V. D. DIBNER (Editor)

GEOLOGY OF FRANZ JOSEF LAND

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GEOLOGY OF FRANZ JOSEF LAND

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translated by R.V. Fursenko

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PREFACE

The Franz Josef Land archipelago is situated in the outermost, not easily accessible, part of the northeastern European Arctic. Geologists experience severe obstacles when working in the archipelago, not only in moving between islands but also between capes on one and the same island. Unpredictable ice conditions along the sounds and straits and commonly occurring weather conditions that prevent flying are responsible for these difficulties. When they are overcome, the 85% ice cover and extensive block fields (felsenmeer) make stratigraphical correlation very difficult. Consequently, even though all but a few expeditions that have visited the archipelago have undertaken geological exploration, we still do not possess a full geological picture of Franz Josef Land. However, a wealth of good data, mainly accumulated in recent decades and presented in numerous, but not always accessible, publications, has been awaiting revision and synthesis. A number of authors have jointly endeavoured to take on this task here.

From the outset, this work has formed part of the joint Norwegian-Russian project entitled "The North Barents Geotraverse", which is providing a basis for resuming geological exploration in Franz Josef Land. The authors hope that this monograph will be of interest to Arctic geologists and wider circles of scientists who wish to take a closer look at the geology of these islands, which are a mere 900 km from the North Pole.

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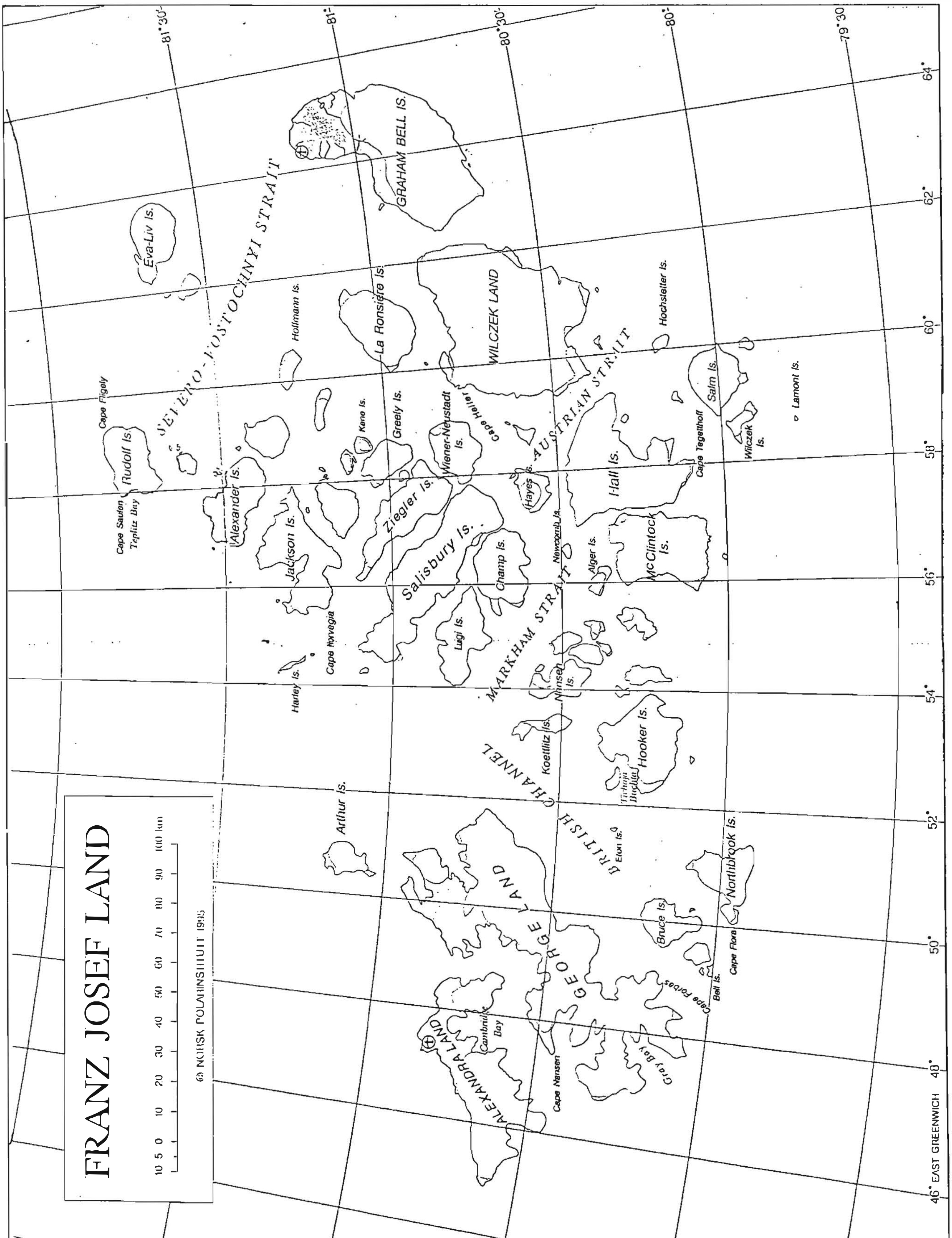
V.D. Dibner
Editor


FRANZ JOSEF LAND
© NORSK POLARINSTITUTT 1995
10 5 0 10 20 30 40 50 60 70 80 90 100 km
81°30'
81°
80°30'
80°
79°30'
64°
62°
60°
58°
56°
54°
52°
50°
48°
46° EAST GREENWICH
GRAHAM BELL IS.
Eva-Liv Is.
SEVERO-VOSTOCHNYI STRAIT
Hoffmann Is.
La Ronsière Is.
WILCZEK LAND
Hochstetter Is.
AUSTRIAN STRAIT
Salm Is.
Lamont Is.
Wilczek Is.
Cape Tegetthoff
Cape Fligely
Rudolf Is.
Cape Saulen
Teplitz Bay
Alexander Is.
Kane Is.
Greely Is.
Wiener-Neustadt Is.
Cape Heller
Ziegler Is.
Jackson Is.
Hayes Is.
Hall Is.
McClintock Is.
Salisbury Is.
Champ Is.
Newcomb Is.
Alger Is.
Cape Norvegia
Harley Is.
Luigi Is.
MARKHAM STRAIT
Nansen Is.
BRITISH CHANNEL
Koettlitz Is.
Hooker Is.
Tikhaja Bukhta
Arthur Is.
Eaton Is.
Northbrook Is.
Bruce Is.
Cape Flora
Bell Is.
Cape Forbes
GEORGE LAND
ALEXANDRA LAND
Cambridge Bay
Gray Bay
Cape Nansen

1. HISTORY OF THE GEOGRAPHICAL AND GEOLOGICAL EXPLORATION OF FRANZ JOSEF LAND – V.D. DIBNER

A naval officer, Nikolai Gustavovich Schilling, an active member of the Russian Geographical Society, wrote in an article published in 1865: "...it is hardly possible that one group of the Spitsbergen islands could keep huge masses of ice, occupying space measuring several thousand square miles, in a permanently similar position between Spitsbergen and Novaya Zemlya. Does not this circumstance, as well as relatively easy access to the northern part of Spitsbergen, suggest that between there and Novaya Zemlya there is a hitherto unknown landmass which stretches northwards farther than Spitsbergen and retains ice" (Schilling 1865) (see also Kremer 1957, 1961 and Dibner 1959a). This land proved to be Franz Josef Land, discovered by the Austro-Hungarian Polar Expedition in 1873. Thus, Schilling's hypothesis was splendidly corroborated (Fig. 1.1).

Fifty-seven years later, in 1930, Gunnar Horn, a Norwegian geologist, advanced his version of the discovery of Franz Josef Land by Norwegian sealers in the same year of 1865. This was related to the beginning of the extension of hunting operations beyond the north and east coasts of Nordaustlandet in the early 1860's. He claimed that, in 1865, the sealing ship "Spitsbergen" with skipper Nils Fredrik Rønnbeck and a harpooner named Johan Petter Aidijärvi sailed and sealed on an easterly course from northeast Svalbard and after 180 miles discovered new land which they called North-East Spitsbergen, or Rønnbeck Land. In Horn's view, it was Alexandra Land, or the Prince George Land islands. The sealers kept their discovery a secret so as to keep their competitors away from good hunting grounds. This could be demonstrated by the old log books, but they were destroyed by a fire in the 1920's (Horn 1930).

The honour of really discovering and first exploring Franz Josef Land goes to the Austro-Hungarian Expedition headed by Julius Payer and Carl Weyprecht (Payer 1876). This expedition used the "Tegetthoff", a sailing vessel fitted with an engine. In August 1873, the "Tegetthoff" was surrounded by ice and later in the month it drifted to the southern periphery of the archipelago. Payer wrote that the sun suddenly emerged from behind the clouds and lit up the outlines of land of an alpine character in the northwest. The ship stayed in the vicinity of Wilczek Island and in November 1873, Payer visited it and ascertained that it was composed of dolerite.

Payer made three sledge journeys in spring 1874. On the first, he discovered and explored capes Tegetthoff and Frankfurt on Hall Island and continued up Austrian Strait to Wiener Neustadt Island and farther north past the islands of Kane, Becker, Rainer and Hohenlohe to Rudolf Island (Fig. 1.2). He rounded the latter from the west and reached Cape Fligely, the northernmost extremity of the archipelago. On his return trip (the second journey), he found Litke, Hochstetter, Berghaus, Klagenfuhrt and other islands. On his third short journey, he explored the southeastern part of McClintock Island. Payer believed that many islands west and east of Austrian Strait were parts of major land areas, and he called them Zichy Land and Wilczek Land, respectively, thus immortalising the names of the sponsors who funded the Austro-Hungarian Expedition.

Payer collected a variety of data on the nature of the archipelago, including its geological structure. Some of these data have still not lost their significance. In particular, he noted an extensive development of dolerites, building up characteristic columnar cliffs, similar to those on the east coast of Greenland. The northern islands were dominated by coarse-grained, olivine-bearing rocks, whereas aphanitic rocks, resembling basalt, were common in the south. Payer was the first to suggest that Franz Josef Land is part of an ancient volcanic region embracing Greenland, Spitsbergen, Jan Mayen, Scotland and other areas, thus anticipating later notions of the Brito-Arctic plateau-basalt province. On the islands visited by Payer, vast accumulations of dolerites and basalts form the flat summits of table mountains. Professor Tschermak, who studied Payer's collection, noted that in their texture, composition and other details, the dolerites of Franz Josef Land resembled those of Spitsbergen (Payer 1876). According to Payer, sedimentary rocks were represented by quartz sand and sandstone with carbonate cement (we now know that these are unambiguously characteristic of the Upper Triassic and Lower Jurassic continental deposits), and he saw shale in talus displaying imprints of flora and silicified wood.

Fig. 1.1 Sketch map of the Franz Josef Land islands. © Norsk Polarinstitutt.

Fig. 1.2 Julius Payer's sledging party at Cape Säulen (Stolbovoi), Rudolf Island (Payer 1876).

Payer also considered the recent glaciation of the archipelago and noted the unusually coarse granularity of the ice, the small amount of till and the low position (about 300 m) of the firn line. He explicitly concluded that only Franz Josef Land "... exhibits the true severity of high-Arctic nature".

Among the exploration work that followed the Austro-Hungarian Expedition, the British expeditions under Leigh Smith (1880–1882) and Jackson (1894–1897), and the Norwegian Expedition under Nansen (1895–1896) are of particular interest.

During his expedition, the English yachtsman Leigh Smith erected a house of planks on Bell Island in 1881, and called it Eira Lodge. Leigh Smith and his companions were unable to winter there because their yacht "Eira" was trapped in the ice near Northbrook Island and sank not far from Cape Flora, where the explorers had to winter in a turf hut. In summer 1882, they came in boats to the edge of the pack ice near Matochkin Strait (Novaya Zemlya), where they found the "Hope", which had been sent to search for them.

