Tectonic history of Tertiary sedimentation of Svalbard

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Svalbard's Tertiary sedimentary record is important for the understanding of the Tertiary evolution of the entire Svalbard surroundings. Two main phases of Palaeogene sedimentation and establishment of structures have been recognized, both taking place in the West Spitsbergen trough. The first one (transgressive–regressive cycle) resulted in the accumulation of Palaeocene–Eocene deposits, while the second one (regressive phase subsequent to the mid-late Eocene uplift) is represented by Eocene–Oligocene deposits. During the second and tectonically more active phase, sedimentation also started in small isolated grabens in the centre of the west coast horst-like uplift, e.g. in Forlandsundet–Bellsund (mid-Eocene to early Oligocene), in Renardodden and in Kongsfjorden (early Oligocene). The sediments – like those of the second phase of the West Spitsbergen trough – indicate an intense tectonic regime that finally resulted in thrust tectonics along the west coast of Spitsbergen in connection with crustal movements in the Atlantic Ocean. The mid-late Oligocene conglomerates of the Sarsbukta Formation in the Forlandsundet graben, the youngest Palaeogene sediments in Svalbard, probably mark the beginning of a third, post-thrust Tertiary phase (Oligocene–Neogene). Similar sediments fill in the perioceanic troughs to the west of Svalbard. At the end of the Neogene, Svalbard underwent a general uplift against the background of descending movements within the perioceanic troughs.

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Tertiary sediments are very common on Spitsbergen and Prins Karls Forland (Fig. 1) and in adjacent sedimentary basins submerged beneath the sea to the west and north. However, only Palaeogene strata are developed and accessible on the archipelago. The submerged sedimentary basins within perioceanic troughs, as inferred from geological/geophysical data, contain not only Palaeogene but thick Neogene and even Pleistocene formations.

The author has investigated the Palaeogene deposits, the platform structure, and the oil and gas prospects of Svalbard (in 1962–1976), and proposed a stratigraphical scheme for the entire archipelago (e.g. Livšic 1967, 1973, 1974) and a classification of the platform structure and main stages of its development (e.g. Livšic 1965, 1973, 1974). Since 1972, the author has carried out similar studies of the Barents Shelf and Arctic Ocean on the basis of new interpretations from new geological and geophysical surveys (e.g. Livšic & Daragan-Suščova 1990; Livšic & Sokolov 1977; Gramberg 1988). After renewed field work in Svalbard in 1987, the author wants to stress that the Tertiary sedimentary development of Svalbard undoubtedly has important implications on the tectonic history of the adjacent offshore areas.

The purpose of this paper (introduced at a 'Symposium on the post-Caledonian tectonic evolution of Svalbard' in Oslo, November 1990) is to present the tectonic history of the Tertiary sedimentation of Svalbard using new geological and geophysical data, and from a point of view that may appear unusual at present.

Tectonic position

Tectonically, both Svalbard and the adjacent shelf belong to the northwestern Barents plate or rather to the Spitsbergen anteclise (Fig. 2). The basement of this anteclise, separated from perioceanic troughs by extensive fault zones, is composed of the Spitsbergen Caledonides and Karelian crystalline rocks of the ancient North Barents Massif to the west and east, respectively.

A horst on the western coast, which in the central part is interrupted by a chain of narrow Palaeogene grabens (Forlandsundet–Bellsund being the largest), is the westernmost first-order structure within the plate. The Bjørnøya step forms the southern projection of the horst. Farther east lies the West Spitsbergen graben-like trough, based on unpublished seismic data (D. Baturin et al.) from Van Mijenfjorden, inheriting a Devonian graben, composed on the surface of a Palaeogene sequence and bounded by western and eastern marginal fault zones (Fig. 3). Of special interest is the western zone with distinct Alpine thrusts and fault-related folds. A series of swells and depressions cut by faults is reported from the axial part of the trough (Livšic 1973). The trough closes southward and its en-echelon continuation is formed by the East Bjørnøya trough contiguous to the large horst-like Bjørnøya uplift, whose multistage block structure with a Riphean to Triassic cover was studied in detail on Bjørnøya (Krasil'ščikov & Livšic 1974). The Sassendalen monocline, the East Spitsbergen trough, and the Ed-

