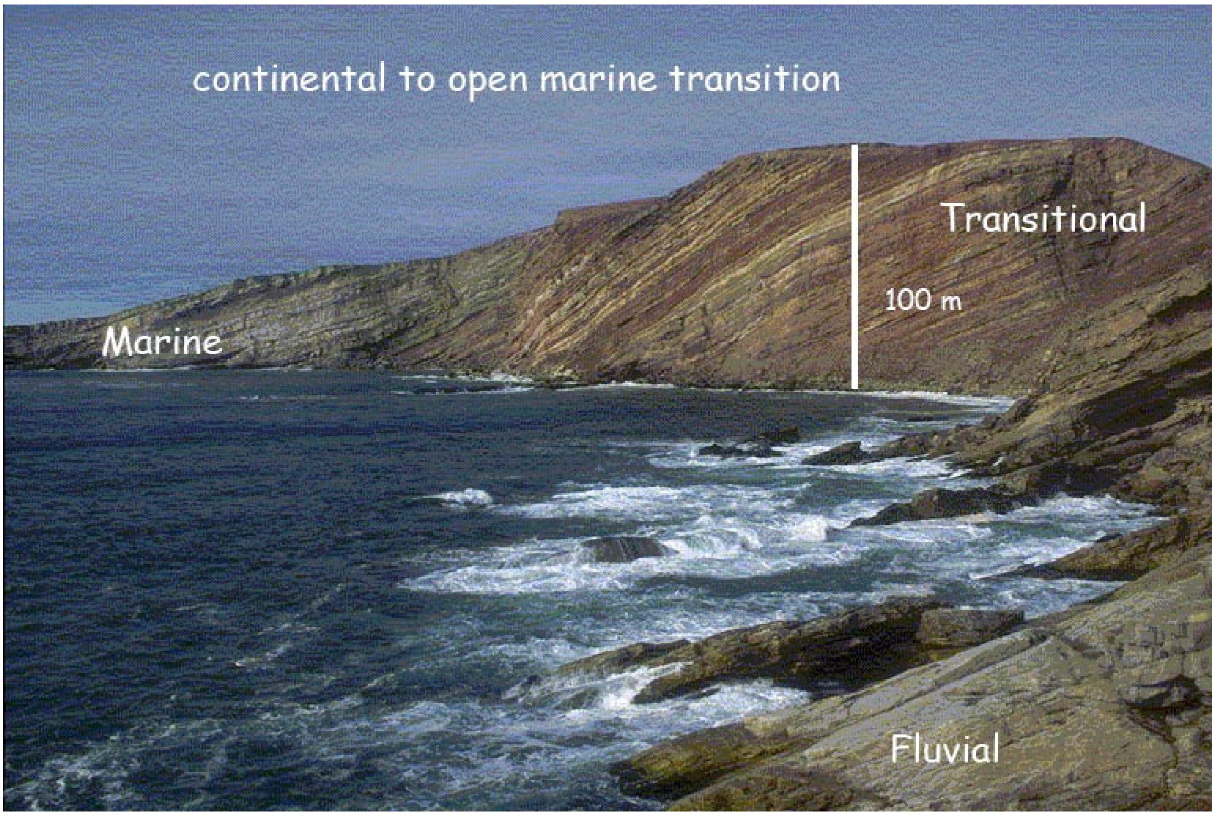



**Figure 26  View of the Landnørdingsvika Formation in its type locality: note the grey sandstones of the Nordkapp Formation (right foreground), the marked change to red mudstones and yellow coarse clastics of the Landnørdingsvika Formation (highest point on the cliff about 120 m) and the transition to the grey carbonate-dominated succession of the Kapp Kåre Formation (far left lower cliffs).**

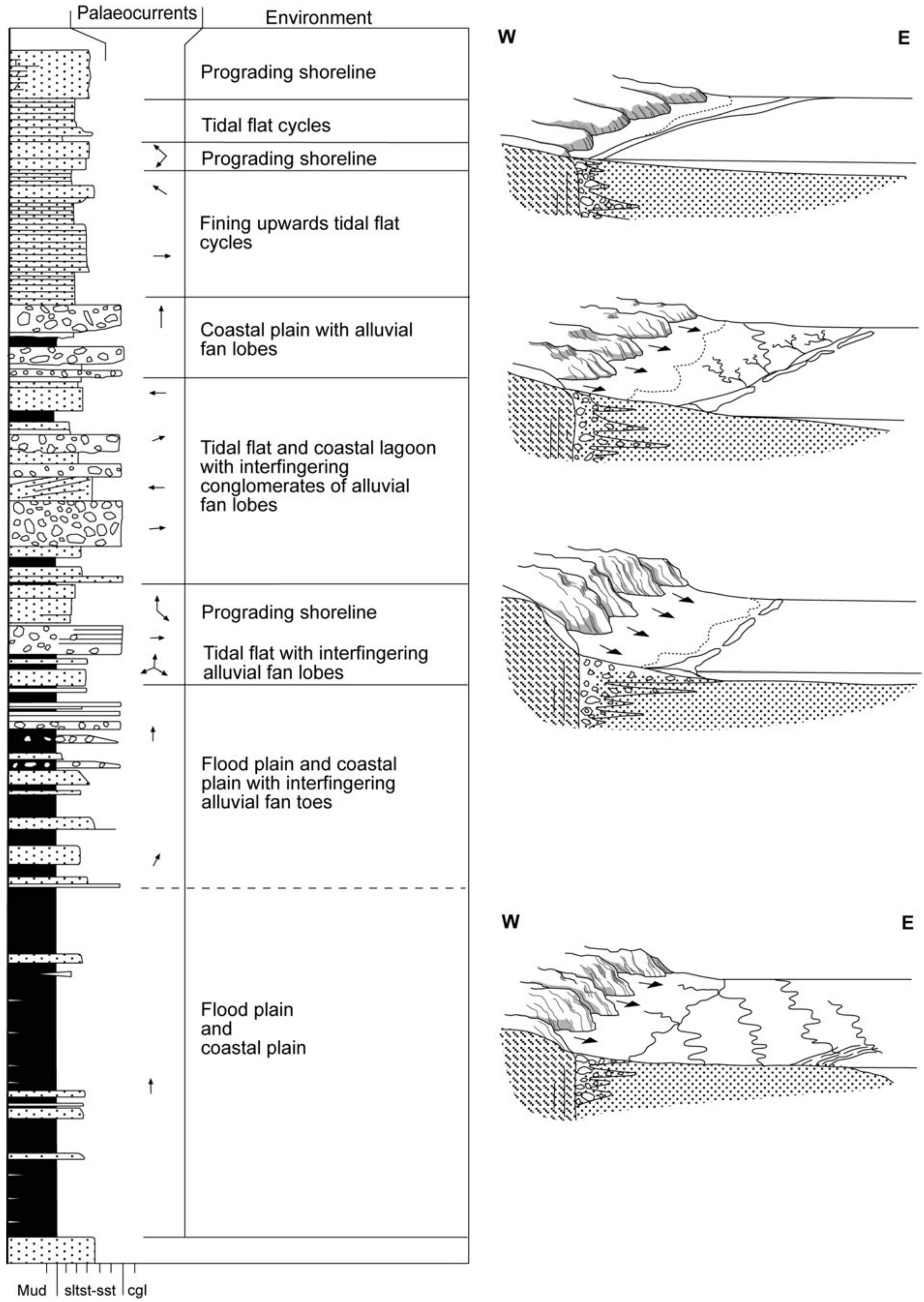



**Figure 27 Interpretative composite log through the Landnørdingsvika Formation, with schematic palaeogeographic reconstructions, based on Gjelberg & Steel (1983)**

## *Bashkirian to Moscovian transgression to the Kapp Kåre Formation*

The transitional base of the 215 m thick Kapp Kåre Formation is defined at the disappearance of conglomerates and the development of mixed clastic and carbonate sequences, the first fusulinds occurring in the carbonates having a late Bashkirian aspect. The only locality showing this transition is in Landnørdingsvika, where the marked colour change from red to grey rocks is clear (Figure 26). The transition from clastic- to carbonate-dominated sedimentation and the generally upward fining trend shown by the lowermost Bogevika Member (best exposed in Kobbebukta; Figure 28 ) reflect the effects of ongoing regional transgression – perhaps combined with more intermittent tectonic activity.

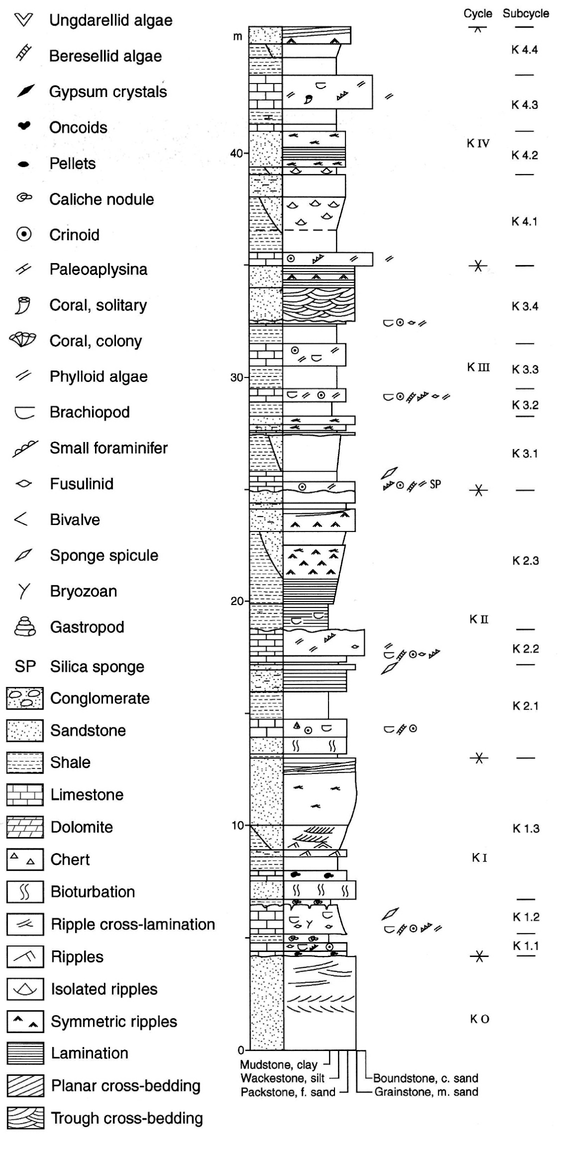



**Figure 28 Rhythmic sedimentation of the Bogevika Member at Kobbebukta, NW coast**

*Bogevika Member rhythms* -- The Bogevika Member consists of limestones, shales and sandstones organized in a series of small-scale (< 12 m thick) shoaling upward rhythms (Stemmerik et al. 1998; Stemmerik & Worsley 2000; Figure 29). Each rhythm (Figure 30) typically shows an upward transition from oncolitic (Figure 31) to coralgal limestones or marine shales (often organic rich) into siltstones and sandstones with either brackish water faunas or plants and roots. Upper contacts are usually sharp and show desiccation cracks, calcrete horizons or an erosional surface under the basal limestone or shale of the overlying rhythm. The entire development reflects deposition in tidally influenced marginal marine environments. The abundance of karst and other discontinuities suggests that the rhythmic development is not a purely autocyclic phenomenon but may rather reflect an interplay of continued local tectonic activity, ongoing regional transgression and glacially influenced eustatic sea-level fluctuations. Sandstones become less common upwards, as decreasing clastic input accompanied submergence of nearby upland provenance areas.