Eira Lodge is the oldest building preserved in Franz Josef Land. By chance, it was erected where no snow accumulates and it has survived the action of ice from inside and outside. It has been visited by, among others, the crew of the icebreaker "Krassin" (1928), the present author (1953), and the geologists Yu. Mikhailov and G. Vidmin-Lobzin of the Institute of Arctic Geology in Leningrad (1977).

The Leigh Smith Expedition discovered the islands of Northbrook, Bell, Mabel, Bruce, George Land, Alexandra Land and the intervening straits, including the largest one, British Channel (Grant 1881, Markham 1881, 1883, Montefiore 1894). On these islands, the naturalist J. Grant collected geological material which was examined by Solms & Graf (1904). On Bell and Mabel islands, the expedition members found Upper Jurassic beds (Oxfordian clays yielding belemnites), overlying basaltic sheets and remains of fossilised wood, also encountered at Gray Bay on George Land.

A notable contribution to the geographical and, especially, geological exploration of the archipelago was made by the Jackson-Harmsworth Expedition in 1894–97 (Jackson 1899), which established winter quarters on Cape Flora. The expedition members explored Northbrook, Koettlitz, Nansen, Scott-Keltie, Hooker, Eton, Bruce, Windworth, Mabel, Bell, George Land, Alexandra

Fig. 1.3 Norwegian Polar Institute personnel setting up a memorial at the site where Nansen and Johansen wintered at Cape Norvegia. Photo: N. Heintz, 1990.

Land, Arthur, Luigi, Salisbury, Jackson and other islands. Koettlitz (1898, 1899) made geological observations on most of these, mainly newly discovered, islands. He described series of basalt sheets and ascertained their effusive nature and their great difference from the holocrystalline rocks, dolerites, described by Payer in the north-central part of the archipelago. He described outcrops of underlying Jurassic marine deposits, from which a rich fauna was collected. He also mapped young marine terraces and described the morphology of recent glaciers and evidence of ancient glaciation. The geological collections made by Koettlitz were studied by the petrologist Teall and the palaeontologist Newton (Newton & Teall 1897, 1899).

The Cape Cook section (southeastern George Land), described by Koettlitz (1899), remains of special interest to the present day. He noted outcrops of sand and clayey shale, along with seams of sporinite coal, and these are now believed to be of Lower Carboniferous (Visean) age. It cannot be ruled out that the underlying bituminous shale (yielding plant remains and fish scales) is an equivalent of the *Frasnian domanik* facies, known on the Timan-Pechora plate, in the Urals and on Novaya Zemlya (Dibner 1970, 1978).

The famous Polar explorer Fridtjof Nansen, who was in command of the Norwegian North Polar Expedition on the "Fram" (1893–96), and his companion Lieutenant Hjalmar Johansen, left the "Fram" in spring 1895 and embarked on a sledge journey towards the Pole. They reached 86° 14' N, setting up a record for that time, and then turned southwards, eventually reaching Franz Josef Land. In early August 1895, they came to a little group of islands which were almost entirely snow covered. The men therefore called them Hvidtenland (White Land). Nansen and Johansen wintered at Cape Norge on Jackson Island, and in spring they left there in kayaks on a very hard and perilous voyage towards Cape Flora, where they met the British Jackson Expedition. During his crossing of Franz Josef Land from northeast to southwest, Nansen made some general geographical and geological observations (Figs. 1.3 & 1.4).

Together, Jackson and Nansen proved that Franz Josef Land is an archipelago, not the southern extremity of a land area stretching far north, as some geographers had believed. Nansen established the presence of a ubiquitous development of basalt crossing the archipelago. These rocks, described by Professor Brøgger (Nansen 1897b), were shown to vary in texture from porphyritic to

Fig. 1.4 Log (driftwood) from the ruins of the hut built by Nansen and Johansen. Photo: N. Heintz, 1990.

amygdaloidal and to have vesicles filled with zeolite and calcite. Coarse-grained basalt on Cape McClintock showed a doleritic texture, resembling the dolerites and basalts of Spitsbergen. The basalt of Nansen's collection mostly differs from the plateau basalt of northwestern Europe, the Faeroe Islands, Iceland and Greenland by having low contents of olivine and magnetite. Nansen only observed basalt underlying sedimentary rocks in the Cape Flora area. Here he made a bed-by-bed description of a section of Jurassic (Aalenian, Bathonian, Callovian) marine deposits from which he collected a rich fauna, as well as collecting plant fossils from the continental beds between the basalts (Nansen 1897a, b, 1900, Nathorst 1900, Pompecky 1900). An assemblage of Jurassic and Lower Cretaceous pollen and spores from the collection Nansen made at Cape Flora was studied by Smelror (1986).

At the turn of the century, a number of expeditions were fired with the ambition of being the first to reach the North Pole. Some embarked from bases on Franz Josef Land, then regarded as the most suitable starting point for a decisive push northwards. These expeditions, including the Wellman Expedition (1898–99), the Duke of Abruzzi Expedition (1899–1900), the Ziegler Expeditions (1901–1902), 1903–1904) and the Sedov Expedition (1912–14), ignored the consistent pattern in the motion of old ice in the central Arctic recognised by Schilling as early as 1865, and tried in vain to reach the Pole from Franz Josef Land, i.e. against the vigorous drift of the pack ice. However, they made notable contributions to the scientific investigation of the archipelago.

The following is a brief account of the geological and geographical exploration undertaken by these expeditions.

In summer 1898, an expedition led by the American journalist Walter Wellman, using the Norwegian sealer "Frithjof", circumnavigated Wilczek and Salm islands, and reached Cape Tegetthoff on Hall Island. In spring 1899, the sledge party came to Rudolf Island, but Wellman and his companions reached no further than latitude 82°, from where they returned to Cape Tegetthoff. Simultaneously, Lieutenant Evelyn B. Baldwin, a meteorologist, mapped the east coast of Wilczek Land and the newly discovered Graham Bell Island. In August 1899, the expedition was picked up by the Norwegian sealer "Capella". The islands of Alger, Brice, Bliss and Pritchett were discovered on the way back to Norway. In other respects, the scientific results of the Wellman Expedition were rather modest (Wellman 1899), as its main purpose was the pretence of a dash for the Pole, which had practically no chance, or even hope, of success. In 1920, Nansen wrote that the whole point had been to know what material was expected by newspapers, and in this respect Wellman had had no match.

In summer 1899, the Duke of Abruzzi Expedition, sailing on the "Stella Polare", entered the Victoria Sea and reached 82° 04' N where winter quarters were established in Teplitz Bay on the west coast of Rudolf Island. From there, a group led by Umberto Cagni and two auxiliary parties made a futile dash for the Pole. Cagni reached the record position of 86° 34' N. The members of one of the auxiliary parties, Querini, Ollier and Støkken, perished in the ice on their way back. In

August 1900, the expedition left Franz Josef Land on the "Stella Polare". While wintering in Teplitz Bay, the explorers measured magnetic field variations and gravity, and studied the basic rocks making up Rudolf Island. Petrographical descriptions of the rocks were made by Colomba (1903), Piolti (1903) and Spezia (1903). Dolerites were found to dominate on Cape Germany and Cape Säulen, a coarse-grained basalt flow was noted on Cape Auk, basalts on Cape Fligely and amygdaloidal basalts in Teplitz Bay.

In 1901–1905, two expeditions funded by the American millionaire William Ziegler, operated in Franz Josef Land. The first one, led by Baldwin, reached the archipelago with three vessels in summer 1901. In spring 1902, a sledging party took provisions to Rudolf Island. An advance towards the North was not even attempted, and in August 1902 the "America" took the expedition from the archipelago without any scientific investigations having been made.

In 1903, aboard the same vessel, the Ziegler Expedition in charge of Anthony Fiala, a photographer, returned to Franz Josef Land. In the open Victoria Sea, the vessel penetrated to 82° 14' N and then returned to Teplitz Bay to winter there. Depots were established on Cape Flora and Alger Island, which were used by separate parties of expedition members. Fiala made some pushes northwards, but failed to get beyond 82° N. In August 1905, the expedition returned to Europe with the "Terra Nova" (Fiala 1907). Failure to achieve its main objective, to reach the Pole, was compensated for by a considerable collection of scientific material. A map showing the central-eastern part of the archipelago and the islands of McClintock and Hooker, was greatly improved. William Peters and Russel Porter studied magnetic field variations, tidal currents, made weather observations and studied the geology. Seams of brown coal were found in the Cape Flora area, on Coal Mines Island, and on Cape Washington and Cape Richthofen; fossils were collected from the underlying Jurassic deposits on Cape Flora (Whitfield 1906, Fleming 1907).

In summer 1901, the first Russian icebreaker, the "Yermak", under the command of the noted scientist and designer of the "Yermak", Admiral S.O. Makarov, cruised along the southern coasts of the archipelago (Makarov 1943). It was the third voyage made by Makarov to the Arctic. During their stay on Hochstetter Island, Weber, a geologist on the expedition, described basaltic sheets and thin, interlayered, coal-bearing seams, exposed on the coast (Weber 1908).

In 1913, the first Russian Arctic Expedition, led by Lieutenant George Sedov, came to Franz Josef Land in the schooner "St. Foka". The expedition wintered in Tikhaya (Calm) Bay on Hooker Island. In spring 1914, Sedov, who was ill at the time, made a suicidal attempt to sledge to the North Pole. He died not far from the southern coast of Rudolf Island, where he was buried by his companions, seamen Linnik and Pustoshny (Kushakov 1920, Yesipov & Pinegin 1933). W. Wiese surveyed the coastline of the islands of Hooker, Leigh Smith and Royal Society, and made observations of tidal currents and ice conditions (Wiese 1924, 1928). Pavlov (1921) made geological and glaciological observations. In 1954, a small part of Pavlov's collections was found in the Chernyshev Central Museum of Geology and Prospecting in Leningrad.

In summer 1914, some of the crew of the schooner "St. Anna" (Lieutenant Brusilov Expedition) led by the first mate V.I. Albanov, reached Cape Mary Harmsworth, the western extremity of the archipelago, after an exhausting journey over drift ice. From there, only two men, Albanov himself and a seamen named Kondrat, succeeded in reaching Cape Flora in kayaks. They were taken from the cape by the Sedov expedition on its way home. Albanov's book (Albanov 1917) contains many brief, but precise and vivid, descriptions of dangerous straits and sounds, glaciers, sea cliffs and wildlife from the southwestern part of Franz Josef Land.

In 1925, a British expedition led by Commander F.A. Worsley and Grettir Algarsson on the sailing schooner "Island" visited the waters north of Spitsbergen before sailing to the southwestern islands of Franz Josef Land. They went ashore at Cape Barents (Northbrook Island), whose basic magmatic rocks were studied by the geologist S. Bisset, and also made some hydrographical and hydrological observations in British Channel (Bisset 1927).

By a Decree of the Soviet Government, Franz Josef Land was claimed as Soviet territory on April 15th, 1926.

An expedition led by Professor R. Samoilovich visited the archipelago aboard the icebreaker "Krassin" in 1928 while searching for the Nobile expedition on the airship "Italia". Samoilovich and Ivanov described outcrops of basalt and found coal fragments in talus after landing at Cape Neale on George Land (Belyankin & Vlodavets 1931, Samoilovich 1931).

The western part of the archipelago was visited in summer 1930 by a scientific expedition led by the Norwegian geologist Gunnar Horn aboard "Bratvaag". Horne (1932) described an occurrence of basalt underlying sedimentary strata at Camp Ziegler on Alger Island, and also surveyed Cape Flora and Hunter Bay on Northbrook Island, the southern capes of George Land (Forbes, Stephen and Grant), and Cape Mary Harmsworth, the western tip of Alexandra Land. Horn's samples of fossilised wood from the basalt series were studied in detail by Florin (1936), who also revised collections made by Grant, Koettlitz and Nansen, and identified new species and even genera of ginkgoaceous flora, all of which he assigned to the Wealden.

In 1929, the icebreaker "Sedov" carried an expedition from the Institute for the Exploration of the North, in Leningrad, to the north coast of Tikhaya Bay where a polar station, the first on the archipelago, was established. R.L. Samoilovich and I.M. Ivanov made geological and geomorphological observations on Hooker Island, where they collected a Jurassic fauna. They also surveyed the islands of Newton, Nansen and Cape Brook on Rudolf Island (Samoilovich & Ivanov 1931, Samoilovich & Bodylevsky 1933).