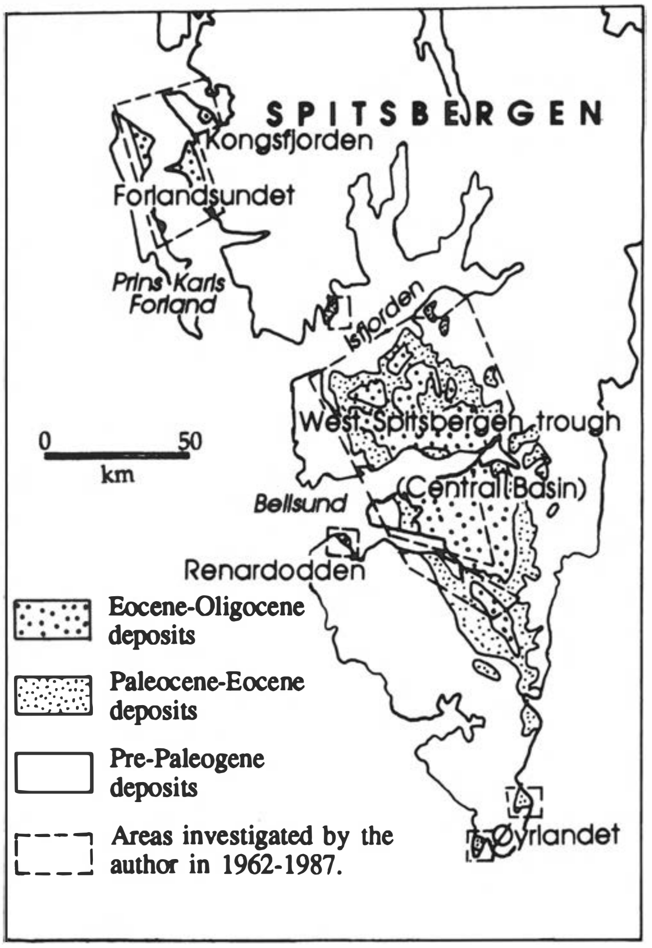

Fig. 1. Areas of Palaeogene deposits in Svalbard.

geøya uplift complete the list of submeridional structures of the Spitsbergen anteclise (Fig. 2). The remaining Spitsbergen anteclise structures located above the ancient massif are mainly brachyform and northeasterly oriented: the West Hopen trough, the Hopen uplift, the Perseus uplift and the Olga trough (Fig. 2). An exception is the east Edgeøya trough, which is northwesterly oriented along the extensive Hinlopenstretet fault.

The main stages of formation of the platform mantle

The accumulation of Tertiary sediments took place during the Alpine stage, which terminated the platform history of the plate subsequent to the stabilization of the Caledonian folded structures. The platform history usually starts with peneplanation and deposition of a Lower Carboniferous coal-bearing succession. However, in some localities, such as Bjørnøya and in the Pyramiden area near Billefjorden, the platform cover starts with the Upper Devonian.

The Alpine stage was preceded by the Hercynian and Kimmerian stages separated by epochs of overall uplift and erosion (see fig. 7 in Livšic 1974). For example, during the Bashkirian, a series of horst-like uplifts and graben-like troughs was formed. The most extensive among them are the Billefjorden and St. Jonsfjorden troughs parallelling fold systems and gradually merging into single troughs. Non-deposition and even an angular unconformity (e.g. pre-Upper Permian on Bjørnøya) were recorded in the sedimentary cover above the North Barents Massif.