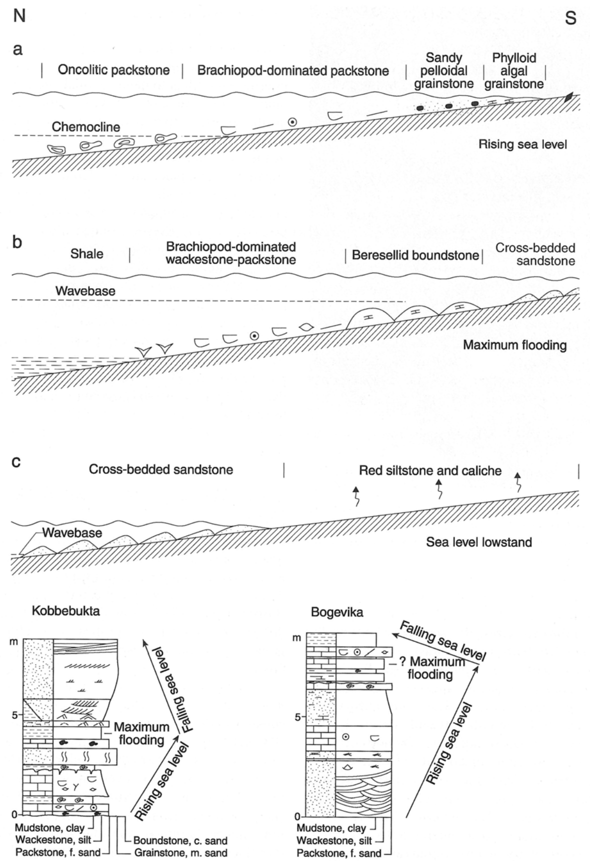



**Figure 29 Depositional model for the Bogevika Member reflecting rhythmic sea level changes. Note the different cycle development in the North (Kobbebukta) and in the South-West (Bogevika)**

**Figure 30 Typical rhythms of the Bogevika Member in Kobbebukta**

**Figure 31 Oncolite beds from the Bogevika Member in Kobbebukta**

## Moscovian platform carbonates

The gradual transition through limestone and shale intercalations from the Bogevika Member's rhythms to the overlying carbonate-dominated Efuglvika Member reflects the establishment of carbonate shelf sedimentation throughout the entire area by the early Moscovian. The 80 m thick Efuglvika Member is dominated by white to grey, thinly to massively bedded and variably cherty limestones with textures ranging from grainstone to wackestone (Figure 32). Constituent microfacies and stenohaline faunas suggest deposition on an open marine shelf of moderate depth.

Exposures show a series of shoaling-upwards rhythms passing from bioturbated chert-rich wackestones with *Thalassinoides* burrows into chert-free grainstones, sometimes with erosive or karstified tops The cyclicity seen lower in the succession thus continued, but clastic input decreased. The rhythmic development, the karstic surfaces and the cherts themselves suggest some measure of continued tectonic activity during sedimentation. The chert fills *Thalassinoides* burrows and occurs in various morphotypes indicative of "diapiric" movement within the unconsolidated sediments. The resultant chert masses vary in form from bulbous to sheet-like "dykes" subperpendicular to the bedding (Figure 33). These elongate structures follow NE-SW and NW-SE trending zones of deformation. Large-scale fractures with penecontemporaneous sediment infill also crosscut the bedding subvertically with a NE-SW trend. The fractures and the chert bodies are thought to be related to subaerial exposure and karstification: a few discontinuity surfaces show clear microkarstic features and bedding truncations, while angular unconformities are occasionally associated with these surfaces. These phenomena collectively suggest intermittent syn- and early post-sedimentational tectonism, the chert deformation being precementation in age and the fractures postconsolidational; this tectonism is more clearly shown by the facies of the overlying units.

**Figure 32 Kapp Kåre Formation limestones, Kapp Maria – bedded cherty limestones of the Efuglvika Member are unconformably overlain by intraformational conglomerates of the Kobbebukta Member. These are eroded to form the bridge through which we glimpse the southern cliffs (Day 4)**

**Figure 33 Chert dykes in the Efuglvika Member at Ærfuglvika (Day 4).**

## *Late Moscovian to Gzelian tectonism*

Intraformational conglomerates occur uppermost in the Kapp Kåre Formation, and reflect renewed tectonic activity on Bjørnøya in the Late Moscovian. The top surface of the Efuglvika Member represents a pronounced erosional break with clear karstification. The overlying Kobbebukta Member consists of interbedded marine limestones, shales and conglomerates (Figure 34). The latter contain mostly intraformational chert and limestone clasts - in contrast to the significant extrabasinal components that characterize the coarse clastic units of the overlying Kapp Hanna Formation. The conglomerates of the Kobbebukta Member were deposited by both subaerial and submarine debris flows triggered by renewed syndepositional tectonism. However, these flows originated from fault blocks over *eastern* parts of present-day Bjørnøya, producing apparent partial inversion of the earlier basin, superimposed over the northerly trend of the underlying Caledonide thrust system. This late Moscovian basinal inversion appears to be represented by normal extensional fractures, which began to form penecontemporaneously with the dykes and fractures described above in the Efuglvika Member. Major block controls seem to have been exerted by the dominantly N-S trending faults, while minor cross-cutting roughly ESE-WNW and ENE-WSW trending sets controlled flow of eroded material from the uplifted flanks of the graben westwards into accommodation areas on the hanging wall of the West Bjørnøya Fault.

A spectacular facies development seen on the northern coast within the Kobbebukta Member (Figure 34) is interpreted as marking the site of repeated synsedimentary small-scale fault activity along such a WSW-ENE trending fault scarp. Debris flows drape over the faulted margin, but the main feature of the downthrown side is a sequence of shales and turbidites, the latter deposited by currents flowing westwards and paralleling the microfault. The overlying conglomerates show no lateral variation over the fault trace, implying cessation of movement on this particular feature immediately below the boundary to the overlying Kapp Hanna Formation. Faulting obscures the boundary itself, but conglomerates apparently draping over the poorly exposed critical fault separating the two formations suggest ongoing synsedimentational tectonism.

Southern outcrops show a highly varied development at this level. Debris flows uppermost in the formation just south of Efuglvika locally form thin veneers on the eroded top of the Efuglvika Member or extrabasinal Kapp Hanna conglomerates may directly infill broad channels cutting down into the Efuglvika Member's limestones.

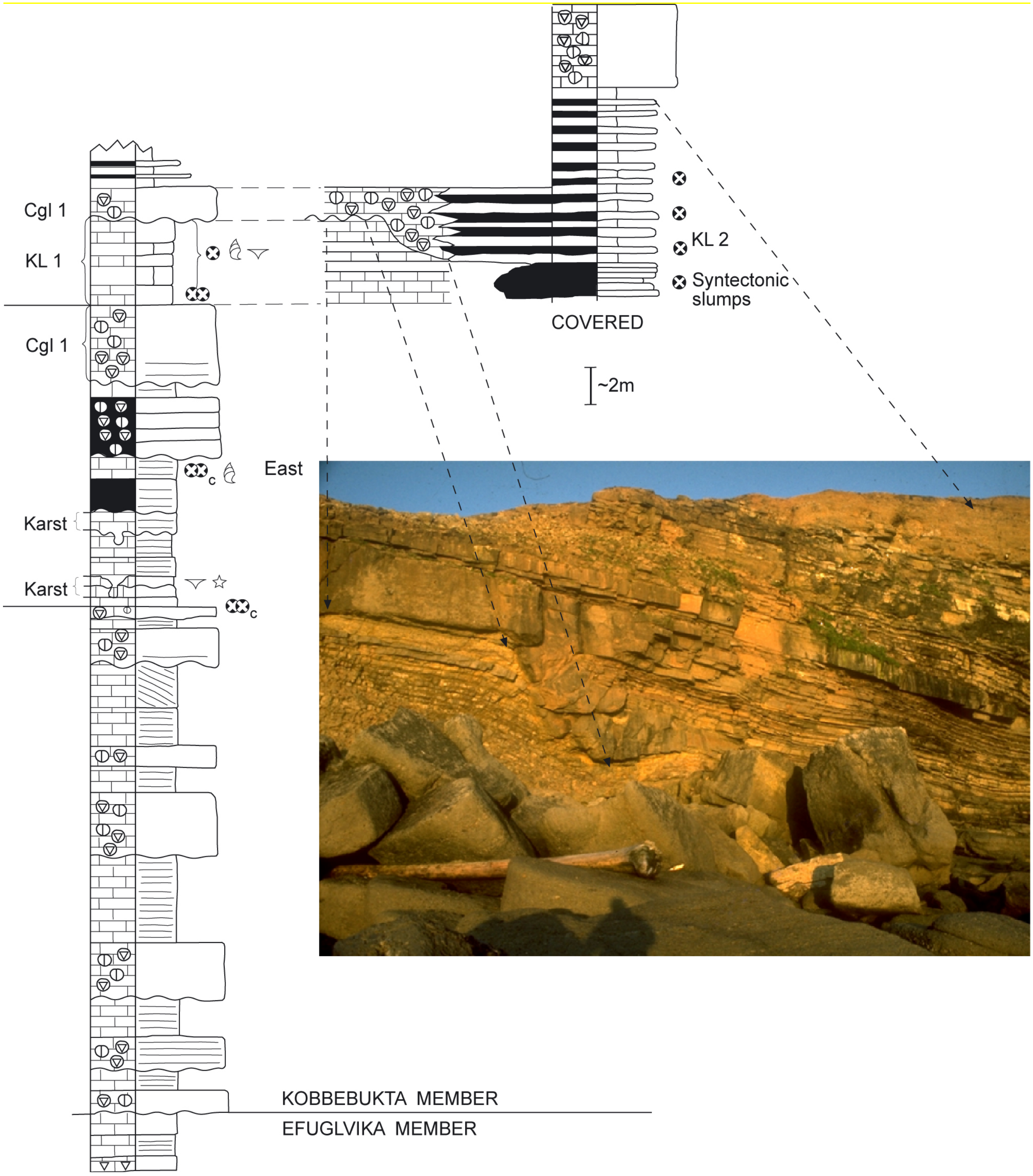



**Figure 34 Intraformational conglomerates in the Kobbebukta Member, uppermost Kapp Kåre Formation show a syndepositional fault that reflects renewed tectonic activity producing small half-grabens which then channelled debris flows and turbidites from the newly emergent eastern high.**