In 1931, I.M. Ivanov, using the Tikhaya Bay station as his base, studied the geology of coal-bearing beds (interlayered with basalt) and mapped coal seams on the islands of Hooker and Scott-Keltie (Ivanov 1935). Petrological studies of basaltic and sedimentary rocks collected by Ivanov on Cape Ugolny (Coaly) on Hooker Island, were made by Vlodavets (1934) and the fauna in the sedimentary rocks was described by Ognev (1933), who assigned it to the Callovian and possibly lower Oxfordian.

In summer 1931, an expedition on the airship "Graf Zeppelin" sent by the International Society "Aeroarctic" made a photogrammetrical survey of the western and northern islands of Franz Josef Land (George Land, Alexandra Land, Rudolf Island and Hvidtenland). Professor Samoilovich, the leader of the scientific group, made important geomorphological and glaciological observations. The outlines of the islands, the degree of their dissection and the extent of ice-covered areas proved to be substantially different from those shown on existing maps (Samoilovich 1933a, b).

In spring 1932, I.M. Ivanychuk, a surveyor, found an outcrop of "quartz dolerite" on Cape Heller, George Land, and roughly surveyed the islands of Alger and Hayes, as well as the Komsomol Islands, which he, himself, had discovered. Basalt was noted on all the capes of Bolshoi Komsomolsky Island (Ivanychuk 1934).

In summer 1932, Lupanova (1932) studied outcrops of basic magmatic rocks on the northwest coast of Hooker Island (capes Markham, Dundy, etc.), Scott-Keltie Island and the west coast of Rudolf Island (Teplitz Bay to Cape Germany). In her petrological account, Lupanova (1953) also described samples collected by Ivanychuk (1934) on Cape Heller and the Komsomol Islands. Lupanova was the first to note the peculiar, fine-grained to pegmatitic schlieren in the basalts and dolerites.

Also in 1932, an expedition from the Marine Institute, "Plavmornin", led by Professor N. Zubov, surveyed the coasts of the islands making up Hvidtenland. The two largest islands, which Nansen had named after his wife Eva and daughter Liv, proved to be a single island, since named Eva-Liv. Zubov (1939) suggested that a hollow on the island had been mistaken by Nansen for a strait. However, taking into account the rate at which the sizes and outlines of Franz Josef Land glaciers are now known to vary, it can be assumed that two islands did indeed exist when Nansen and Johansen found them, but they have subsequently become united owing to the expansion of ice caps.

In 1933–34, T.N. Spizharsky (Arctic Institute, Leningrad), using the Tikhaya Bay polar station as his base, visited the islands of Hooker, Scott-Keltie, Koettlitz, Nansen, Pritchett, Koon, Kane, Alexandra Land (Cape Mary Harmsworth) and part of Alger Island to study their geology. In addition, from the schooner "Lensovet", he made observations of the northern coasts of George Land, the south coasts of Champ, Northbrook and Mabel islands, the north coasts of Jackson and Ziegler islands, all the coasts of Payer, Greely and Bell islands, the west coast of McClintock Island, the northwestern extremity of Salisbury Island and the southwest coast of Alexandra Land. Collections made by Spizharsky were studied by the petrographer Test (1937) and the palaeontologist Ryabinin (1936), who examined a vertebra of an upper Callovian-lower Oxfordian plesiosaur from Hooker Island.

Based on his own and other observations, Spizharsky (1937a, b) outlined the geology of the archipelago as follows. The oldest sediments were marine in origin, yielding Aalenian and Bathonian fauna at Cape Flora. They are overlain by marine Callovian sediments exposed on the islands of Bell and Hooker. Continental psephitic and psammitic strata on the northern part of Hooker Island, and on Nansen, Pritchett and other islands, which yielded unidentifiable plant remains, were also assigned to the Callovian. These beds were placed in the Rhaetian by Nathorst (1900), a decision essentially supported by studies of plant, spore and pollen collections subsequently made from the archipelago, as well as by the examination of a drill core. The presence of marine Jurassic post-Callovian and Valanginian beds, inferred by Ognev (1933) and supported by later studies, was questioned by Spizharsky. He assumed that the basalts overlying the sediments were of Hauterivian-Barremian age. Spizharsky also noted numerous dykes and was the first to infer the presence of central-type volcanoes. He also made observations on structural geology, palaeogeography, Quaternary geology and geomorphology (Spizharsky 1936a) and considered that the recent glaciation of the archipelago was analogous to that of Antarctic islands (but not to Antarctic continental glaciation, as mentioned in some later works). Spizharsky recognised the following types of glaciers on the islands of Franz Josef Land: 1) ice caps, 2) alpine glaciers, 3) valley glaciers, 4) glacier tongues, 5) ice-ridge glaciers, 6) relict glaciers. As a whole, the glaciation of the archipelago was characterised by the predominance of ice sheets and a wide range of glacial forms (Spizharsky 1936b).

Shortly after World War II, two polar stations, Tikhaya and Rudolf (in Teplitz Bay) were made operative again. A third, named after Yan Nagursky (1888–1976), the first Russian polar pilot, was established on Alexandra Land in 1952. In the same year, I. Mazuruk, a well-known polar pilot, discovered that a German military meteorological station had been operating on Alexandra Land during World War II.

Expedition activity resumed, and in 1947–49 a Glaciological Expedition from the Arctic Institute in Leningrad was active in the archipelago under the leadership of P.A. Shumsky. It established a permanent glaciological station on the Ciurlionis ice cap (Tikhaya Bay), which operated until 1952.

In 1952–53, the Western Expedition organised by Trust "Arktikrazvedka", made an aerial photographic survey of the archipelago, thus providing good opportunities for geological and glaciomorphological studies, which commenced at once.

In spring 1953, a Geological Expedition from the Institute of Arctic Geology in Leningrad, led by V.D. Dibner, made detailed airborne geological and glaciomorphological surveys across the entire archipelago. V.D. Dibner and V.K. Razin spent 10 weeks carrying out: 1) aerial observations of all rock outcrops and glaciers (the latter cover 85% of the total land area in the archipelago) (Figs. 1.5 & 1.6), 2) brief (0.5–2.0 hr) surveys on ice-free sites on the islands of George Land,

Fig. 1.5 Tent used by geologists on Graham Bell Island in 1953. Photo: V.D. Dibner.

Fig. 1.6 Plane AN-2 supporting geologists in 1953; Tikhaya Bay. Photo: V.D. Dibner.

McClintock, Komsomol, Nansen, Northbrook, Alger, Greely, Becker, Rudolf and Harley, 3) traverses on Graham Bell Island, the north coast of Wilczek Land, the northwest coast of Hooker Island, and some of the central part of Alexandra Land. The aerial observations covered a flying distance of 14,800 km (requiring over 100 flying hours), and the traverses amounted to 330 km. A total of 770 sites were studied, 600 from the air and 170 during the traverses and the brief surveys of ice-free land (Dibner 1962a).

The study of material collected, interpretation of aerial photographs and revision of published data served as the basis for a Ph.D. thesis entitled "Geological structure, geomorphology and recent glaciation of Franz Josef Land" defended by the author in spring 1956.

In August and September 1956, L.P. Pirozhnikov and V.D. Dibner again carried out field work in Franz Josef Land. They acquired a relatively large amount of data on the geology of the central part of Alexandra Land. In addition, using the hydrographic schooner "Nerpa", the author mapped the southeastern cape of Alger Island, Aagaard Island, the east coast of Hall Island, Cape Tegetthoff (the western extremity of Wilczek Land), the northern part of Berghaus Island and Cape Leiter on Graham Bell Island. At the same time, L.P. Pirozhnikov mapped the northeast corner of Hayes Island, Fersman Island, Cape Greely (McClintock Island), Cape Hofer (Wilczek Land) and Dowes Island. The author also made geological observations along Yermak Strait, thereby covering the facing coasts of Salisbury and Champ islands, as well as the islands of Hochstetter and Derevyanny (Woody). The material collected provided support for the stratigraphical scheme constructed on the basis of the studies in 1953. It was used to compile the 1:1,000,000 sheet of the State Geological Map of the USSR and the accompanying text (Dibner 1957b).

Considerable advances were made in 1957 by the party led by the author (working from the Institute of Arctic Geology) and supported by the Hydrographical Expedition of the Main Northern Seaway Department (Glavsevmorput). In summer and autumn 1957, the geology of the islands of Hayes, Bolshoi Komsomolsky, Hoffmann and Scott-Keltie, as well as Cape Hansa (Wilczek Land), the northwest part of Hooker Island and the capes of Vasiliev (Wiener Neustadt Island) and Goristy (Champ Island) was studied in some detail. In addition, landings from the hydrographical vessel "Gidrosever" permitted V.K. Razin to map the capes of Krugozor (Payer Island), Galkovsky (Becker Island), Savoia (Luigi Island), Astra (Champ Island), Linnik and Kavagli (Salisbury Island), Gidrosever, Washington and Kashalot. He also made geological observations along the coasts between the landing sites. The sea floor was sampled from the whaleboat, the icebreaker itself and the sea ice.

The work done in 1956–57, and the many years of laboratory study of collections proved very fruitful. This is especially true of the stratigraphy. The oldest Mesozoic strata exposed in the archipelago were discovered at Cape Hanza on Wilczek Land. The continental Rhaetian-Lias was divided into three formations on the basis of palynological data. The distribution and biostratigraphy of marine Middle-Upper Jurassic deposits, Lower Cretaceous terrigenous beds and volcanic bodies were clarified. Outcrops of marine Cenomanian and Neogene deposits were found on Hoffmann Island. When the entire archipelago is considered, the outcropping sedimentary beds have a total apparent thickness of about 2200 m. New data on magmatism, block tectonics, geomorphology, Quaternary deposits, recent glaciation and the sea-floor geology of the straits were obtained.

The results of the geological work during the 1953–57 seasons are widely used in the following chapters, and the many publications cannot be considered individually here. They are therefore listed in four groups.

1. Overviews of the geology of the archipelago as a whole: Dibner (1957a, b, 1970, 1978).
2. Stratigraphy, palaeontology, lithology, coal-bearing series and palaeogeography: Korzhenevskaya (1957), Dibner (1958, 1960, 1961a, b, c, d, f, g, 1962b, 1973, 1978), Dibner & Sedova (1959), Dibner & Shulgina (1960, 1972), Shulgina (1960), Dibner & Krylova (1963), Dibner & Krylov (1970), Dibner et al. (1962), Pirozhnikov (1958, 1961a, b), Shilkina (1960, 1967), Shilkina & Chudaiberdiev (1971).
3. Quaternary deposits, geomorphology, recent glaciation, marine geology: Dibner (1959b, 1961e, 1962a, 1963, 1965a, b), Dibner & Radygin (1955), Dibner et al. (1959), Basov (1961), Kordikov (1963).
4. Igneous rocks and minerals: Pirozhnikov (1959, 1960), Komarova & Pirozhnikov (1960), Karasik & Dibner (1965), Dibner (1978).

In 1957–59, the International Geophysical Year, the Glaciological Expedition from the Geographical Institute of the Academy of Sciences of the USSR, led by V.L. Sukhodrovsky, operated near the Tikhaya Bay station. Stationary observations were made on the Ciurlionis ice cap and the Sedov outlet glacier. The whole of Hooker, Scott-Keltie, Alexandra Land and Graham Bell islands were covered by semi-stationary and traverse observations and almost all the islands in the central group were covered by aerial observations. The initial results were published in six volumes in 1960–64. A catalogue of glaciers on Franz Josef Land (Vinogradov & Psareva 1965) and a monograph dealing with the recent glaciation of the archipelago (Groswal'd et al. 1973) were published later. Some other geographical, mainly geomorphological, observations were also published (Krenke & Fedorova 1961, Sukhodrovsky 1961, Groswal'd 1963, Groswal'd et al. 1964, Chigir 1965). A few measurements on the Ciurlionis ice cap suggest the absence of fresh, above-zero, intra-permafrost water below the glaciers of Franz Josef Land. In other words, the glaciers rest on frozen ground (Razumeiko 1963, Neizvestnov et al. 1971).