The Kimmerian stage, preceded by an overall uplift, was fairly quiet, except for minor uplifts in the Early–Mid-Jurassic, and is marked by a typical platform magmatism during the Jurassic and Cretaceous. Kimmerian structures are gentle compared with the older ones. Movements were less intense than during the Upper Palaeozoic. However, they affected the sedimentary conditions by the emplacement of structures. For example, in the west Spitsbergen trough sedimentation was more intense than in the adjacent areas. During the Early–Mid-Jurassic uplift, however, it was even lower than during the upper Permian uplift, and Lower Jurassic sediments have not been reported at all. It is noteworthy that, starting from the Barremian, the depocentre of the West Spitsbergen trough migrated southward. As a result, the greatest thickness of the Barremian (185 m) and Aptian (190 m) is reported from southernmost Sørkapp Land (Pčelina 1967). As known from seismic data (Faleide et al. 1984) from the Bjørnøya area, the thickness of terrigenous Cretaceous sediments in troughs increases southward and locally attains 1–2 km.

The Alpine stage was the most active during the entire platform history of the region. Its beginning was marked by a general uplift in the Late Cretaceous. It was during that time that Svalbard could have moved along the so-called De Geer line, or Spitsbergen fault zone, from its former position north of Greenland near the Wandel Sea basin to its present location. The interpretation that Spitsbergen in pre-Palaeogene times was located near Greenland (Harland 1961) is widely accepted now. Similarities of the Wandel Sea basin, Svalbard and the Barents Sea shelf were discussed by Håkansson & Stemmerik (1984). However, both Harland (1961) and later authors (e.g. Lowell 1972; Kellogg 1975; Birkenmajer 1981; Steel et al. 1985; Worsley et al. 1986; Nøttvedt et al. 1988) believe that the movement of Svalbard along the De Geer line began no earlier than the Late Palaeocene and was associated with spreading in the Norwegian–Greenland Sea.

The author is of the opinion that this statement about the age of Svalbard's movement is contradictory to the development of thick terriginous and volcanic Palaeogene rocks in Greenland, but not reported from Svalbard, as well as data on the stratigraphy and structure of the Palaeogene strata of Svalbard. However, the accumulation of Palaeogene strata was undoubtedly affected by the developing ocean. For example, the West Spitsbergen Palaeogene trough exhibits a distinct graben-like pattern since the end of the Palaeocene. The sedimentation rate of Palaeogene sediments (72 m/Ma) is higher than that