Inland exposures around the hill of Raudnuten near the west coast show complex relations: on eastern hillsides almost flatlying Efuglvika carbonates are erosively overlain by a cm-scale veneer of conglomerates, while western slopes show a monoclinal flexure in the top of the Efuglvika Member before these dip steeply to the west. ENE - WSW trending fractures and minor faults dissect the N-S axis of the monocline and define an erosional relief infilled by up to 10 m thick coarse conglomerates of the Kapp Hanna Formation. The relief shown by the faulted, eroded and infilled top of the Efuglvika Member is clearly a late Moscovian phenomenon - isolated thin outliers on the hilltop contain limestones with fusulinids assignable to the overlying Kapp Dunér Formation of late Asselian age (see also below) and these limestones onlap the whole of the underlying irregular relief.

## *Ongoing late Carboniferous tectonism*

Coastal exposures of the Kapp Hanna Formation display laterally variable alternations of conglomerates, sandstones, shales and dolomites. This complex development in numerous small fault blocks on the western and northwestern coasts and in poorly exposed outliers inland makes lateral correlation and synthesis difficult, but detailed studies suggest a composite maximum thickness of 145 m. We will study the cliff exposures from the boat, with brief visits ashore where/when possible.

Most of the coastal exposures display both fining and coarsening upward packages in which alluvial, coastal and marginal marine environments are represented. However, several localities show shallow marine dolomite and shale units cut into by valley forms with up to 20 m observed relief; these incised valleys also trend generally ESE-WNW and are controlled by minor syndepositional faults. Valley infill consists of thinly interbedded sequences of conglomerates and sandstones of stream-flood origin. Abundant palaeocurrent data in the alluvial sequences indicate an eastern source, with flow directions along the valley floor to the WNW. Desiccation cracks found in shaly laminae on bedding planes throughout the conglomerates indicate repeated subaerial exposure between intermittent depositional episodes. Other features indicative of local tectonic activity include fissures infilled with clastic material and intraformational angular unconformities of up to 5° overlain by conglomerates containing angular clasts of the underlying penecontemporaneous sandstones.

Earlier workers mapped inland exposures south of Miseryfjellet near the southeastern coast as containing isolated outliers of basal Rødvika Formation conglomerates. These are now interpreted as Kapp Hanna conglomerates deposited directly on eroded basement, with similar WNW palaeocurrent directions as seen in the coastal exposures. Some of these outliers show the conglomerates passing up into carbonates which have not yet been dated.

Southernmost cliffs show almost 400 m sheer exposures of basement, generally with a thin onlapping mid- to Upper Permian overlying sequence; however, three local half-grabens which have been identified in these cliffs show a presumed Kapp Hanna to Kapp Dunér wedge infill resting directly on an abutting basement; the uppermost Permian overlaps and is not involved in the graben infill (Figure 6).

The total association of unusual features displayed by exposures of the Kobbebukta Member and the Kapp Hanna Formation strongly suggest intrabasinal tilting which uplifted the eastern flanks of the earlier West Bjørnøya depositional graben. Older Carboniferous and Devonian deposits must have already been well consolidated so that the flanks were dissected into a series of N-S trending fault blocks now exposed over eastern parts of present-day Bjørnøya (Figs. 4). Subaerial erosion of this newly created structural high complex produced the conglomeratic material infilling the incised valleys in the Kapp Kåre and Kapp Hanna formations. Fault trends and palaeocurrent directions associated with these events indicate main movements along N-S to NNE-SSW directed lineaments with a different alignment from the NW-SE trending Early Carboniferous West Bjørnøya Fault. Conjugate sets of minor faults controlled the general westerly trend of the incised valleys themselves. Analyses of sandstone mineralogy and conglomerate clast composition in the Kapp Hanna Formation provide additional evidence for basinal evolution at this time (Figure 35). The clasts were derived from older local units and both clasts and matrix show a well-developed inverse stratigraphy, reflecting the progressive erosion of these units on the newly uplifted graben flanks. The marked dominance of Hecla Hoek clasts in southwestern exposures contrasts with the dominantly Lower Carboniferous clast content of the northwest exposures. This suggests that unroofing and erosion of Hecla Hoek rocks in the south and southeast of the island happened largely during deposition of the Kapp Hanna Formation, so that this syntectonic depositional phase apparently involved tilting and creation of most accommodation space in the north and northwest. This interpretation is supported by the inland outliers of coarse Kapp Hanna conglomerates and by several features in the Kapp Dunér Formation discussed below; this also suggests that much of the present exposure pattern on the island essentially reflects Late Carboniferous faulting, subsequently modified by early Permian uplift and peneplanation of the entire area. The incised valleys (Figure 35) and the irregular relief produced by this tectonic phase were not completely infilled during the Gzelian: uppermost fine clastic beds in valley fills in Nordvestbukta (Figure 35), for example, contain fusulinids with a clear Asselian aspect; these beds apparently correlate with carbonates from the upper parts of the overlying Kapp Dunér Formation in westernmost exposures. Similar deposits occur above thin Kapp Hanna lithologies on Raudnuten, possibly also in isolated localities south of Miseryfjellet and in at least one of the half-grabens described from the southern cliffs (Figure 6), suggesting that the Kapp Hanna Formation was only locally deposited over most of the eastern and southern parts of the island - and then only in the fault-defined incised valleys.

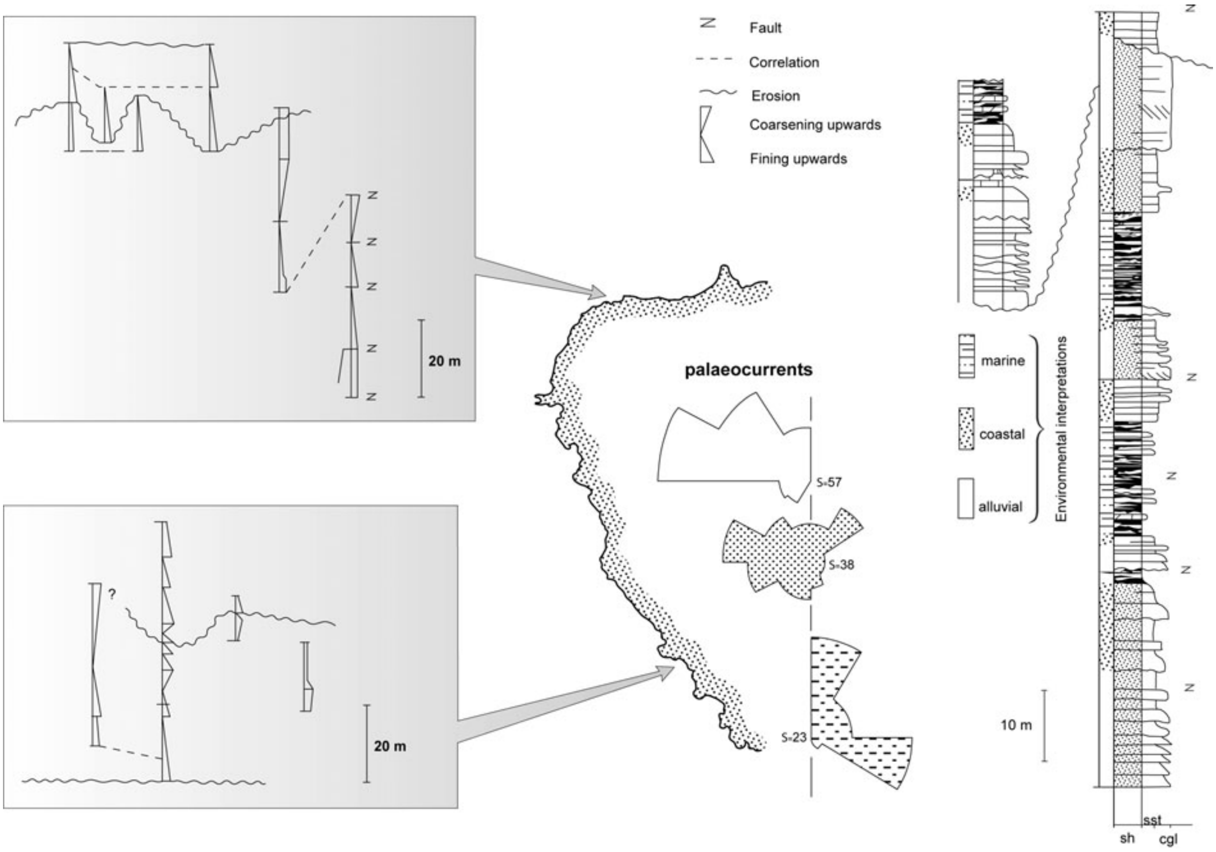



**Figure 35 Composited interpretative logs through the Kapp Hanna Formation, indicating the complex local variations in facies developments, but with clear relationships between lithofacies and palaeocurrent directions.**

*Tectonic summary* **--** The total association of unusual features displayed by exposures of the Kobbebukta Member and the Kapp Hanna Formation strongly suggest intrabasinal tilting which uplifted the eastern flanks of the earlier West Bjørnøya depositional graben. Subaerial erosion of this newly created structural high complex produced the conglomeratic material infilling the incised valleys in the Kapp Kåre and Kapp Hanna formations. Analyses of sandstone mineralogy and conglomerate clast composition in the Kapp Hanna Formation provide additional evidence for basinal evolution at this time. The clasts were derived from older local units and both clasts and matrix show a well-developed inverse stratigraphy, reflecting the progressive erosion of these units on the newly uplifted graben flanks.