In 1960, the palaeobotanists L.Yu. Budantsev and I.N. Sveshnikova (Botanical Institute, Academy of Sciences of the USSR) worked on the islands of Franz Josef Land. Rich collections of fossil flora taken on Cape Kavagli, Salisbury Island, in the Cape Flora area and at some other sites allowed the ages of Mesozoic deposits underlying the marine Middle and Upper Jurassic and younger sedimentary strata interbedded with basaltic sheets to be determined more accurately (Budantsev & Sveshnikova 1961, 1964, Sveshnikova & Budantsev 1967, 1969).

In the same field season (1960), L.P. Pirozhnikov joined L.Yu. Budantsev and I.N. Sveshnikova at Cape Kavagli for a month and took part in collecting specimens. On Berghaus Island, he described the lower 106 m of the section containing Kimmeridgian and lower Volgian fauna. However, poor correlation between his samples and the actual beds resulted in unfortunate contradictions in the stratigraphical column (Pirozhnikov 1961a, b).

In 1960–62, the Arctic and Antarctic Institute organised a new glaciological expedition led by L.S. Govorukha. This studied recent glaciation on the islands of Hayes, Harley, southern Hochstetter, Ziegler, Arthur, Jackson, Rudolf, Wiener-Neustadt and Wilczek Land. The glaciology of these islands was almost unknown and the expedition obtained new data which supported the views previously put forward by the expedition from the Institute of Geography, mainly based on material obtained on Hooker Island, that a considerable reduction in the recent glaciation was currently taking place. It was found that not only there, but also on more northerly islands, the lower boundary of firn alimentation lies relatively high, at about 400 m above sea level. The reduction in glaciation, the last phase of which began during the first decades of the 20th century, is responsible for considerable changes in coastlines and, in particular, for the appearance of new islands from beneath the ice sheets of neighbouring large islands. Hence, the total number of islands in Franz Josef Land has increased continuously. In 1962, 187 were recognised (Govorukha & Mikhailenko 1964) compared with only about 150 recorded by aerial photographic interpretation in 1952–53. Data obtained by the 1960–62 expedition enabled a map of avalanche zones and landscape maps of Franz Josef Land (Govorukha & Simonov 1961, Govorukha 1965, 1968).

In 1962, the Geophysical Expedition organised by the Institute of Arctic Geology and led by D.V. Levin carried out an aeromagnetic survey of Franz Josef Land. The data obtained were used to study the Earth's crust here and to define the areal distribution of volcanic terrane and hypabyssal intrusions; in particular, they allowed dykes to be traced below glaciers and on the sea floor. Overall, the aeromagnetic data obtained permitted the major features of the geological structure of the archipelago to be delineated (Volk 1964, Karasik & Dibner 1965, Kovaleva 1975, Kovaleva & Piskarev 1977).

In 1968, an expedition from the Institute of Arctic Geology, led by Ya.V. Neizvestnov, studied the structure and composition of the Lower Cretaceous plateau-basalt series using electrical and magnetic instrumentation, including the measurement of magnetic properties and densities. With this end in view, 2000 specimens of igneous rocks were taken on the islands of Alexandra Land, George Land, Hooker, Scott-Keltie, Hayes and Graham Bell. Surprising data were obtained on the intense block tectonics of Alexandra Land, where the basalt series is dissected into numerous, narrow (20–60 m), NW-SE oriented blocks. Transverse (NE-SW) and N-S faults are less evident (Gusev 1971, Piskarev & Kovaleva 1975).

Associated hydrogeological investigations showed that the basalts of Alexandra Land and, indeed, the whole of western Franz Josef Land form a great volcanic basin with (i) saline infrapermafrost waters (cryopag) with a temperature of less than 0°C, (ii) permafrost zone, and (iii) superpermafrost waters. The permafrost in Franz Josef Land attains a thickness of more than 200 m, and the temperature in the cryopag zone ranges from –7 to –13°C (Neizvestnov et al. 1971).

In 1968–70, G.P. Avetisov and N.K. Bulin processed earthquake data recorded by seismographs at the Arkticheskaya station on Alexandra Land and the Hayes station. The epicentres were found to be located in the Franz-Victoria and St. Anna troughs to the west and east of Franz Josef Land. At the latitude of the archipelago, magnitudes do not exceed 5 points, but they reach more than 6 points where the troughs cross the continental slope. PS waves allowed the Moho to be recognised and the composition of the upper mantle to be investigated down to 50 km, namely, crust 23–25 km, "basaltic" layer 10–12 km, "granitic" layer 7–10 km and semi-consolidated Mesozoic deposits 1.5–4.0 km (Avetisov 1971, 1974, Avetisov & Bulin 1974).

During the period from 1973 to 1980, five geological parties from the Institute of Arctic Geology worked on Franz Josef Land.

In 1973, a party led by Yu.Ya. Livshitz re-examined the Kholmisty Peninsula on Graham Bell Island. The Upper Triassic Vasiliev Formation, recognised by the author, was divided into two members. At Cape Kohlsaat, the upper Vasiliev member is disconformably overlain by marine Upper Jurassic (Oxfordian, Kimmeridgian and Volgian) deposits.

In 1975, Graham Bell Island was remapped by a geological team led by Tarakhovsky (unpubl. manus. 1976), who subdivided the Vasiliev Formation into three members. This showed that the beds are most uplifted in the southern part of the Kholmisty Peninsula and under the northern periphery of the Vodopyanov glacier to the south.

In 1976, N.I. Shulgina, V.D. Dibner, Yu.A. Mikhailov and D.V. Sergeev carried out detailed biostratigraphical studies on capes Lamont and Hofer (Wilczek Land), where Lower Jurassic, Callovian, Upper Jurassic and Lower Cretaceous deposits, including a sedimentary-effusive sequence, were recognised. On Cape Hofer, an ichthyosaurus skeleton was found in the upper Kimmeridgian (judging from ammonites) beds. On Cape Lamont, a stock in Upper Triassic (from palynological data) sandstone pierces sandy and silty beds of middle Volgian age (Dibner 1978, Shulgina & Mikhailov 1979, Shulgina 1986, Nesov et al. 1988).

In 1977, Yu.A. Mikhailov and G.K. Vidmin-Lobzin (unpubl. manus.) described sedimentary and volcanic rocks making up Bell Island. These include, in ascending order, (i) the Eira sequence (equivalent to the Upper Triassic Vasiliev Formation), (ii) the Bell sequence, characterised by Lower Jurassic foraminifera, (iii) a sedimentary-effusive sequence, composed of eleven basaltic sheets (Hauterivian and Albian).

In 1979–80, A.V. Ditmar and coworkers compiled a large-scale structural map of Hayes Island and studied the Upper Triassic, Middle to Upper Jurassic and Lower Cretaceous sections on the islands of Salisbury, Champ, Hooker and Mabel. A shield subvolcano was recognised at Nepristupnye (Inaccessible) Rocks (Tarakhovsky et al.unpubl. manus.1980).

In 1977–81, the Nagurskaya, Severnaya and Hayes boreholes were drilled in Franz Josef Land by the Volgokamskgeologia Association (Gramberg et al. 1985).

The Nagurskaya borehole was drilled in 1977 on the north coast of Dezhnev Bay, Alexandra Land, and reached a depth of 3204 m. Down to 1900 m, it penetrated a sedimentary cover comprised of (i) basaltic sheets interlayered with clay and coaly mudstone (Barremian-Aptian), (ii) silty and clayey deposits (Middle Triassic), (iii) mudstone yielding well-preserved fish remains (Lower Triassic), (iv) bioaccumulated limestone (Upper Carboniferous), (v) coal-bearing sandy and silty deposits (Lower Carboniferous). This cover overlay a highly deformed metamorphic basement of Vendian age. Its upper 1000 m consisted of quartzite and the remainder (down to the base of the borehole) was dominated by phyllite and fine-grained quartz-sericite schist. Substantial angular unconformities were recognised at the base of the Lower Cretaceous, Lower Triassic and Lower Carboniferous. The borehole encountered 21 intrusions, varying in thickness from 2 to 20 m. Their ages range from 203 to 94 m.y. (Sinemurian-Cenomanian). The results of lithobiostratigraphical, geochemical and petrographical examinations of core that was recovered are given in publications by Verba et al. (1980), Selezneva (1982), Tarakhovsky et al. (1983), Kasatkina (1985), Korchinskaya (1985) and Preobrazhenskaya et al. (1985a, b).

The Severnaya borehole was drilled in 1977–79 at the northern end of Graham Bell Island, reaching a depth of 3523 m. It encountered both Upper Triassic (silty and clayey deposits) and Middle Triassic (Ladinian and Anisian). These were intruded by six basaltic sheets ranging in age from the latest Early Cretaceous to the beginning of the Palaeogene (Korchinskaya 1985, Vasilevskaya 1985, Preobrazhenskaya et al. 1985a, b).

The Hayes borehole was drilled in 1980–81 to a depth of 3344 m. The log is very similar to that from the Severnaya borehole, and both differ greatly from the Nagurskaya borehole. The differences are related to the tectonic contrasts found in the various parts of the archipelago. Seven sills, ranging from 20 to 73 m in thickness, intruded the Middle to Upper Triassic deposits during the Early Jurassic and Late Cretaceous (Verba et al. 1980, Tarakhovsky et al. 1983, Preobrazhenskaya et al. 1985a, b, Vasilevskaya 1985).

The data obtained through the efforts of several generations of geologists are inadequate to enable us to compile a detailed geological map. Even on many islands in the relatively readily accessible southern part of Franz Josef Land (most of George Land, Koettlitz, Nansen, Bromwich, Pritchett, Royal Society and Leigh Smith), we still only possess reconnaissance data obtained from the air, unsupported by direct geological observations. On other islands in this area (Northbrook, Bruce, Hooker, McClintock, Hall, Wilczek, Salm, Hochstetter and Klagenfuhrt), geological work has only been done on some capes, leaving nunataks completely unknown. North of the Markham and Yermak straits, the islands of Champ, Wiener-Neustadt, Salisbury and Luigi are also inadequately explored. The central part of Alexandra Land, Hayes Island, the Komsomolsky Islands and the Kholmisty Peninsula on Graham Bell Island have been studied in greater detail. With a few exceptions (Hoffmann, Becker and Harley islands, and some capes on Greely, Jackson and Rudolf islands), our knowledge of the geology of all the other islands situated to the north is based on observations from the air made by the author in 1953 and on many landings made by V.K. Razin in 1957.

Future workers must constantly be aware of the complicated geological structure of the Franz Josef Land islands, which rules out field mapping on scales smaller than 1:50,000 to 1:100,000.

2. GEOLOGICAL OUTLINE OF FRANZ JOSEF LAND – V.D. DIBNER

This chapter briefly outlines: 1) the tectonics of the archipelago, including the deep-seated framework and rift genesis, 2) the structural features of the sedimentary cover and peculiarities in its development, and 3) the characteristics of the plateau-basalt series. In addition, it presents some poorly known (especially in the West) data and new theories which are considered in greater detail in Chapters 5, 7 and 9.

The Franz Josef Land archipelago measures about 25,000 km^2. Together with Svalbard, it forms an arctic outpost of the European continent. It constitutes the uplifted and strongly dissected northern margin of the Barents Sea Shelf. In tectono-sedimentary terms, the islands and offshore areas occupy the northern closure of the East Barents Sedimentary Basin. Their complex morphology is also related to tectonic features.

The Archaean-Proterozoic cratonic basement and its platform cover is believed to have been deformed and metamorphosed during the Svalbardian phase of the Caledonian orogeny. Evolution continued in association with deep-seated processes in what are referred to as asthenospheric lenses. These have minimal density. Their rise up to the Moho discontinuity was responsible for the upwarping of overlying lithosphere. Arches formed by this process began to fracture, especially above fold zones. This caused their replacement by rift zones which originated in the early Neocomian. The rifts served as pathways for the deep-seated transfer of heat and mass, mostly resulting in the degassing of the asthenospheric lenses. This gave rise to downwarping of the lithosphere above the lenses, which was accompanied by an increase in sedimentation and the eruption of plateau basalt. The sediment infills that were thus formed are referred to as depocentres. Thus, the post-Caledonian structural development of Franz Josef Land took place in two principal stages, an intrarifting stage and a depocentric stage.