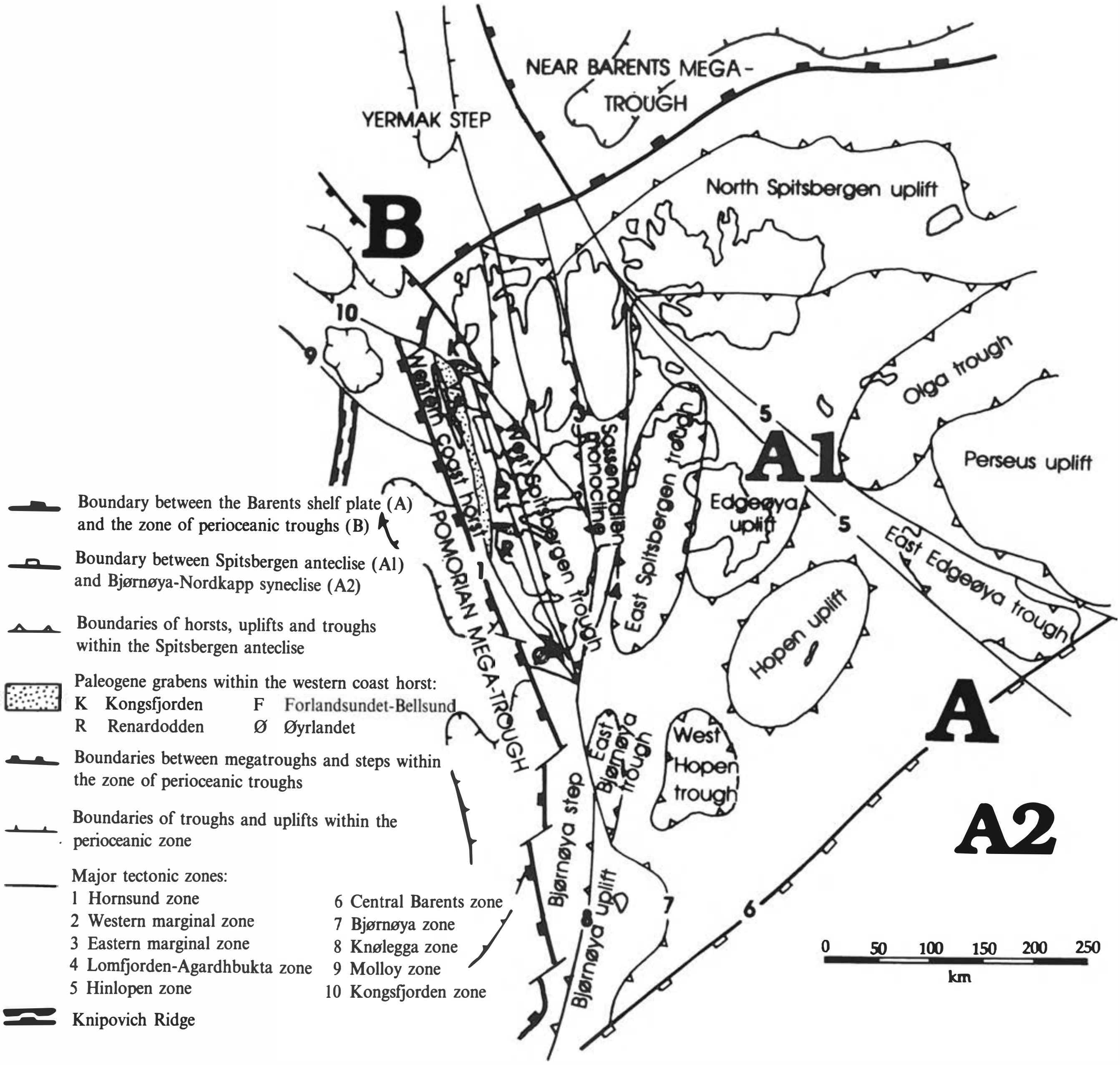

Fig. 2. Structural scheme of the Svalbard shelf and adjacent areas.

of the Mesozoic (16 m/Ma) and the Upper Palaeozoic (35 m/Ma) (see fig. 8 in Livšic 1974).

Palaeogene sedimentation in the West Spitsbergen trough (Central Basin)

In the West Spitsbergen trough (often called the 'Central Basin') the Palaeogene sedimentation exhibits two main phases or macrocycles embracing cycles of lower orders (Livšic 1973, 1974). The first transgressive–regressive cycle of Palaeogene sedimentation and emplacement of structures resulted in the accumulation of the Barentsburg (Firkanten of Major & Nagy 1972), Colesbukta (Basilika of Major & Nagy 1972), Grumantbyen and Hollendardalen (together constitute the Sarkofagen of Major & Nagy 1972) Formations during the Palaeocene–Eocene under conditions of general downwarping, which was most intense in the centre of the trough (see fig. 2 in Livšic 1974; Table 1). The Palaeocene Barentsburg Formation (80–130 to 210–230 m thick), subdivided by Nøttvedt (1985) into two members (Todalen and Endalen Members), rests on the erosion surface of different Albian beds. The deposition of this formation, whose lower part is coal-bearing (Todalen Member), began first within a low depositional flat with numerous lakes and swamps, and later under shallow conditions between islands. Some workers recognize fan facies (in the Longyearbyen and Sveagruva mine areas), and deltaic plain facies with sandy barriers and shallow sea facies (Steel et al. 1981; Nøttvedt 1985; Worsley et al. 1986). On the whole, the Barentsburg Formation, yielding abundant

Table 1. Correlation scheme of Palaeogene deposits in Svalbard.