**Figure 36 Channel filled with yellow sandstone in the Kapp Hanna Formation**

## *Mid-Gzelian to Asselian stabilization.*

The upper parts of the Kapp Hanna Formation show a marked fining trend into interbedded thin sandstones and dolomitic mudstones, reflecting increasing local tectonic stability and a relative rise in sea level. The transition to the carbonates of the Kapp Dunér Formation is marked by the development of two thick beds of massive dolomite interpreted as dolomitized paleoaplysinid build-ups (Figure 38).

*Kapp Dunér mounds* -- The two lowermost tabular mound sets are overlain by a karstic surface with 2 m relief before deposition of more paleoaplysinid build-ups with a lenticular cross-section. Bituminous limestones and dolomites are common in the inter- and back-mound sequences. We cannot establish the original lateral extent of the build-ups in the Bjørnøya area, but both axial and accretionary trends conform to the basinal pattern suggested by the underlying Kapp Hanna sequences.

*Ongoing Asselian transgression* -- Uppermost lenticular mound horizons are overlain by another pronounced karstic surface. The overlying 40 metres of the formation consist of bedded dolomites without build-ups; these beds represent deposition in lagoonal to restricted shelf environments through the Late Asselian. The present-day exposed top of the Kapp Dunér Formation on the western coast probably approximates to the eroded surface resulting from these Sakmarian movements; fractures and fissures up to about 10 m deep (Figure 37) are filled with clasts and sediments of presumed mid- to Late Permian age. The major erosional surface overlying the mounds in the middle of the formation is correlated with a regional relative fall in sea level in the Late Gzelian now recognised over large areas of the Barents Shelf (*c.f.* Cecchi 1992).

The subsequent Asselian transgression progressively onlapped the entire Bjørnøya area, as shown by the crucial exposures in Nordvestbukta, on Raudnuten and in the southern cliffs (Figure 6). The incised valley observed in the Kapp Hanna Formation in Nordvestbukta has an uppermost infill of Asselian age, directly overlying? Kasimovian coarse clastics. As noted earlier, fusulinids in thin limestone beds that directly overlie both Kapp Kåre and Kapp Hanna Formation lithologies on Raudnuten indicate a late Asselian age. At least one of the previously unrecognized small graben structures in the southern cliffs contains bedded carbonates which we consider to be lateral equivalents to the upper parts of the Kapp Dunér Formation in its main exposure area.

**Figure 37 Karst infilling within the Kapp Dunér Formation**

## *Early to mid-Permian uplift and peneplanation*

Renewed uplift during the Sakmarian and/or early Artinskian produced a broad, apparently gentle and slightly asymmetric anticline, which is cut by large numbers of N-S trending largely normal faults. The axis of this structure corresponds roughly to the margins of the Late Carboniferous high, with the more steeply dipping western limb containing the Upper Carboniferous to lowermost Permian basinal sequences. However, most of the structuring of the area had already occurred in the late Carboniferous rather than now in the early Permian.

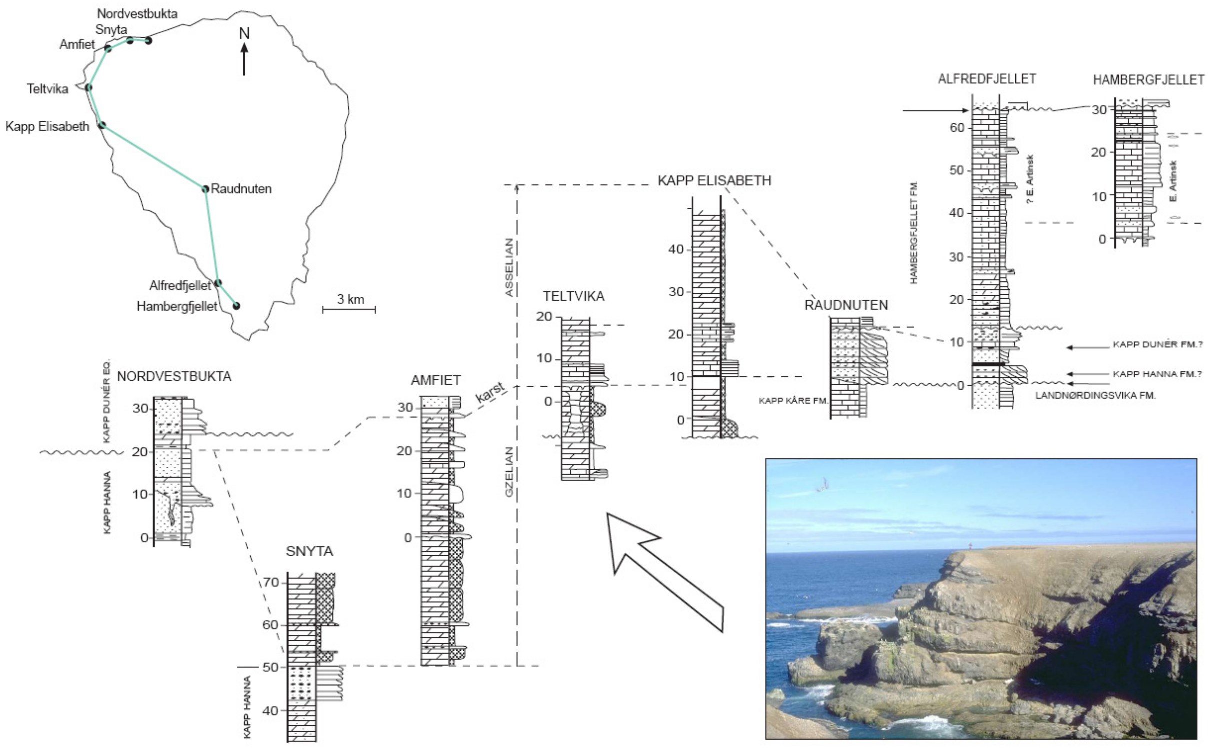



**Figure 38 Correlation of several partial sections through the Kapp Dunér Formation with (inset) an example of stacked palaeoaplysinid buildups.**

This phase of uplift, peneplanation and erosion was therefore probably minor, on the scale of only 100 to 200 m in the eastern and southern parts of the island, rather than the 1 - 2 km apparently suggested by cross-sections of earlier workers (notably Horn & Orvin 1928), which did not recognize the nature and extent of the Late Carboniferous tectonism. These eastern and southern areas were thus essentially sites of uplift and erosion from Late Moscovian Kobbebukta Member time onwards, penecontemporaneously with deposition immediately further west; these areas were only demonstrably transgressed during the Late Asselian immediately prior to regional uplift.

The entire Devonian to Carboniferous sequence is largely affected by extensional faulting with a N-S direction and dip-slip westerly downthrow. The large-scale compressional features advocated by Krasilscikov & Livsic (1974) as being Tertiary in origin could equally well be reverse drag phenomena, produced by movements along listric normal faults during the late Carboniferous. Although some lateral movement with a compressional element may be suggested by isolated faults, and by the small scale horizontal slickensides cross-cutting the earlier phase of dip-slip movements, these are minor in comparison to the bulk of the faulting. Important points to note:

- No major faults affecting the Upper Devonian to Lower Permian succession extend upwards into the Upper Permian strata. Major tectonic movements had in fact ceased prior to the deposition of the carbonates of the Hambergfjellet Formation, so that neither this nor younger units are affected by any significant faulting or show large-scale angular unconformities.

- Horizontal slickensides post-date other indicators of movement, but again are not observed in Upper Permian strata,
- Fault frequency in outcrop decreases markedly upwards stratigraphically and only a very few minor faults affect the relatively large coastal exposure line of the Kapp Dunér Formation, as compared to the high fault frequency observed in the Kapp Hanna and Kapp Kåre formations.

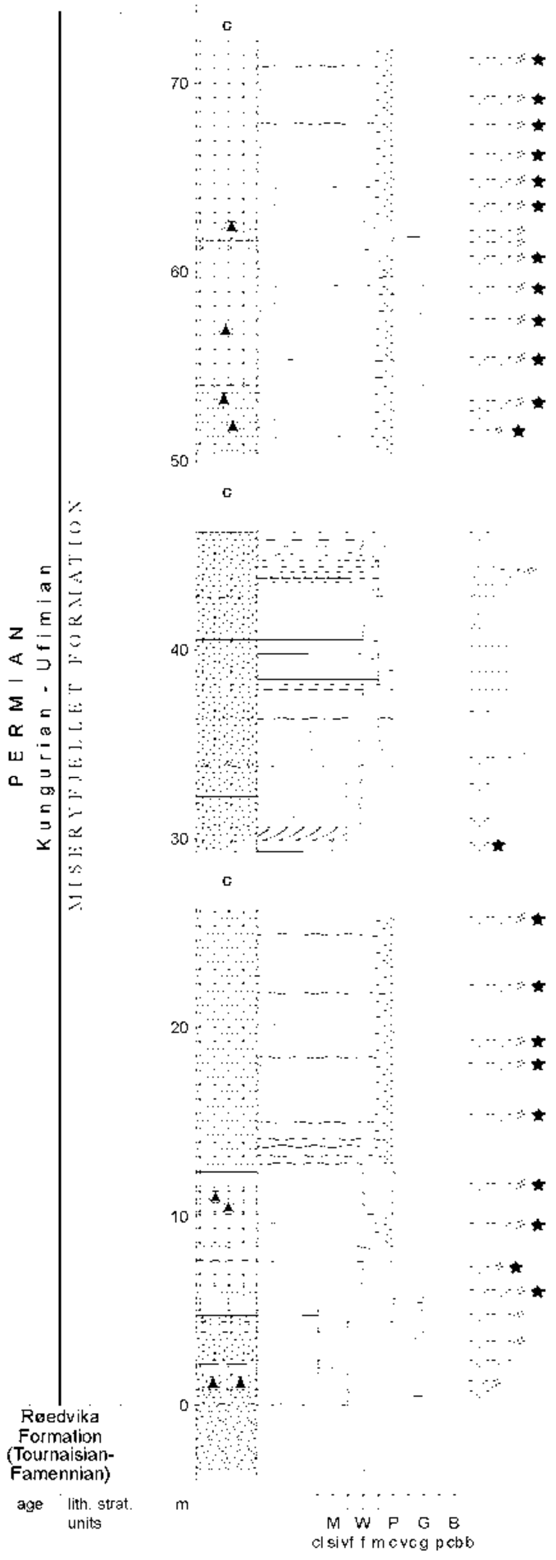
## *Stabilization of the Stappen High*

*The Hambergfjellet Formation* forms an up to 60 m thick sedimentary wedge, which is preserved only on the island's southwestern mountaintops (Figure 6). The unit thins rapidly northwards and eastwards: it oversteps all older sequences before itself being overstepped by the mid- to upper Permian Miseryfjellet Formation. There is a minor angular unconformity between the two formations, so that some additional rotation did occur between these two depositional phases. Rotation was accompanied by some local, probably slide-induced contortion of the Hambergfjellet Formation: this is seen most clearly in the half-grabens which we hope to demonstrate from the boat, where there was small-scale renewed movement before deposition of the overlying Miseryfjellet Formation. Only one of these structures (on Alfredfjellet) shows pronounced faulting affecting the Hambergfjellet Formation and extending down into the underlying Nordkapp Formation (see map).