Direct evidence for the intrariftic stage has only been seen in cores from the Nagurskaya borehole on Alexandra Land. The drilling revealed a relatively thin cover pierced by some hypabyssal intrusions. Distinct sequences of Palaeozoic and Mesozoic strata are separated by lengthy gaps. Below the sedimentary-volcanic series (Barremian-Albian), the borehole passed through Middle Triassic, Lower Triassic, Upper Carboniferous and Lower Carboniferous strata. At a depth of 1900 m, it entered the Vendian, consisting of rocks which had undergone deformation and greenschist facies metamorphism during the Svalbardian phase of the Caledonian orogeny at the Devonian-Carboniferous boundary, 360 m.y. ago.

The depocentric stage was identified in the Hayes and Severnaya boreholes on the islands of Hayes and Graham Bell. Geological and geophysical data show that two depocentres, called the Hallclint and Grahamwil depocentres, overlie stable crustal blocks. Both these boreholes and numerous exposures in their vicinity, and also above some other crustal blocks, revealed steady accumulations of Anisian and Upper Triassic, essentially silty, deposits which have a total apparent thickness of about 3400–3500 m. Outcrops on the islands of Graham Bell, Wilczek Land, Hall and many others suggest that these beds are overlain, as a rule without any break, by a Lower Jurassic, essentially sandy, sequence. These are overlain by Middle and Upper Jurassic and Berriasian-Valanginian sandy, silty and clayey deposits, and variegated deposits of Valanginian-Hauterivian age, this sedimentation being interrupted by many breaks. The total apparent thickness of these sediments in a composite section is about 1000 m. These data, supplemented by the results of seismic surveys in more southerly parts of the East Barents Sedimentary Basin, suggest that the sedimentary cover in these depocentres attains a thickness of up to 10–12 km. However, gravimetric data indicate that the maximum thickness is 8–9 km. These figures include the pre-Anisian Triassic and the Palaeozoic strata. It can also be suggested that the depocentric cover strata are underlain by the ancient (Proterozoic-Archaean) basement of the crustal blocks appressed between zones of Caledonian deformation which later served as the loci for fracturing and rifting.

The intrariftic and depocentric structural stages are unconformably overlain by a cover complex composed of Barremian-Albian sedimentary-volcanic rocks. These include basic effusives and tuffs, which are a major component of the plateau-basaltic rock association in Franz Josef Land. Spanning a wide age range, this association includes a hypabyssal intrusive facies, mainly composed of dolerites, including leucocratic, quartz-bearing and (only on Alexandra Land) subalkaline varieties. The dolerites include three generations of dykes, some of which contain characteristic magnetite-rich swells, and sills which are up to 120 m thick.

Observations on many other islands of Franz Josef Land have revealed hypabyssal intrusions in the Upper Triassic, Jurassic and Cretaceous strata, including the Cenomanian on Hoffmann Island. Many K-Ar datings of dykes and sills sampled from the boreholes and outcrops suggest their intrusion between 203 and 34.5 m.y. ago (Sinemurian-Oligocene). The overwhelming majority of hypabyssal intrusions apparently date from 175 to 92 m.y. (Aalenian-Turonian), whereas the sedimentary-volcanic series, which is extremely rich in igneous rocks, falls into the age range of 123–100 m.y.

As was mentioned above, basaltic flows and, particularly, sheets covering both intrariftic and depocentric cover complexes frequently overlie them with a major, angular, pre-Barremian unconformity, thus providing an approximate minimum age for the uplift, fracturing and rifting. Hence, the sedimentary-volcanic strata lie on an intensely faulted and eroded surface. The sedimentary-volcanic sequence, and the plateau-basalt series as a whole within and outside the limits of the sequence, are extremely widespread in Franz Josef Land and mostly determine its physiography. Abundant leaf imprints, silicified wood and, particularly, miospores, enclosed in the interbeds of terrigenous, sometimes coal-bearing, rocks allow the sequence to be subdivided into two units, the Tikhaya Bay Formation and the Salisbury Formation, of Barremian-lower Aptian and upper Aptian-Albian age, respectively. The total apparent thickness of the sedimentary-volcanic sequence (including subordinate doleritic intrusions) reaches 600 m, but geophysical data indicate a much greater true thickness.

The sea-floor topography, the composition of rock samples from the sea floor and the nature of magnetic anomalies suggest that basic rocks are also common on the floors of straits and sounds, and on the adjacent Barents Sea Shelf. For example, north of the archipelago, separate NW-trending dykes can be followed as far as the continental slope and beyond into the Eurasian deep-sea subbasin of the Arctic Basin.

A single outcrop of marine lower Cenomanian, about 45 m thick, is known on Hoffmann Island. This could represent rocks which may directly overlie the Aptian-Albian basalts. Shallow-marine sediments with an apparent thickness of about 25 m were found near the Cenomanian outcrop. The composition of foraminifera and miospores suggests a Neogene age for these deposits.

Some pre-Quaternary sedimentary rocks have been dredged from the sea floor. Of particular interest are fragments of organic, locally dolomitic or recrystallised, Palaeozoic limestones. These rocks are similar in composition to, and probably coeval with, the Moscovian (Upper Carboniferous) limestone and dolomite found on Victoria Island, and/or Upper Carboniferous limestones found in the Nagurskaya borehole. Briquette-like clay, resembling the Upper Jurassic siltstone on Cape Medvezhy and yielding lower Callovian forms of foraminifera, was found in bedrock samples taken in bays on the islands of Hooker and Rudolf, as well as in Cambridge Strait.

Quaternary deposits include: 1) Upper Pleistocene glacial drift, related to the continental glaciation of the whole archipelago and laid down mainly below sea level, 2) Holocene raised beach material, 3) glacial and fluvioglacial drift deriving from recent glaciers, fluviolacustrine, talus, alluvial (including deposits of ephemeral streams) and aeolian deposits, and also weathered rock debris. About 85% of the archipelago is covered by ice.

The pre-Barremian cover is locally deformed by flexures and faults, which are particularly well displayed by the hypabyssal sills. A set of nearly E-W listric faults was found on the islands of Northbrook and Wilczek Land. The Barremian-Albian sedimentary-volcanic sequence is usually gently dipping.

Diapiric stocks, represented by Upper Triassic carbonate and terrigenous rocks, emplaced in younger rocks have been found on Graham Bell Island and on some capes on Wilczek Land, as well as on Cape Tegetthoff on Hall Island. Some dislocations of a diapiric nature are known to occur in the Neogene rocks on Hoffmann Island.

The present-day relief is mainly a result of Pliocene faulting. Rift-related structures, such as secondary rift grabens, were rejuvenated at this time. They appear in the sea-floor topography as graben-shaped depressions forming relatively deep channels in the straits and sounds, and usually traceable onto adjacent islands, and in troughs on the adjacent shelf. The rift grabens separate and flank individual islands and groups of islands, which are recently uplifted crustal blocks characteristically forming the loci of depocentres.

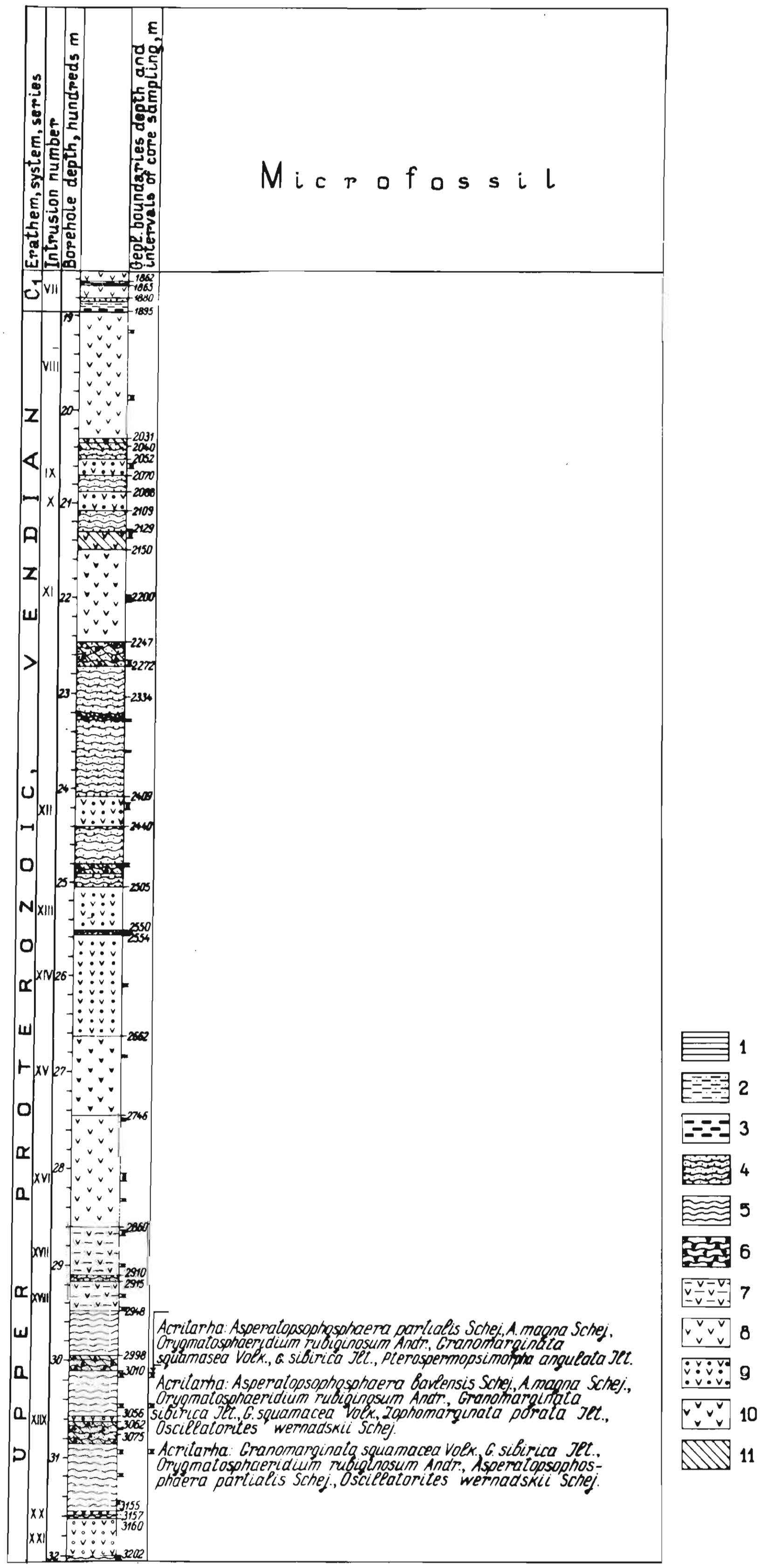


Fig. 3.1.1 Section through the Upper Proterozoic metamorphic basement in the Nagurskaya borehole. Key: 1 mudstone, 2 clayey shale, 3 graphite, 4 fine-grained quartzite, 5 quartz-sericite schist, 6 brecciated and cataclastic rocks, 7 fine-grained dolerite, 8 coarse-grained dolerite, 9 coarse-grained quartzose dolerite, 10 coarse-grained taxitic dolerite, 11 shatter zones.

3. STRATIGRAPHY

The strata exposed on Franz Josef Land largely consist of Palaeozoic (Lower and Upper Carboniferous), Triassic, Jurassic and Lower Cretaceous sedimentary and igneous rocks; only a few exposures of Upper Cretaceous and Palaeogene-Neogene rocks are known. Deformed and metamorphosed Vendian sedimentary rocks encountered in a borehole can be supposed to be a product of the Caledonian orogeny, like similar rocks in northeastern Svalbard (Harland et al. 1993). Quaternary sediments consist of Late Pleistocene and Holocene glacial and marine sediments, mostly block fields and talus on land and bottom sediments on the sea floor.