AGE	MACRO-CYCLE	West Spitsbergen trough (Central Basin)	Kongsfjorden	Renardodden	Forlandsundet: 1. Prins Karls Forland	Forlandsundet: 2. East coast of Forlandsundet
OLIGOCENE	III					SARSBUKTA FORMATION
OLIGOCENE	II	STORVOLA FORMATION	NY ÅLESUND FORMATION KONGSFJORDEN FORMATION	RENARDODDEN FORMATION SKILVIKA FORMATION	*northeastern coast*: MARCHAISLAGUNA FORMATION	*area near Sarsbukta to the north of Aavatsmarkbreen*
EOCENE	II	COLLINDERODDEN FORMATION FRYSJAODDEN FORMATION			*Selvågen area*: KROKODILLEN FORMATION REINHARDPYNTEN FORMATION SESSHØGDA FORMATION SELVÅGEN FORMATION	*area between Snippen and Tjørnnes*
EOCENE	I	HOLLENDARDALEN FORMATION GRUMANTBYEN FORMATION				
PALEOCENE	I	COLESBUKTA FORMATION				
PALEOCENE	I	BARENTSBURG FORMATION	Øyrlandet ?			

fossils, marks the initiation of the transgressive sedimentation as evidenced by a gradual transition to the black mudstones and siltstones of the Colesbukta Formation containing Thanetian (?) (Upper Palaeocene) fauna upsection. The thickness of the formation is highly variable (20–630 m), attaining its maximum in central Torrell Land, and its minimum (20–100 m) in the eastern part of the trough. The Grumantbyen fossiliferous sandstone (160–240 m thick), marking the beginning of a regression, has been assigned tentatively to the Lower Eocene, while the overlying mudstones, siltstones and sandstone with coal seams of the Hollendardalen Formation, containing fossils and plant remains, is supposed to be Middle Eocene. The coal-bearing deposits of the upper member mark the regression maximum and terminate the first transgressive–regressive cycle of Palaeogene sedimentation and establishment of structures. Some workers (Steel et al. 1981; Worsley et al. 1986) consider the Hollendardalen Formation as a part of the overlying argillaceous Frysjaodden (Gilsonryggen of Major & Nagy 1972) Formation, which is a wedge of tidal-influenced deltaic deposits. Nevertheless, these authors also recognize the Hollendardalen Formation as a seperate unit, and it is the top of the formation which is used as a key marker horizon in structural studies (Dalland 1979). In the author's opinion, based both on the detailed study of sections and systematic geological mapping, thick mudstones of the Frysjaodden Formation (200–370 m) deposited in a marine, prodeltaic environment rest on the erosion surface of the Hollendardalen Formation and in the southeastern part of the area rest directly on the Grumantbyen Formation marking the beginning of the second phase (macrocycle). It is of interest that the dominant source areas changed at that time. During the first phase they derived mainly from the north and east, sometimes from the southeast. These sediments are characterized by quartz–feldspar sandstones. After the uplift during the late, mid- to early Late Eocene, dominant source areas were mainly from the west and northwest as evidenced by polymictic sandstones with numerous chloritoid and zircon fragments. These features are characteristic of Precambrian rocks intruded by granites that built up northern and western Svalbard.

The deposition of the Hollendardalen Formation, based on tectonic and sedimentological studies, has been attributed recently by many authors to the early spreading in the Norwegian–Greenland Basin (e.g. Steel et al. 1985; Nøttvedt et al. 1988). However, except for the study of dinoflagellates by Manum & Trondsen (1986), no special palaeontological studies have been made. These authors consider the age to be latest Palaeocene and emphasize that sediments below the Hollendardalen

Formation were deposited under extensional conditions, whereas younger sediments were deposited under compressional conditions. However, comprehensive studies of some faunal and floral groups show that the above formations are most likely of Eocene age (Ravn 1922; Livšic 1973, 1974).

The second phase of Palaeogene sedimentation and establishment of structures in the West Spitsbergen trough starting from the Frysjaodden (Gilsonryggen of Major & Nagy 1972) Formation shows a distinct regressive pattern. The marine (prodeltaic) Frysjaodden mudstone containing pollen and spores forms the transition to deltaic Eocene deposits of the Collinderodden (Battfjellet of Major & Nagy 1972) Formation (135–350 m) containing fauna, microfauna, flora, pollen and spores. The deposits exhibit a strong variation along strike and the thickness increases generally from east and north to west and south. The thickness increases towards the axes of depressions and decreases towards swells and domes (see Fig. 3 in Livšic 1974). Palaeogene structures reflected in the present structural framework have thus developed during sedimentation.