The largely inaccessible cliff exposures of the formation have yet to be studied in any detail. Basal fossiliferous sandstones pass up into sandy packstones and grainstones with a rich and varied marine fauna of bryozoans, crinoids and brachiopods. The fauna is similar to that found in the upper parts of the Gipshuken Formation of Spitsbergen, generally thought to be latest Sakmarian to Artinskian in age. This correlation suggests a regional transgression which elsewhere resulted in deposition of open marine limestones over a thick sequence of platform dolomites and/or sabkha evaporites. Much thicker equivalents of the Bjarmeland Group are penetrated by offshore wells in the Barents Sea show a packstone/wackestone limestone development with no dolomites, contrasting to the underlying dolomites and evaporates. Faunas also show marked changes prominent limestone build-ups containing bryozoans and *Tubiphytes*, in contrast to the underlying paleoaplysinid and algal build-ups. These and other biota suggest a transition to the cooler water conditions of the Late Permian. Although no reefal facies are seen in the thin onlapping development of the Hambergfjellet Formation on Bjørnøya, cooler water biotic elements are common and skeletal remains are often partially silicified. A strikingly similar development is shown by the contemporaneous Great Bear Cape Formation of the Sverdrup Basin and the lowermost Kim Fjelde Formation of North Greenland.

The Hambergfjellet Formation may have primarily been deposited over the whole Bjørnøya area and then preferentially eroded in the north during tilting prior to deposition of the Miseryfjellet Formation. Equally, the present wedge may be a primary depositional feature, perhaps reflecting preferential subsidence of the southern part of the newly formed Stappen High. Neither remnants nor clasts of Hambergfjellet lithologies are found at the unconformable contact between the Nordkapp and Miseryfjellet formations in the northern parts of the island. It may also be significant that conglomerates with clasts similar to those in the Miseryfjellet Formation directly infill karstic fissures in the present-day truncated top surface of the Kapp Dunér Formation on the northwestern coast (Figure 37). These features together suggest that the northern parts of present-day Bjørnøya were not the site of deposition of any significant Hambergfjellet equivalents.

*The Miseryfjellet Formation* comprises a 115 m thick sequence of silica-cemented sandstones and limestones (Figure 39), which unconformably overlie all older units exposed on the island. The formation lacks the typical development of spiculitic shale seen in more basinal situations represented by the Kapp Starostin Formation of central Spitsbergen and the Røye Formation of the southwestern Barents Sea. Both litho- and biofacies suggest shallow, high energy depositional environments on the newly stabilized and submerged - but still positive – structural high which had developed after the cessation of faulting activity earlier in the Permian.




**The locality Osten ("the cheese") is formed of dolomitic limestone representing a submarine hiatus developed during the late Permian and early Triassic**

**Eastern slope of Miseryfjellet with the vertical cliff "Skrekkjuvet" formed by the silicified carbonates of the Miseryfjellet Formation**

**Miseryfjellet Formation carbonates rest with angular unconformity on sandstones of the Nordkapp Formation. Nordkapp on the northern coast**

**Figure 39 Type section of the Miseryfjellet Formation from Brettingsdalen, a valley on the northeastern slopes of Miseryfjellet**

The karstic fissures in cliff exposures of the uppermost Kapp Dunér Formation (Figure 37) are up to 10 m deep and 1.5 m wide, and are infilled with clasts typical of the basal development of the Miseryfjellet Formation seen elsewhere on the island. Occasional small hillocks of frost-shattered sandstone blocks are seen scattered throughout the northern plain of Bjørnøya. We interpret these as eroded outliers of the Miseryfjellet Formation's basal development rather than glacial erratics as previously assumed (*c.f.* Horn & Orvin 1928, Salvigsen & Slettemark 1995). Thus the entire northern plain of the present-day island approximates to the peneplain upon which the basal sandstones of the Miseryfjellet Formation were deposited. The karst features show that the dolomites of the Kapp Dunér Formation were well cemented by the onset of the late Permian transgression. In contrast, basal sandstones of the Miseryfjellet Formation in northeastern exposures show vertical burrows of *Skolithos* extending down into the underlying sandstones of the Nordkapp Formation. This indicates that the uppermost decimetres of these sands were poorly consolidated in the mid-Permian, although exposures only a few metres beneath the contact show faulting and fracturing with slickensides indicating brittle deformation in at least two phases between the early Carboniferous and mid-Permian. The poorly consolidated sands must therefore reflect early Permian subaerial erosion of exposed and previously cemented sandstones rather than poor consolidation of the entire formation at the time.

The Miseryfjellet Formation's basal conglomerates and sandstones pass up into irregularly bedded sandy packstones and grainstones with distinctive silica cement. These shallow shelf limestones contain a rich shelly fauna, including unusually large individuals of the same brachiopod taxa found elsewhere in the Upper Permian Kapp Starostin Formation of Svalbard. An up to 20 m thick sandstone developed in the middle of the formation contains both tabular and low-angle cross-bedding and *Skolithos* burrows (Figure 39). This unit is interpreted as a shoal complex paralleling the margins of the earlier Gzelian high, suggesting continued subtle tectonic controls on facies patterns in the area (Figure 40). These exposures represent a condensed development of the Tempelfjorden Group, comparable to the even more highly attenuated 5 to 10 metre thick succession seen along the eastern margins of the Sørkapp-Hornsund High in southern Spitsbergen. The continued positive nature of the Bjørnøya area throughout the Late Permian is therefore apparent.

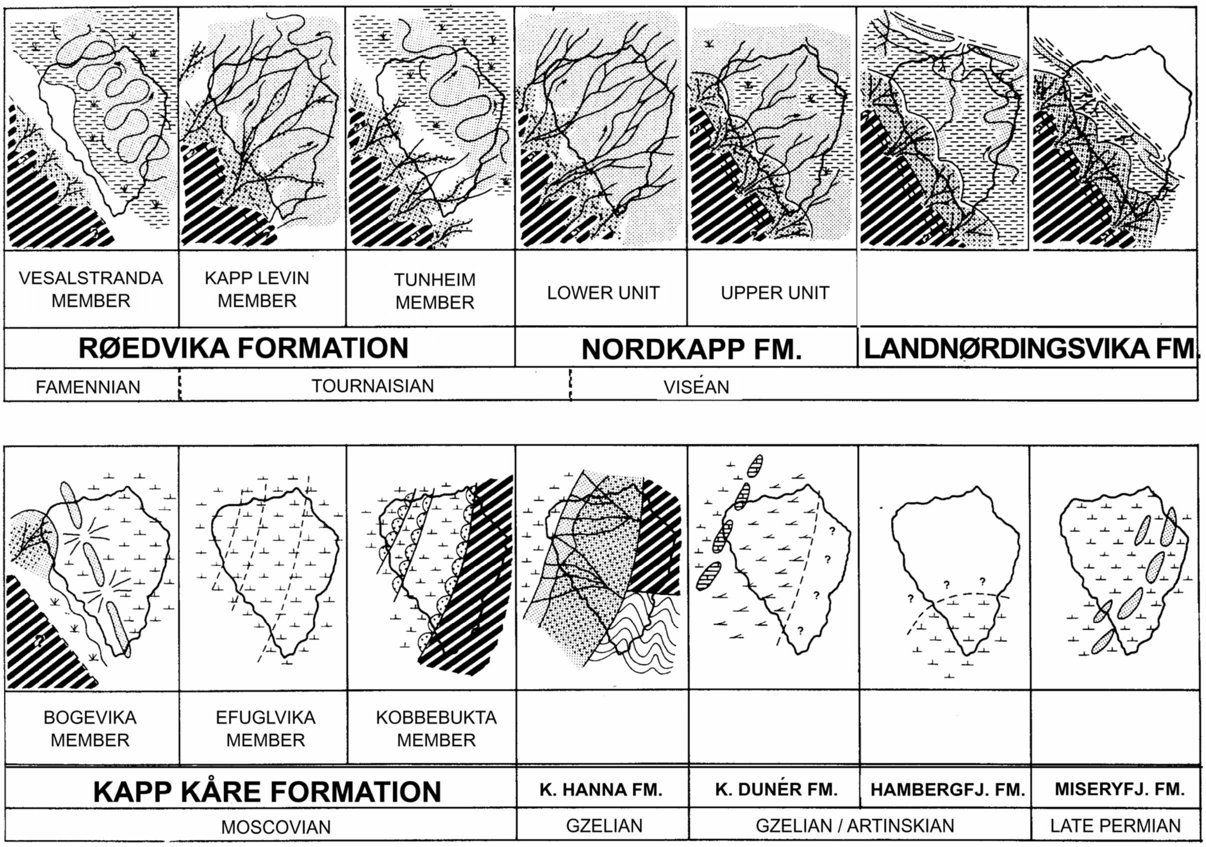



**Figure 40** ***Palaeogeographic summary maps for main late Palaeozoic depositional phases.***

## *Triassic exposures*

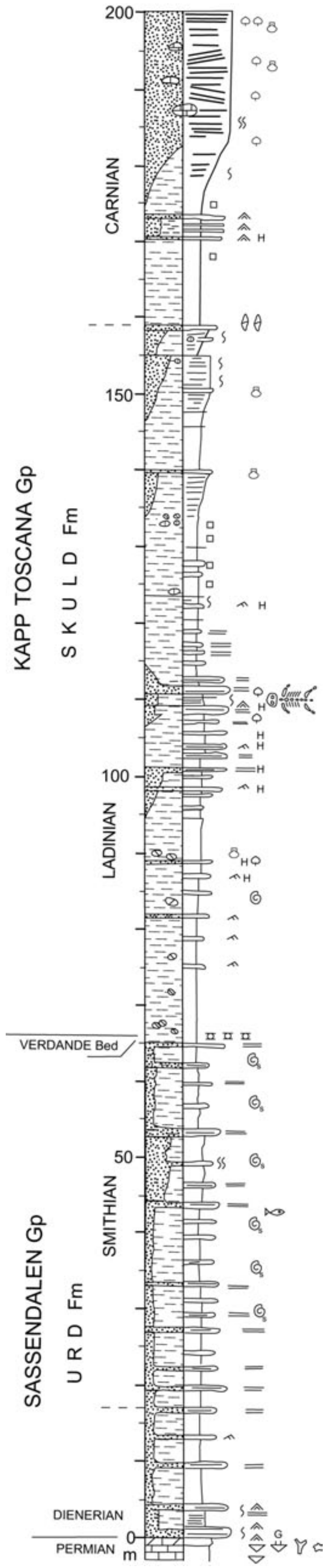
The shale-dominated Triassic sequence, exposed on the highest peaks in the SE of the island, is approximately 200 m thick and rests disconformably on the uppermost resistant limestones of the Miseryfjellet Formation (Figure 41). The lowermost 65 m of the Urd Formation are assigned to the Sassendalen Group - elsewhere on Svalbard dated to the early to mid-Triassic. Palynological studies indicate that the earliest Triassic is not represented - oldest datings suggest a Dienerian age, while a poorly preserved ammonoid fauna of Smithian age occurs in the middle and upper parts of the formation. The lack of Spathian and Anisian palynomorphs indicates sporadic deposition, with major breaks, through to the Late Ladinian.