3.1 UPPER PROTEROZOIC – VENDIAN

3.1.1 Nagurskaya Formation – I.V. Shkola, L.V. Fedorov & E.G. Bro† 1997

The Nagurskaya borehole drilled in 1977 on the north coast of Severnaya Bay, Alexandra Land, at the western end of the archipelago, passed through greenschist-facies metamorphic rocks from a depth of 1895 m to its base at 3204 m. This Upper Proterozoic sequence has been named the Nagurskaya Formation and consists of fine-grained quartzites, phyllites and quartz-sericite schists which are intensely dislocated by subvertical faults marked by shatter zones and cataclastic rocks. Fourteen doleritic intrusions made up 806 m, or 63%, of the total thickness in the borehole (Fig. 3.1.1) (see Fig. 5.16). However, they are clearly discordant and since the borehole crossed them at an acute angle their apparent thickness was much greater than their true thickness. The metamorphic rocks consist of a lower schist and an upper quartzite unit, but their true relationships are uncertain since a number of intrusions totalling 356 m in apparent thickness separate them (depth interval 2554–2910 m).

Schist

The schistose unit was encountered in the borehole at depths of 3202–3204 m, 3062–3160 m, 2948–3056 m and 2910–2915 m and consists of fine-grained quartz-sericite schists and phyllites. Its apparent thickness, including hypabyssal intrusions, is 659 m.

The schists are dark grey with a tinge of green, and foliation surfaces have a silky sheen. The foliation varies from parallel banding to flaser or corrugated, and is marked by thin, light-coloured, fine-grained quartz laminae alternating with thicker, dark beds dominated by coarse flakes and tabular megablasts of mica. The laminae are mostly 1–15 mm thick (Fig. 3.1.2), but locally reach 30–50 cm. The rocks are entirely recrystallised, but relict primary lamination is visible in some horizons. The rhythmic alternation of laminae and thicker beds, and the composition of the rocks, suggest that these schists are reworked flyschoid, terrigenous, sandy and silty rocks containing little carbonate. In general, they are transitional between metasiltstone and quartzite.

Tiny, subparallel sericite flakes define the schistosity, which is sometimes emphasised by the parallel orientation of small, elongate quartz grains. Equidimensional biotite flakes are randomly distributed and commonly lie transverse or oblique to the schistosity (Fig. 3.1.2).

The schists mainly have a microporphyroblastic texture, but granoblastic, corrugated and platy textures are seen in places; blastocataclastic texture occurs in shatter zones. A primary lamination is locally discernible through alternating quartzose and sericitic laminae. The groundmass grain

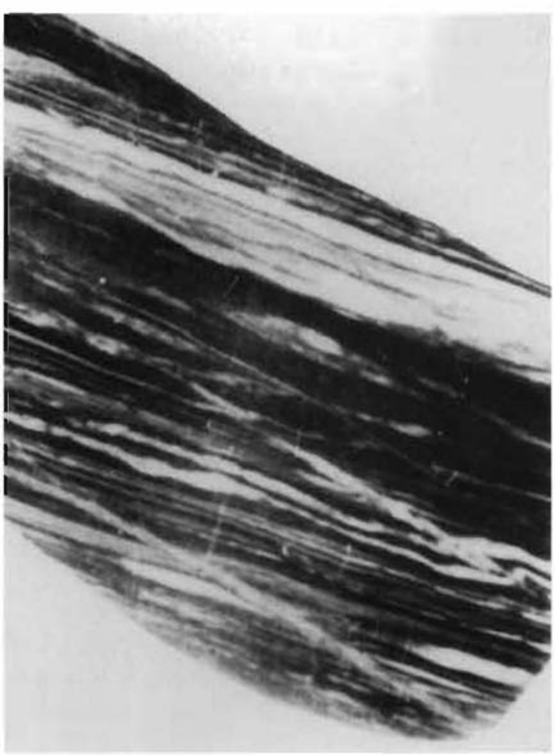


Fig. 3.1.2 Intercalated quartzite and fine-grained quartz-sericite schist. Borehole depth 3200 m. Full size.

size of micaceous layers is commonly 0.05–0.15 mm, whereas that of the quartz-rich intercalations is about 0.1–0.2 mm.

Quartz grains are usually equigranular or slightly elongate (in schistose varieties), polygonal or sutured, and subangular. Some primary quartz may not have been made up of single grains, but of mosaic aggregates which have undergone further granulation. In intercalations of pure quartzite, it is readily seen that fine-grained aggregates of this nature fill spaces between large quartz grains. These granoblastic quartz aggregates were clearly formed *in situ* by regeneration of clasts simultaneous with the recrystallisation of the siliceous cement. Small (0.1–0.3 mm), usually anhedral, porphyroblasts of greenish-brown biotite frequently have a sieve texture produced by abundant minute inclusions of quartz, ore minerals and plagioclase. Carbonate, when present, sometimes forms relatively large grains and veinlets. Ore minerals, mostly pyrrhotite, also occur as small porphyroblasts and lenticular, rounded crystals.

In addition to the remnants of sedimentary textures, the schists show well-preserved primary structures. Primary bedding is doubtless reflected by the compositional and textural differences of alternating laminae. Extremely fine-grained bands, primarily sericitic but locally rich in ore grains and minute quartz granules, weave through the scaly groundmass. These bands may represent the primary argillaceous partings in the silt, the procursor of the schists.

On mineralogical grounds, the fine-grained schists can be divided into two varieties: 1) quartz-mica schists made up of 50–60% quartz, 30–40% sericite (muscovite), up to 7% biotite, 10% plagioclase and potash feldspar, up to 5% chlorite, up to 5% secondary carbonate and up to 2% ore minerals; 2) calcareous quartz-mica schists, which differ from the first variety by having more carbonate (up to 20%) at the expense of quartz and sericite. Subordinate (10–15%) phyllitic horizons are intercalated with the quartz-sericite schists. In the upper part, they contain thin (up to 1.5 m) beds of fine-grained, chlorite-sericite quartzites. The phyllites are dark grey, greenish grey or greenish brown, fine grained and finely schistose to foliate, with a silky sheen on foliation surfaces. Their composition is identical with that of the quartz-sericite schists and relict textures suggest that they, too, have originated from silty sediment. Equigranular quartz grains, up to 0.1 mm, form 45–60% of the rock. The primary argillaceous cement is fully recrystallised into minute sericite flakes (20–45%) interspersed with ore minerals (3–5%). The subparallel arrangement of the scaly aggregates produces a finely foliated texture.

Accessories for all the schist varieties include leucoxenised sphene, zircon, tourmaline, apatite and rutile. Ore mineralisation (pyrrhotite, pyrite, chalcopyrite) is ubiquitous, but minor (up to 1%), and chiefly occurs as thread-like veinlets and chains of lenses superimposed on the schistosity. Magnetic iron ore is disseminated more uniformly.

The age of the schists was determined by L.N. Ilchenko (pers. comm. 1979) from a rich assemblage of acritarchs and trichomes recovered from samples taken at depths of 3015.3 m, 3045.35 m, 3094.2 m and 3095.1 m. The acritarchs are round to oval in shape, thick walled, and show a variety of sculptures (cancellate, reticulate, tubercular). The assemblage is dominated by typical Vendian forms, which differ strongly from Riphean forms. Predominant species are *Asperatopsaphosphaera patrialis* Schep., *A. magna* Schep., *A. bavlensis* Schep., *Origmatosphaeridium rubiginosium* Andr., *Gramomarginata squmacea* Volk., *G. sibirica* Ilt., *Zophomarginata portata* Ilt. and *Pterospermophimorpha sumulata* Ilt., as well as the trichome *Oscillatoites wernadskii* Schej.

The middle portion of the unit is characterised by a corrugated, or flaser, texture formed by alternating layers of mainly micaceous and mainly quartzose material interspersed with lenticular intercalations of quartz, up to 3–5 cm long (Fig. 3.1.3). The schist flows round the quartzose lenses, and significantly larger sericite flakes line the quartz lenses.

Boudinage is common in this part of the schist unit. The boudins mainly consist of quartz or quartzite. Several varieties of boudinage have been recognised, each marking the increasing plasticity of the deformed rock. They include: 1) incompletely ruptured boudins joined by necks and forming chains of swells; 2) isolated, sharply angular blocks; 3) barrel-shaped boudins; 4) widely spaced, lenticular or cylindrical boudins (Fig. 3.1.4).

The schists differ from the overlying fine-grained quartzite in having relatively low values of Neutron Gamma Rays (NGR) (about 1.6–1.7 arbitrary units) and Epithermal Neutron Gamma Rays (ENGR) (4.4–4.8 arbitrary units). Igneous rocks within the sequence are characterised by a sharp decrease in gamma-ray activity from 10–11 to 2.4, or less commonly, 6 mR/h. Fracture zones

Fig. 3.1.4 Finely corrugated and lenticular, fine-grained quartz-sericite schist, with completely transposed, barrel-shaped boudins. Borehole depth 3143.7 m. Polished section, full size.

Fig. 3.1.3 Corrugated, fine-grained quartz-sericite schist (alternating, mainly micaceous and mainly quartzose material). Lenticular boudins consist of competent, fine-grained quartzite in an incompetent matrix of sericite schist. Borehole depth 3116.5 m. Polished section, full size.

sometimes show a decrease in apparent resistivity and are sometimes marked by resistivity anomalies or a relatively greater differentiation of the gamma-ray log.

Quartzite

The fine-grained quartzite forming the upper part of the Nagurskaya Formation was encountered in the borehole at a depth of 1895–2555 m. It is more than 650 m thick, including seven dolerite intrusions ranging in thickness from 18 m to 140 m. These are mostly dykes intruded along faults, but some are sills, concordant to the steeply dipping metamorphic rocks.

The sequence is composed of sericite-feldspar quartzites that are white or light grey with a tinge of blue. Massive beds of pure quartzite alternate with thinly laminated beds which are 0.3–0.6 m thick and contain feldspars and sericite flakes. All primary argillaceous material is entirely recrystallised to sericite. The quartzites are commonly transected by very narrow, vertical, branching joints filled with calcite or a chlorite-mica aggregate. The unit is characteristically light coloured and very finely laminated, thus differing sharply from the dark rocks of the underlying schist sequence.

The quartzite has an extremely to very fine-grained, granoblastic texture. Locally (e.g. thin section 2266.3 – the number corresponds to the depth in the borehole), the quartzite is shattered, displaying blastocataclastic texture and brecciation. Larger quartz grains, sometimes showing evidence of primary rounding, are embedded in a fine-grained aggregate of quartz and some sericite (locally with carbonate) produced by recrystallisation of argillaceous-quartzose sediment. The boundaries between the clastic grains and the sericite-quartz groundmass are not always discernible and the texture becomes lepidogranoblastic. Where a granoblastic mosaic and a sutured texture is present, the outlines of primary quartz grains are marked by ore dust.