As mentioned above, the presence of the uplifting source area in the west and north is evidenced by the abundance of chloritoid among terrigenous minerals. Also, the number of sandy layers increases westward and northward. The Collinderodden Formation seems to have been deposited during tectonic movement within the contiguous ocean. Rhythmic pattern of lagoonal type, numerous indications of subaquaous erosion, exotic clasts, and the appearance of polymictic sandstone are easily discernible in the Collinderodden Formation.

Later, the connection with the sea was interrupted and the second phase was terminated with Oligocene coal-bearing deposits, the Storvola (Aspelintoppen of Major & Nagy 1972) Formation containing fauna, flora, pollen and spores and having a thickness of over 700 m. Deposition took place on a lake–swamp deltaic plain. Only freshwater molluscs were reported from the formation, unlike the brackish molluscs recorded in the Collinderodden and Hollendardalen Formations.

Despite the fact that Tertiary strata younger than Oligocene are absent, the sedimentation seems to have continued until the Pliocene, as evidenced by the presence of gas coal in the Storvola Formation. This fact is consistent with the presumed existence of Neogene sediments in perioceanic troughs surrounding Svalbard.

Palaeogene sedimentation in the grabens within the Western coast horst

Palaeogene deposits within the western coast horst (except for the Øyrlandet area) accumulated mainly in grabens directly on Precambrian rocks during the second Palaeogene sedimentary cycle and structural formation (Forlandsundet – Bellsund, Kongsfjorden, Renardodden). Generally, rocks are much more coarse-grained and lithic sandstone are polymictic, like those of the upper part of the West Spitsbergen trough sediments.

The Forlandsundet graben continues to the Bellsund graben as inferred from geophysical data. In these grabens, sedimentation apparently began in the Eocene in a narrow intermontane depression at the foot of rapidly emerging mountains. The Selvågen Formation, at the base of the Forlandsundet graben, is represented mainly by blocky variegated conglomerates and breccia conglomerates interbedded with mudstones, siltstones, and sandstones, 30–130 m thick on Prins Karls Forland to 1000 m in the Snippencap area. The coal-bearing Sesshøgda Formation (110 to over 300 m) conformably rests upon the Selvågen Formation. It contains Eocene plant remains and Late Eocene fauna. Calcareous siltstone and mudstone of the overlying Reinhardpynten Formation (210 m) yield Late Eocene fossils, while interbedded mudstones and sandstones of the Krokodillen Formation (400 m) have not provided fossils. The unconformably overlying Marchaislaguna Formation is over 2000 m thick and tentatively assigned to the Oligocene. It consists of rhythmically alternating sandstones, siltstones and mudstones, conglomerates and gravelstones. This succession exhibits numerous traces of subaquaous sliding, slump folds and boudinage similar to features reported from the Collinderodden Formation. Deformation affected the rocks both during and after sedimentation, i.e. they indicate an intensification of tectonic movements. Rhythmically alternated small-pebble and block conglomerates (blocks up to 4 m) in the Sarsbukta area seem to be the youngest Palaeogene succession in the Forlandsundet area. The rocks are not as strongly lithified and deformed as the underlying formations. The conglomerates contain a unit of weakly lithified silty clay from which dinoflagellates, spores and pollen grains were reported by Feyling-Hanssen as early as 1950 and later assigned to the Late Palaeocene-Eocene (Manum & Throndsen 1986). However, marine foraminifers implying a Mid–Late Oligocene age were reported from the same horizon (Feyling-Hanssen & Ulleberg 1984). The author of the present paper during studies in 1967 (Livšic 1973, 1974) assigned the above formations to the Selvågen conglomerates. However, in the course of a more detailed study carried out in 1987, foraminifers were collected and the statement made by Feyling-Hanssen about the Mid–Late Oligocene age of the succession was confirmed (based on V. Ja. Slobodin's determinations). It was also shown that these conglomerates with their weak lithogenesis and huge blocks up to 4 m are quite unlike the Selvågen conglomerates. The total documented thickness of conglomerates of the Sarsbukta Formation is greater than 55 m, but the upper and lower boundaries of the formation are not exposed. A unit of silty clay 12–15 m thick grades along strike into conglomerates, its minimum thickness being 4 m.