The Urd Formation comprises silty marine shales comparable in thickness and development to the condensed Lower Triassic sequences seen on the Sørkapp-Hornsund High of southern Spitsbergen. A significant marker at the top of the formation is the Verdande Bed - a 20 cm thick bed of remanié phosphorite concretions, some with the distinctive "petroliferous odour" noted by Hoel & Orvin (1928). This bed is correlated with the organic rich shales with phosphorites deposited elsewhere in Svalbard and throughout the Barents Sea during the mid-Triassic. The remanié clasts suggest that deposits initially formed during a regionally widespread Anisian transgression were subsequently locally uplifted and eroded. However, no similar condensed units are seen elsewhere at this horizon - indeed this was a time when there were fewer and smaller differences between basinal and block subsidence patterns than either earlier or later in the region's evolution.

The 135 m thick Skuld Formation, which is preserved on uppermost mountain peaks, forms a major coarsening upward succession defined by several minor rhythms (Mørk et al. 1990, 1992). The basal beds consist of bluish-grey shales with purple weathering siderite nodules similar to those seen in the Tschermakfjellet Formation elsewhere on Svalbard. The basal beds (of Late Ladinian age) represent a shallowing upwards prodeltaic facies. Rippled thin sandstone-shale alternations in the middle part of the formation have yielded a three metre long amphibian; hummocky bedding and wave ripples and occasional marine fossils indicate deposition in shallow shelf environments. An ammonoid fauna found in the upper part of the formation is diagnostic of the Ladinian/Carnian transition (Dagys et al. 1993). The top of the formation, on the highest peak of Miseryfjellet, consists of a 20 m thick sandstone of Carnian age. The development of the Skuld Formation is not remarkably different, either in thickness or facies development, from the lower parts of other penecontemporaneous coarsening and shallowing upwards sequences seen throughout Svalbard. Comparisons with the Austjøkelen Formation of southern Spitsbergen and the Snadd Formation of offshore wells, for example, suggest that the Skuld sequence originally passed up into deltaic deposits only a matter of metres above the present youngest preserved exposures.

## *Subsequent development of the Stappen High*

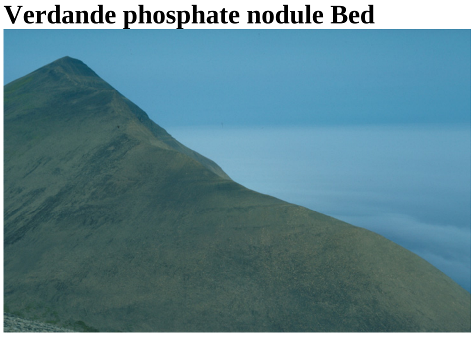
The broad features of the subsequent evolution of the area can be partially reconstructed from the results of organic geochemical and other thermal maturation studies (Bjorøy et al. 1983; Ritter et al. 1996) and by comparisons with the history shown by geophysical studies of the adjacent shelf (Rønnevik et al. 1982; Rønnevik & Jacobsen 1984; Faleide et al. 1984; Nøttvedt et al. 1992). Bjorøy et al. (1983) suggested a post-Triassic overburden in the range of “a few kilometres” based on vitrinite reflectance data ranging from 0.9 to 1.5 % Ro in the upper part of the oil window. Ritter et al. (1996) used these and additional vitrinite reflectance data to estimate maximum burial temperatures to somewhat over 160 °C on the north coast and 150 to 160 °C further south on the island. These apparent local variations may either reflect early oxidation (perhaps related to Late Carboniferous uplift) or slightly varying depths of maximum burial at some post-Triassic stage in the island's development. The present-day base of the Miseryfjellet Formation outcrops between 200 and 350 m above sea level on Miseryfjellet and in the southern cliffs, while it is near sea-level in outliers on the northern plain; this is a result of gentle northerly downtilting of the entire platform, away from the highest point on the Stappen High represented by the basement massif in the south of Bjørnøya; this differential is enough to have produced these variations - if the present tilting also reflects varying maximum burial at some stage in the late Mesozoic or Palaeogene.




**Top of mountain, Carnian sandstone**

**Amphibian covered by silicone**

**Verdande phosphate nodule Bed**



**The Triassic succession at Urd**

**Osten, Triassic shale on top of Permian dolomitic limestone**

**Figure 41 The Triassic type section of the Urd and Skuld formations, measured along the southern slope of Urd, the southern peak of Miseryfjellet**

Palaeogeothermal gradients estimated from the vertical vitrinite reflectance profile at Miseryfjellet range from less than 10 °C/km to over 40 °C/km. A geothermal gradient of 30 °C/km (not unreasonable in view of nearby measurements of present-day heatflow by Sættem et al. 1994) would indicate that 4 to 5 km of post-Permian overburden has been eroded; extrapolations based on sonic velocities in the Triassic shales indicates about 3 to 4 km of eroded section. Apatite fission track data indicate cooling below ~100 °C, beginning at some time during the late Cretaceous to early Tertiary (60 to 90 Ma). Ritter et al. (1996) used all of the available data (including fluid inclusions in the Nordkapp Formation's sandstones) to construct an "optimal" thermal history. However, their reconstructed burial curve for the base Rødvika Formation takes no account of the complex block development through the Late Carboniferous and indicates massive and - in our belief - unrealistic mid- Permian uplift.

Figure 42 presents a reinterpreted burial curve based on the tectonic models proposed here. The total maximum post-Palaeozoic overburden suggested by these studies is thus in the range 3 to 5 km. Axial parts of the Tertiary Central Basin of Spitsbergen appear to have had a maximum total primary thickness of about 3 km of Mesozoic sediments, while estimates suggest thicknesses in the order of 10 km in the central parts of the Bjørnøya Basin to the SE of the Stappen High. In comparison, Triassic to lowermost Jurassic exposures in several northern areas of the Svalbard archipelago show very low (< 0.3 % Ro) vitrinite reflectances, implying minimal later overburden. The estimate for Bjørnøya is therefore "mid-range" and in no way suggests that the area remained a structural high throughout the Mesozoic. The present-day horst structure of the Stappen High therefore probably represents final moulding by the early to mid-Tertiary transpressive movements that preceded the opening of the Norwegian- Greenland Sea. These movements rejuvenated the Late Palaeozoic high, leading to erosion of an appreciable cover of Upper Triassic and younger Mesozoic sediments. We reiterate that the complex faulting and fracturing seen to affect the Carboniferous to Lower Permian succession of Bjørnøya was a result of pre-Late Permian tectonism. There is no evidence of faults or extensive fracturing affecting Upper Permian or younger units wherever these overlie older rocks. The essential fault patterns displayed on Bjørnøya are therefore not a result of Tertiary tectonism - as has been suggested in several regional reviews: such Tertiary movements seem to have been restricted to the master faults along the Stappen High's present margins.