The mineral composition of the quartzites is rather monotonous, but the minerals vary slightly

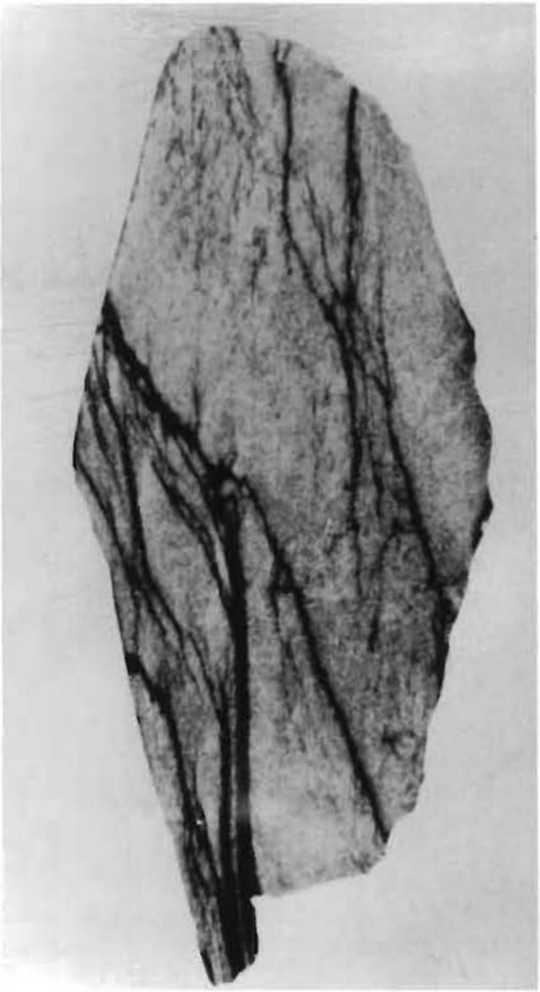


Fig. 3.1.5 Sheared, fine-grained quartzite. Borehole depth 2361 m. Polished section, full size.

in abundance, reflecting a progressive change in the composition of the original sedimentary rocks from quartzose-silty sandstone to argillaceous-quartzose siltstone. The quartzites consist of 60–80% quartz, 20–25% feldspar and 3–5% sericite. Some samples (e.g. thin section 2480.2) contain up to 10% plagioclase. Rutile, zircon, tourmaline and apatite are accessories. Locally, in shatter zones, up to 3–5% of secondary carbonate occurs as aggregates of grains, or irregularly shaped grains with inclusions of quartz and opaques. Two varieties of feldspar are seen, fresh lattice-twinned microcline and sericitised, untwinned orthoclase.

No fossils have been found in the quartzite, but its position in the succession and the degree of metamorphism and deformation suggest that, like the underlying schists, it belongs to the folded basement and has an Upper Proterozoic (Vendian) age.

The dip of the primary lamination varies from 40–65° at different horizons. The rocks are intensely deformed. They are isoclinally folded and overfolded, and are transected by many vertical faults marked by mylonitisation, cataclasis and jointing (Fig. 3.1.5). Six units of metamorphic rock (depth intervals 2035–2052 m, 2070–2088 m, 2109–2129 m, 2247–2409 m, 2440–2505 m and 2550–2554 m), corresponding to various tectonic blocks and separated by intrusive bodies, were recognised in the drill log.

Where core material was recovered near the contacts between quartzites and intrusions, shatter zones and evidence of dislocation metamorphism were seen in both the country rocks (2266.1–2272.8 m, 2554.7–2555.3 m) and the dolerites (2129.2–2138.4 m).

In the fault zones, the rock is very light coloured, almost white, highly brecciated and consists of sharply angular fragments of laminated quartzite, 2–3 mm to 4–5 cm in size, embedded in fine-grained, carbonate-rich material (Fig. 3.1.6 and Fig. 3.1.8). Cataclasites are common, represented by deformed and shattered quartz grains embedded in finely granular, polymineralic cement. Mylonitisation is seen at depths of 2266.1–2272.8 m and 2554.7–2555.3 m. The shattered, finely milled, compact rock (originally quartzite) displays a distinct, superimposed schistosity at an angle of 75°, which is probably parallel to the fault planes.

The quartzites show up very well on gamma-ray logs due to anomalously high NGR and ENGR values and they and their contacts with intrusive rocks can therefore be easily recognised. On neutron gamma-ray

Fig. 3.1.6 Fine-grained schistose quartzite with small boudins. Borehole depth 2145 m. Polished surface, full size.

logs, values for the quartzites are generally 2.3–2.4 arbitrary units, anomalies reaching 2.8, whereas 1.5–1.7 arbitrary units are typical of the schist sequence and intrusions. Much more significant variations are seen on epithermal neutron gamma-ray logs, where values for quartzites are several times the background values; these are shown by a sharply differentiated curve. GR values of 6–9 mR/hr are somewhat lower than those obtained for the schist sequence. Taken together, these values suggest that the rocks have a high density, low porosity and low hydrogen content, an extremely low capacity to retain moisture and an insignificant content of hydrous aluminosilicates. According to petroleum geophysics data, the fault zones are marked by a decrease in apparent resistivity down to 50 ohm/m, some decrease in NGR values, an increase in gamma-ray activity up to 10 mR/h, and a decrease in spontaneous potential (SP) values. Thus, examination of core material and comparison of this with gamma-ray logs enables fault zones to be recognised at depth intervals of 2031–2040 m, 2120–2150 m, 2247–2272 m, 2320–2326 m and 2480–2490 m.

Metamorphism

The present mineral assemblages of the metamorphic rocks making up the Nagurskaya Formation show that the sedimentary rocks have, on the whole, undergone greenschist facies metamorphism. The quartzites are characterised by two assemblages: 1) quartz + sericite + ore minerals + microcline; 2) quartz + sericite + carbonates + ore minerals ± microcline _ plagioclase. The schists have the following assemblages: 3) quartz + sericite + plagioclase + biotite + ore minerals ± microcline ± epidote, 4) quartz + sericite + ore minerals, 5) quartz + sericite + carbonates + biotite + chlorite + ore minerals ± plagioclase ± epidote. The mineral fabric indicates that not all these assemblages are stable. Thus, assemblage 5, where biotite and replacing chlorite are present, is unstable, and assemblage 2 is stable only in the absence of carbonate. The mineral assemblages suggest that the rocks of the Nagurskaya Formation belong to two subfacies of the greenschist facies. Assemblages 1, 2 and 4 are consistent with the quartz-albite-muscovite-chlorite subfacies, and assemblages 3 and 5 comply with the quartz-albite-epidote-biotite subfacies. The mineral composition and texture of the rocks suggest that the quartzites may have derived from sandy siltstone, the phyllites from semipelites, and the carbonate-mica-quartz schists from siliceous marl.

The rocks of the Nagurskaya Formation are highly cleaved throughout, with subparallel joints and small-scale shears inclined at an angle of 50–60°. Sulphide mineralisation, represented by –pyrrhotite or, less commonly, chalcopyrite and pyrite, is generally developed along the cleavage. Vertical joints, formed when the rock cooled, are also seen; they are filled with calcite, representing the final phase of hydrothermal mineralisation. The bedding dips 20–25° and the schistosity 35°, measured in unoriented drill core, although intensely deformed rocks showing disharmonically overturned folds are seen in places (Fig. 3.1.7).

At depths of 2994–3010 m and 3062–3075 m, the borehole crossed fracture zones marked by tectonic breccia composed of sharply angular quartzite fragments, 2–3 mm to 1.5–2.5 cm in size, embedded in quartz-sericite-chlorite cement (Fig. 3.1.8). The fragments display an indistinct orientation at an angle of 30° to the core axis. The schistosity is emphasised by veinlets, lenses and aggregates of pyrrhotite replacing pyrite.

Fig. 3.1.7 Cleaved and folded, fine-grained quartz-sericite schist. Fissures filled with secondary calcite. Borehole depth 3046.3 m. Polished section, full size.

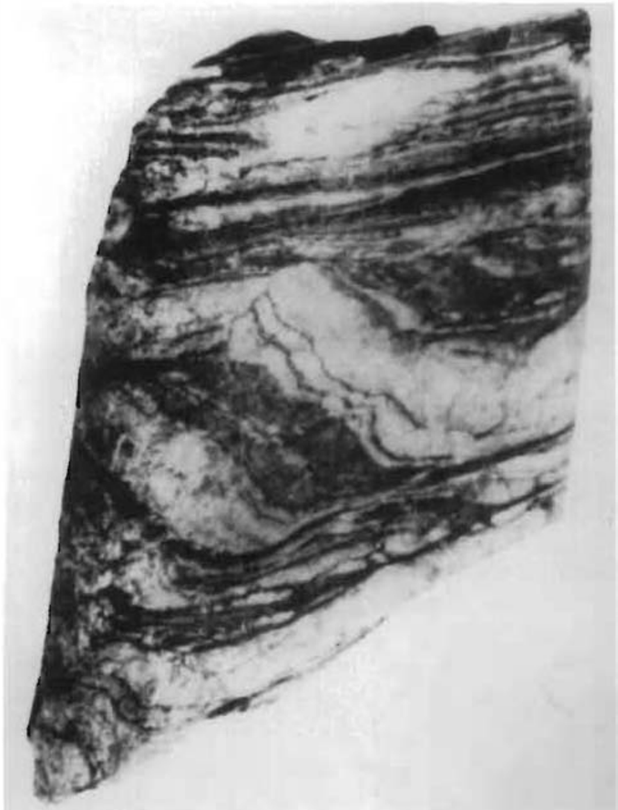


Fig. 3.1.8 Tectonic breccia composed of fragments of fine-grained quartzite in quartz-sericite schist. Borehole depth 3068.1 m. Polished section, full size.

3.2 PALAEOZOIC

Carboniferous

Despite earlier reports of Carboniferous coal deposits and Carboniferous fossils found in drift, the Nagurskaya borehole drilled on Alexandra Land in 1976–1977 provided the first proof of the presence of Lower and Upper Carboniferous strata in Franz Josef Land (Figs. 3.2.1 & 3.2.2).

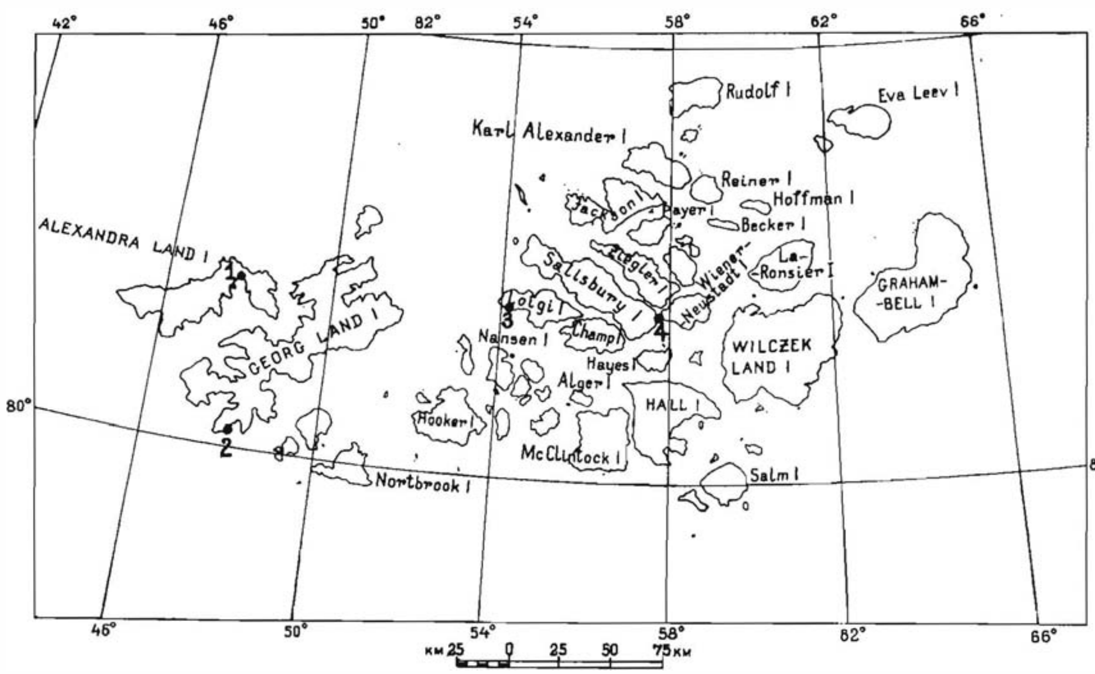


Fig. 3.2.1 Location of outcrops and other evidence for the Lower Carboniferous: 1 Nagurskaya borehole, 2 Cook Rocks, 3 Cape Richthofen, Luigi Island, 4 Cape Washington, Ziegler Island.