The Sarsbukta conglomerate seems to have been deposited in an environment similar to that of the Selvågen conglomerate and they are probably most similar to

Tertiary terrigeneous sediments filling in the perioceanic troughs west of Svalbard. Apparently, these conglomerates mark the beginning of a third phase of Tertiary sedimentation continuing into the Neogene. Palaeogene sediments filling in the Forlandsundet graben crop out on either side of the trough in isolated exposures and are cut by numerous faults. Therefore, the stratigraphy of the Palaeogene succession of the region is much more tentative than that of the West Spitsbergen trough.

Coevally with the intense tectonic movements during the deposition of the Marchaislaguna Formation in the Forlandsundet graben, the deposition of Oligocene beds starts on Upper Permian and Lower Triassic(?) rocks in the Kongsfjorden graben (Challinor 1967), and in the Renardodden graben on Precambrian rocks.

Coal-bearing strata containing plant remains similar to those reported from the Storvola Formation were deposited in both areas (Kongsfjorden Formation, 110–120 m, and Ny-Ålesund Formation, over 120 m; Skilvika Formation, 112 m and Renardodden Formation, over 300 m). Oligocene spores and pollen grains and dinoflagellates also were recorded in the Renardodden area.

Generally, tectonic activity was greater during the second Palaeogene sedimentary phase than during the first one. This is supported by the extremely high sedimentation rate of 247 m/Ma in the Forlandsundet graben. Apparently, starting from the Mid-Eocene, a thick (up to 12 km in the Atka trough) terrigenous sedimentary cover accumulated also in the perioceanic trough bordering Svalbard to the west.

Tertiary development of Svalbard and adjacent oceans

In Oligocene times, the ocean development strongly affected Svalbard, as shown by basic magmatism and formation of major tectonic zones. Thrusts were formed in the western marginal zone at the junction of the Western Coast horst and the West Spitsbergen trough, now mainly exposed within a belt 20–25 km wide.

Compressional faults also have been described recently by Gabrielsen et al. (this volume) and Kleinspehn et al. (this volume) from the Forlandsundet graben. In the present author's opinion, mainly extensional faults are developed in the Palaeogene grabens on the west coast horst and in the perioceanic troughs, while compressional faults are manifested much less clearly than in the western marginal zone (see Fig. 7.17 in Livšic 1973).

Many authors (e.g. Nøttvedt et al. 1988) assume that thrusting not older than Eocene is not confined to the western marginal zone, but continues under the entire West Spitsbergen trough, being responsible for the almost complete absence of Early to Mid-Jurassic deposits. Yet results of unpublished marine seismic surveying by D. Baturin in Van Mijenfjorden provides no clear evidence for such thrusting. In the present author's opinion, the age of intensive thrusting in Svalbard is not older than Early Oligocene, corresponding to the most active part of the second phase of Palaeogene sedimentation and establishment of structures, which took place prior to the deposition of the Mid- to Late Oligocene conglomerates of the Sarsbukta Formation. The Sarsbukta conglomerates probably introduce the third phase, which continues into the Neogene.

At the end of the Neogene a general uplift against the background of descending movements in perioceanic troughs took place. This may explain the absence of Neogene sediments in Svalbard, while their thickness may attain 2–5 km within troughs to the west.

Starting from the Palaeogene, intense processes of thermo- and dynamometamorphism took place in Svalbard. They caused an unusually high density of the sediments, recrystallization of their matrix, strong carbonization of organic matter and high-intensity seismic activity. Extremely high heat-flow values were recorded in the West Spitsbergen trough (Sellevoll 1982). The rock density considerably decreases eastward away from the Svalbard margin. There is no doubt that all these processes are due to the influence of contemporaneous ocean formation. It is of interest that processes operative in the Norwegian–Greenland Sea directly affect the overcompaction of a sedimentary cover. The ocean formation in the Eurasian basin and the rift zone of the Gakkel Ridge did not influence so strongly the rocks and structures of the Barents plate.

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