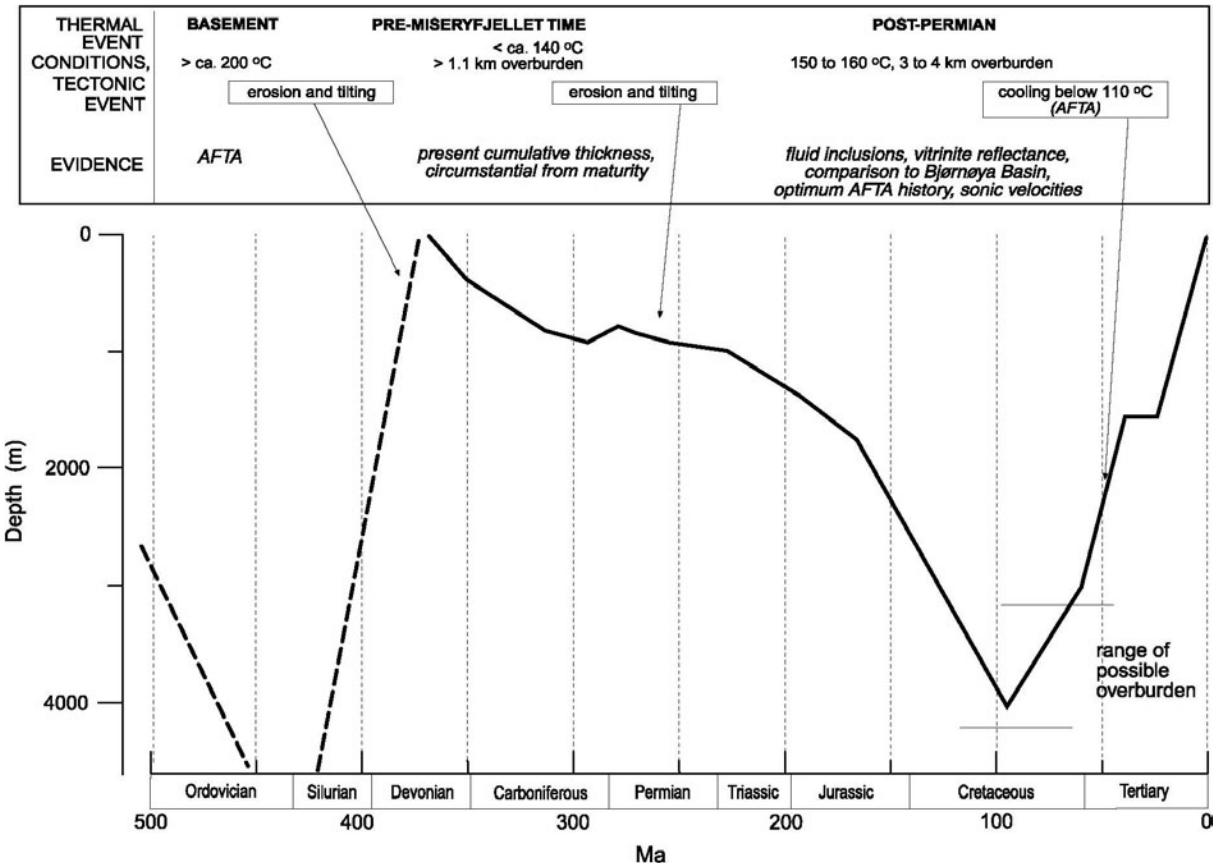



**Figure 42 Modelled post-Triassic depositional and thermal history (from Worsley et al. 2001)**

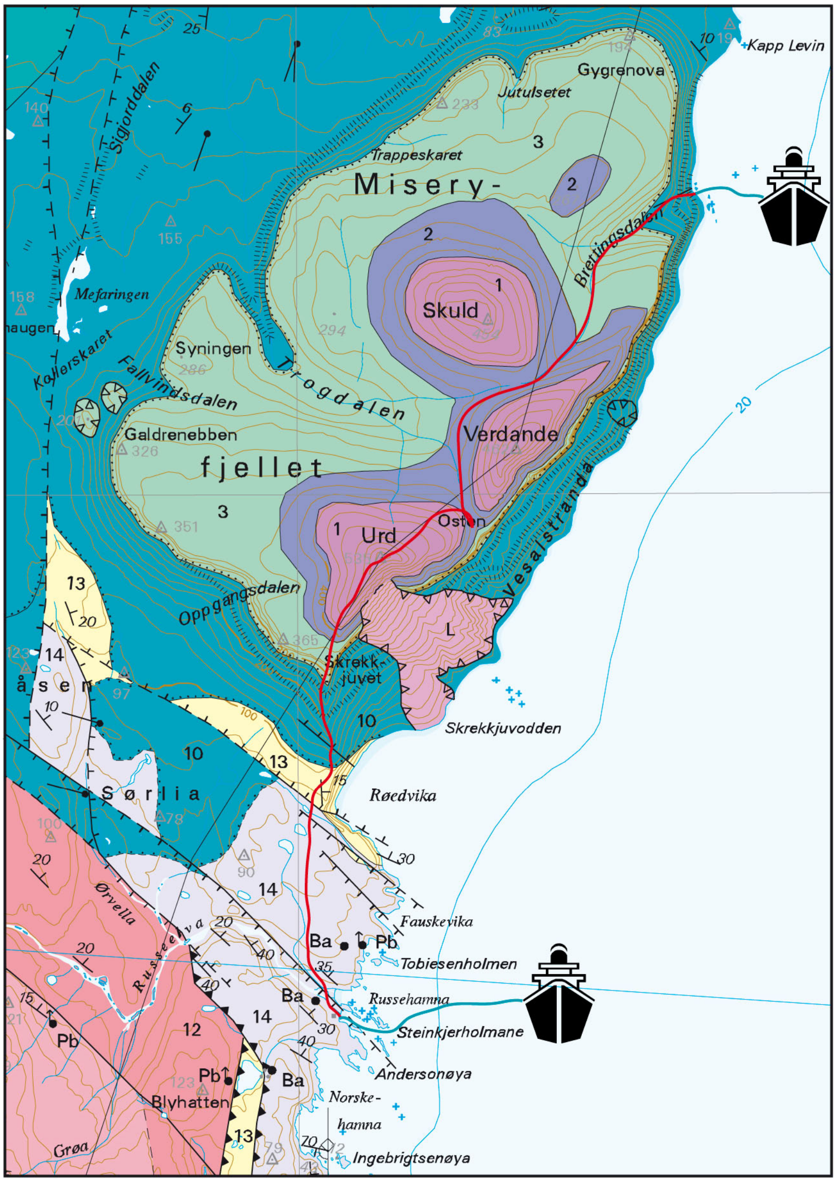
# Field activity

## *Day 1: Sailing to Bjørnøya, lectures onboard*

Sailing from Tromsø to Bjørnøya is estimated to take 24 hours, implying that we can go ashore after lunch on Day 2.

## *Day 2. SE coast, Russekjegla – Miseryfjellet*

*(Ordovician - Devonian - Permian - Triassic)*



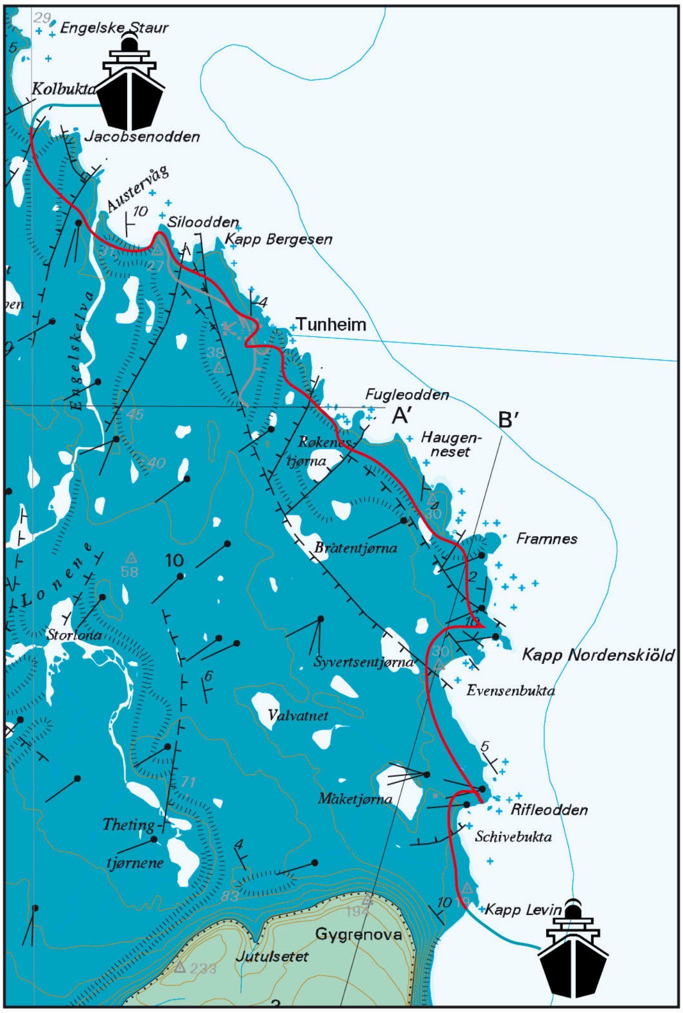

This trip can only take place on a day with nice weather as we will walk up to the highest peak of the island at 536 m asl. Ashore in Russehamna (SW coast) a bay in Late Precambrian dolomite. We will pass along a cliff of uppermost Devonian interbedded sandstone and shale with thin coal beds (Rødvika Formation), before reaching the cliff made up of silicified interbedded limestones of the Miseryfjellet Formation of late Permian age, over which we will climb the shoulder of Urd mountain. The top of the mountain is formed by Triassic shales and siltstones of the Urd and Skuld formations. Weather permitting, we will round Urd and see sandstones in the mid-Miseryfjellet Formation in Oppgangsdalen before briefly visiting a galena sharp in the Hecla Hoek before returning to Russehamna.

A short boat-based visit to Sørhamna will be included now or later to view the thrusted relationship of the older and younger Hecla Hoek dolomites.

A Zodiac trip through the famous Perleporten in dolomites of the Russehamna Formation and a boat-based viewing of Upper Paleozoic grabens in the basement will also be included if/when weather permits.

## ***Day 3. E coast, Tunheim mining town***

*(Devonian – Carboniferous)*



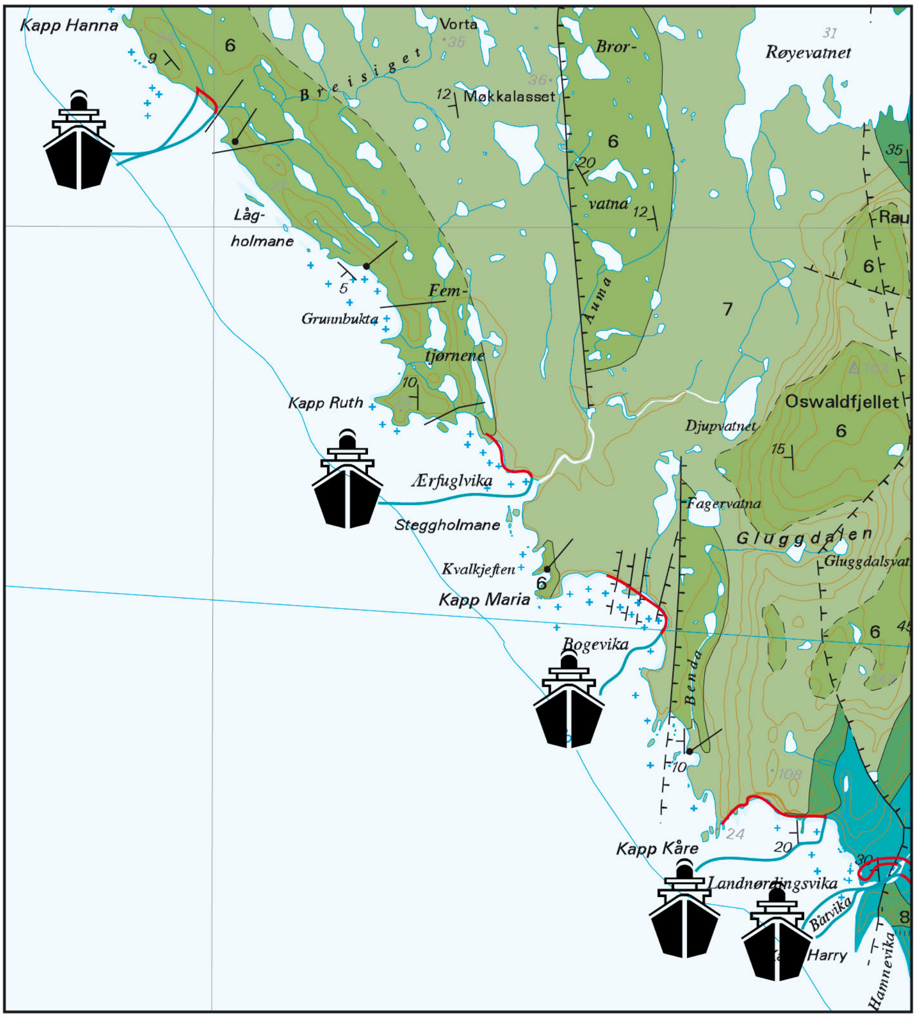

We will go ashore at Kapp Levin to examine uppermost Devonian braided stream deposits with conglomerates, cross-bedded sandstones and minor coal.

Weather permitting we will follow the coast to Tunheim, viewing braided stream, meandering river and interbank deposits and descending the cliff to view a worked-out coal seam.

Collection point near Tunheim, in or around Kullbukta.

## *Day 4. SW coast, Landnørdingsvika – Kapp Ruth*

*(Carboniferous)*

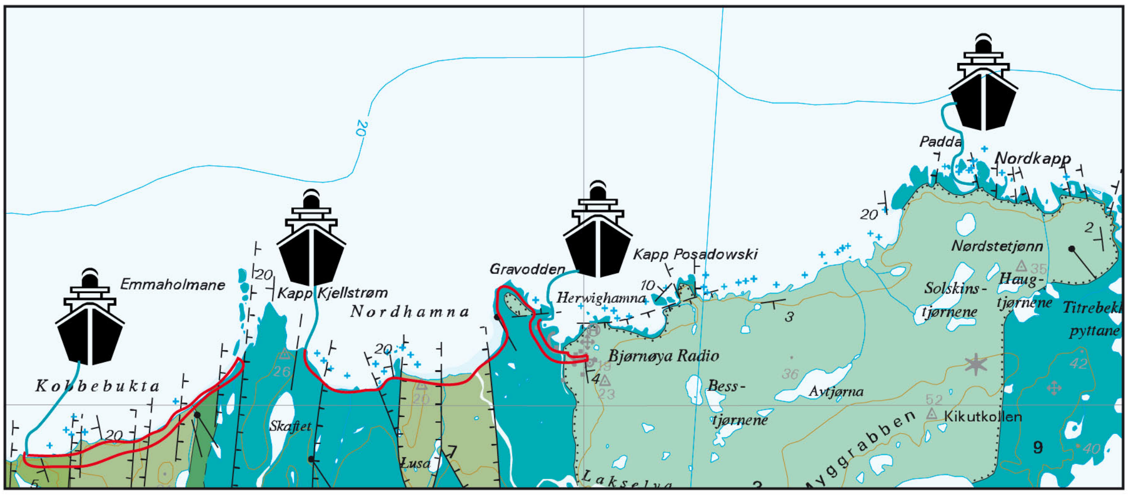



Zodiac safari with brief stops at the foot of the cliffs where considered secure to examine:
Braided stream deposits of the Viséan Nordkapp Formation,
The transition to the red and yellow complexes of the mid-Carboniferous Landnørdingsvika Formation, grading up into grey limestones of the Moscovian Kapp Kåre Formation,
Small –scale cycles in the lower Kapp Kåre Formation in Bogevika,
Limestones and cherts in the upper Kapp Kåre Formation at Ærfuglvika,
The "Bridge of sighs" – uppermost intraformational conglomerates in the formation at Kapp Maria.

Time permitting, conglomerates of the Kapp Hanna Formation south of Bogevika.

## *Day 5. N Coast, Nordkapp - Kobbebukta*

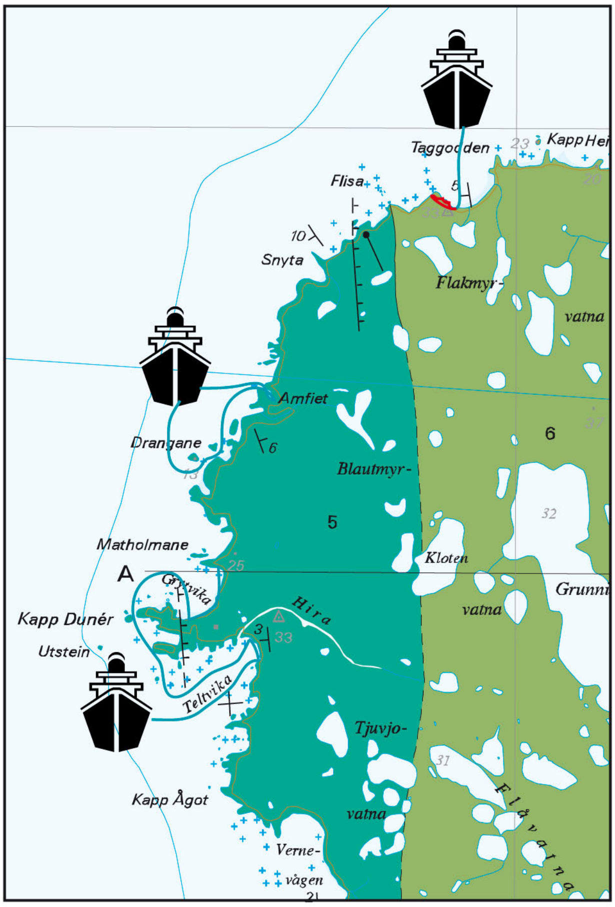
*(Carboniferous - Permian)*




Zodiac stops along the north coast:
The angular unconformity between the Nordkapp and Miseryfjellet formations,
The Radio Station and Bjørnøya Museum,
Synsedimentational deformation in sandstones of the Nordkapp Formation around Gravodden,
Well-developed cycles in the lower Kapp Kåre Formation in Kobbebukta,
Intraformational conglomerates infilling a micrograben uppermost in the Kapp Kåre Formation.

## *Day 6. NW Coast, Kobbebukta to Kapp Duner*

*(Carboniferous – Permian)*




From the boat & Zodiac, examine:
Fault-defined incised valleys cut into lagoonal shales and filled with conglomeratic sandstones of the Kapp Hanna Formation,
The transition to reefal development of the Kapp Duner Formation,
Typical palaeoaplysinid reefs, karst caves and mid-/late Permian infill of karstic dykes.

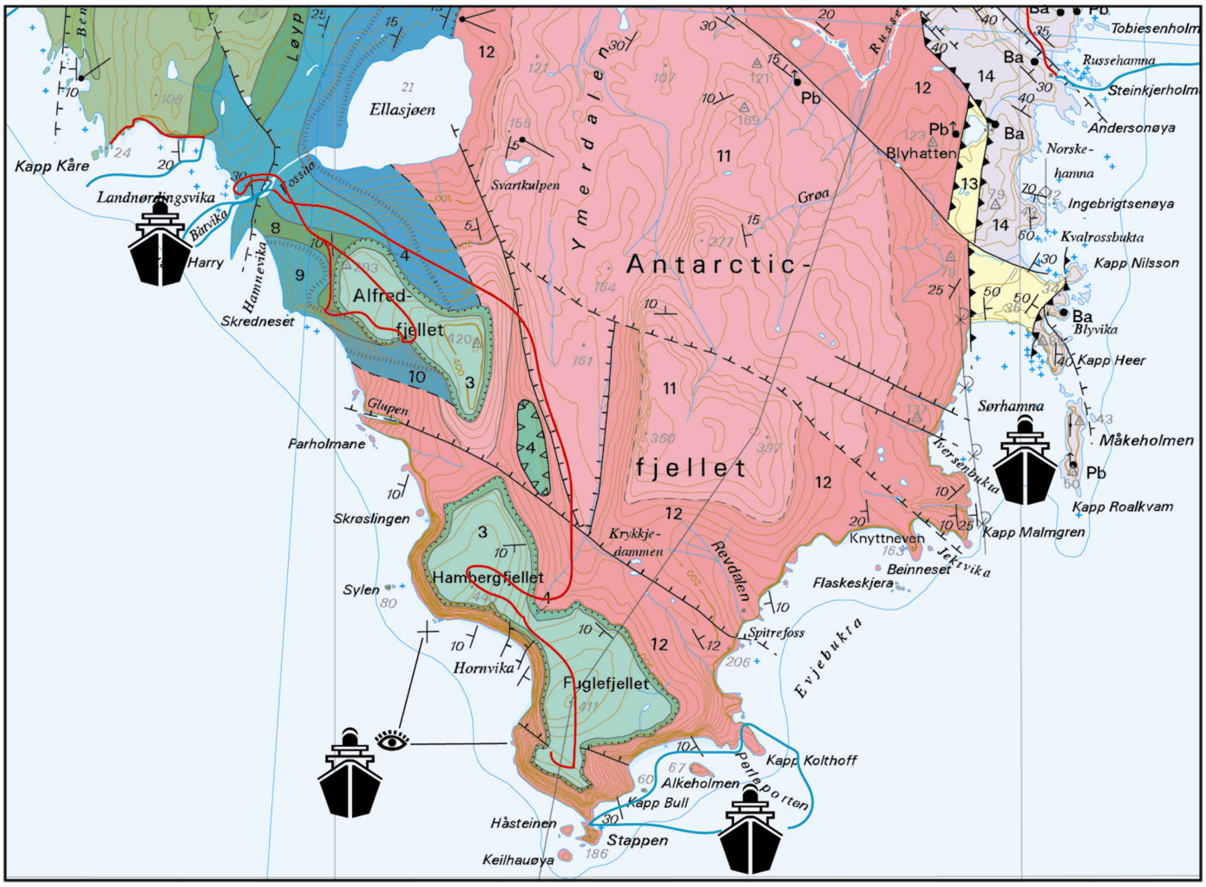
We will go ashore to examine the Kapp Duner Formation at its type locality.

## *Day 7. SW Coast, Hambergfjellet & southern Bjørnøya*

*(Permian & Ordovician)*

In clear weather: We will go ashore at Båtvika, viewing sandstones of the Nordkapp and Røedvika formations around Ellasjøen, then climbing the ridge of Alfredfjellet to oversee the relationship between older units and the Hambergjellet/Miseryfjellet formations.

Weather permitting a Zodiac trip through the famous Perleporten in domolites of the Russehamna Formation and a boat-based viewing of Upper Paleozoic grabens in the basement
.
We may visit Sørhamna to study to view the thrusted relationship of the older and youger Hecla Hoek dolomites




## *Day 8. Sailing to Tromsø, review of excursion*

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