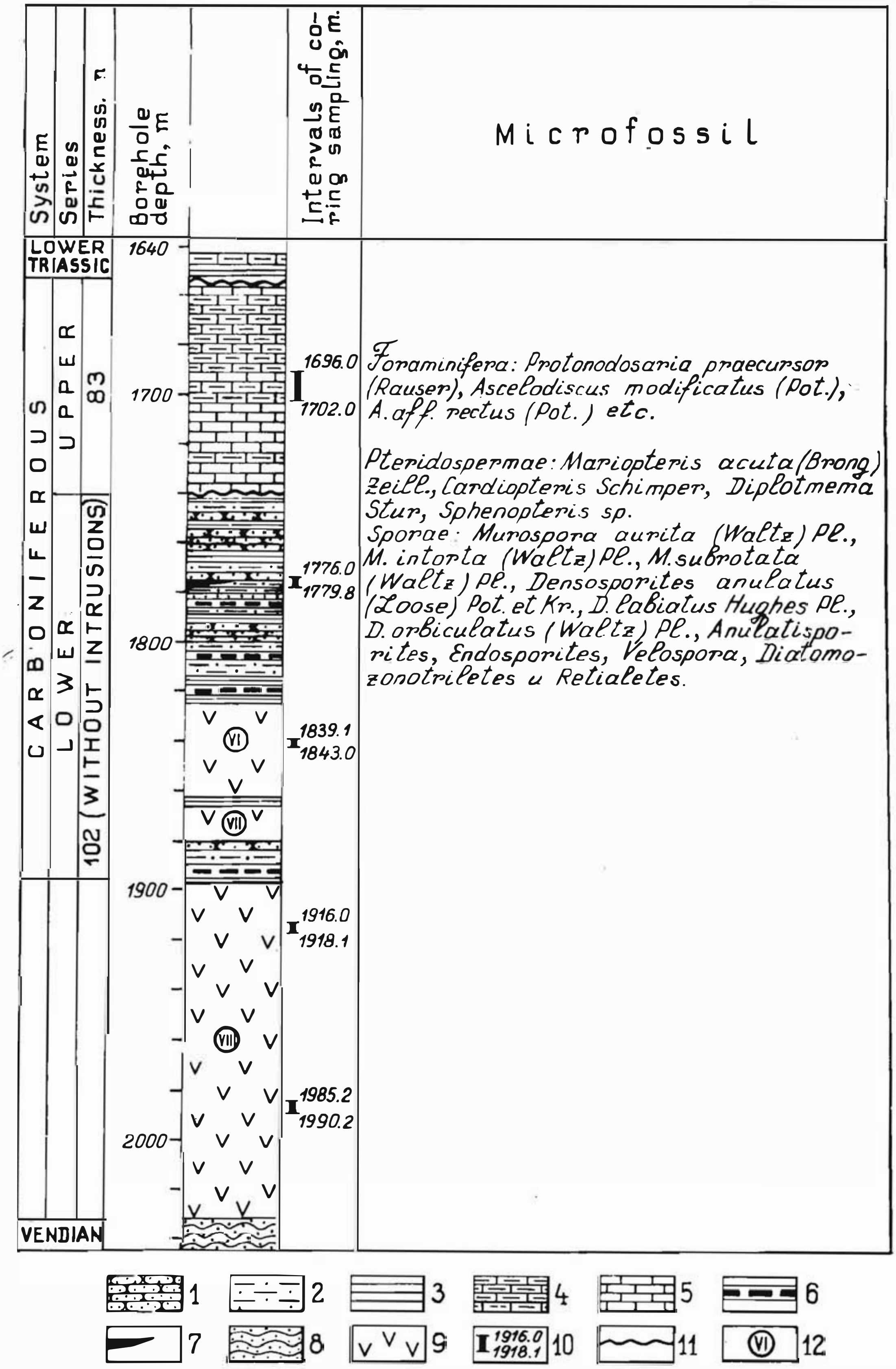


Fig. 3.2.2 Section through the Lower and Upper Carboniferous in the Nagurskaya borehole. Key: 1 sandstone, 2 siltstone, 3 mudstone, 4 marl, 5 limestone, 6 carbonaceous rocks, 7 coal, 8 quartz-sericite schist, 9 basic igneous rocks, 10 coring intervals, 11 disconformity, 12 ordinal numbers of intrusions.

3.2.1 Lower Carboniferous – E.N. Preobrazhenskaya, A.F. Dibner, V.D. Dibner & I.V. Shkola

Stratigraphy and lithology in the borehole

The Lower Carboniferous succession rests unconformably and practically horizontally on the strongly deformed Upper Proterozoic metamorphic rocks. In the Nagurskaya borehole, it occurs at a depth of 1740–1896 m and consists of a cyclic alternation of sandstone, siltstone and mudstone with coal lenses and seams interrupted by two dolerite sills (VI and VII) with an aggregate thickness of 53 m. Another dolerite sill (VIII) separates the Carboniferous strata from the underlying folded basement (Fig. 3.2.2). The thickness of the Lower Carboniferous deposits (excluding intrusions) is 102 m.

The sandstone beds vary in thickness from 0.3 to 10 m, and alternate with dark layers of clayey siltstone and mudstone. The sandstone is light grey, almost white, medium to fine grained, well sorted, and consists almost entirely of quartz. Some beds are very hard. Thinly-bedded stratification, picked out by mudstone laminae, is sometimes seen.

Clastic grains are almost exclusively quartz; shale, feldspar and acid effusives usually amount to less than 1% and only locally reach 10%. The heavy-mineral fraction (zircon, tourmaline, pyrite) is no more than 0.14%. Cement accounts for about 10%. Pores and grain boundaries are filled or coated with chlorite and kaolinite, and encrusted rims consist of chlorite. The sandstone contains recrystallised quartz and corroded calcite.

The mudstone beds have horizontal and lenticular-horizontal lamination and are dark grey or black, depending on the content of carbonaceous fossils. They mainly consist of clayey material, but silty particles occur in extremely fine laminae, lenticules and inclusions which are more light coloured and mark the bedding. Bedding planes are smooth, flat or gently undulating. An increase in the clay content marks the gradual transition to mudstone. Grazing traces and related structures left by deposit-feeding organisms are observed in places.

The mudstones contain abundant plant fossils, thin lenticules of graphitised coal, and lenses and bands of thinly-bedded anthracite. Large fragments of thin-ribbed arthrophytes and fragments of pteridosperm leaves are common on bedding planes. Large detritus fragments have a silky sheen and are graphitised, soiling the hands. The plant fossils are locally replaced by fine-grained pyrite. Small, graphitised plant impressions with a dull lustre are also seen on bedding planes. Striae-like detritus fragments (hundredths of a millimetre across), randomly oriented to bedding planes, are also observed. Aggregates of fine grains and fragments of coal redeposited during the sedimentation process are common.

The nature and distribution of the detritus, as well as the character of the rocks, suggest that the latter were deposited in a stagnant basin.

Abundant fragments of carbonaceous mudstone, 5 x 7 mm in size, containing lenticules of crumbly coal and fine pieces of dull, banded coal occur in cuttings from 1890–1895 m. Petrographic study shows that these fragments derive from older coal lenses and seams. Density logging also indicates the presence of coal seams at a depth of 1890–1895 m.

Carbonaceous material in both the core and cuttings is characterised by the high reflectance of vitrinite, varying from 3.78 to 4.99%, i.e. the material is anthracite. These deposits show a close lithostratigraphical resemblance to the Lower Carboniferous Coal Measures of Spitsbergen.

Biostratigraphy

Abundant plant fossils found at a depth of 1776.1–1779.2 m are dominated by the seed ferns, *Mariopteris acuta* (Brong) Zeill., *Cardiopteris* Schimper and *Diplotmema* Stur., which, according to Yu.G. Gor (pers. comm.), are common in the Lower Carboniferous and the Westphalian of the Middle Carboniferous in the European coal basins. A fragment of another seed fern, *Sphenopteris* sp., of Euramerican habit, similar in morphology to specimens of this genus from Visean-lower Serpukhovian deposits, was identified by G.N. Vasilieva (pers. comm. 1992) from the same depth (1176 m) in the core.

A.F. Dibner examined miospores from the core of the Nagurskaya borehole taken at depths of 1776.1 + 0.4 m, 1776.1 + 1.3 m, 1776.1 + 1.8 m, 1778.1 + 0.1 m and 1778.1 + 1.8 m. Single, moderately and poorly preserved miospores were found in the macerate of the samples, which consisted of dark grey to almost black, clayey siltstone. The taxonomic composition was relatively wide-ranging, including both Visean (*Murospora aurita* (Waltz) Pl., *M. intorta* (Waltz) Pl., *M. subrotata* (Waltz) Pl., *Densosporites anulatus* (Loose) Pot. et Kr., *D. lobiatus* (Hughes), *D. orbiculatus*

(Waltz) Pl.) and younger, Visean-Serpukhovian, elements (*Anulatisporites, Endosporites, Velospora, Diatomozonotriletes* and *Retialetes*). As stated by Playford (1962, 1963), miospores of the genus *Retialetes* are very typical of the Serpukhovian of Spitsbergen. In addition to these taxa, miospores of the genera *Leiotriletes, Trachytriletes, Punctatisporites, Lophotriletes* and some others, all of which show a wide range of vertical distribution and, hence, are of no value for dating purposes, are common.

On the basis of their miospore content, the deposits found at a depth of 1776.1 + 0.4 to 1778.1 + 1.8 m are correlated with the upper Visean-lower Serpukhovian rocks of Mount Pyramiden, Bünsow Land and other parts of Spitsbergen (Playford 1962, 1963, A.F. Dibner 1986). Similar palynological complexes are known from the Lower Carboniferous deposits of the Moscow, Donetsk and other basins in eastern Europe. Broader correlations of the Lower Carboniferous of Franz Josef Land are feasible through the palynological "*Murospora aurita*" zone and a palynological complex yielding "*Retialetes*" identified by Playford from material from Spitsbergen (Playford 1962, 1963). These suggest that, like the deposits of Spitsbergen (according to Playford), the Lower Carboniferous deposits of Franz Josef Land are correlatable with coeval strata in Poland, England (beds containing *Rotaspora knoxi*), the USA (middle and upper horizons of the Meramecian and middle parts of the Chesterian, and Canada (deposits belonging to the Melson and Golata Formations and Kanzo Group).

Thus, the palynological studies suggest not only the presence of upper Visean-lower Serpukhovian deposits in the Lower Carboniferous of Franz Josef Land, but that in the Early Carboniferous the area of the present Franz Josef Land archipelago was a province of the Euramerican palaeofloristic region.

Miscellaneous exposures and erratics

Outcrops of Lower Carboniferous coal, or indirect evidence of Lower Carboniferous strata have been reported from various parts of Franz Josef Land. Records of Palaeozoic coal outcrops can be found in accounts from the Jackson Polar Expedition (1894–1897). At Cook Rocks (also called Twin Rocks) between Cape Steven and Cape Grant on the southern end of George Land, H. Fisher found a unit consisting of variegated, semi-consolidated sandstone and shale 300 ft (about 90 m) above sea level. It had an apparent thickness of about 100 feet (30 m) and dipped very gently north-northeastwards. A bed of sub-bituminous coal, up to 2 feet (60 cm) in apparent thickness, lay

Fig. 3.2.3 Lump of thinly bedded coal found in the ruins of the Wellman Expedition base. Sample 61, full size.

at its base. The coal burnt brightly in the stove. Unlike the lignitic deposits, typical of younger strata, the coal was composed of crushed and compressed detritus. Microscopic examination showed that it contained scattered macro- and microspores (miospores), similar to those in the Coal Measures of the British Isles (Koettlitz 1898, Newton & Teall 1899). The age of the Coal Measures is now determined as Middle Carboniferous – Westphalian (Bennison & Wright 1972).

Fragments of similar coal composed of compressed detritus and characteristically banded, like coal from the Nagurskaya borehole (see above), were found by F. Jackson in the lateral moraine near Cape Richthofen on Luigi Island (Newton & Teall 1897, 1898).

In 1956, V.D. Dibner found a large lump (10 x 15 x 50 cm) of semi-lustrous, finely banded coal composed of alternations of vitrain and fusain (sample 61, Fig. 3.2.3) in the ruins of the Wellman Expedition base at Cape Tegetthoff on Hall Island. Since no cinders were discovered at the site and the building is known to have been heated by driftwood (Wellman 1899), it may be inferred that this piece of coal had been collected somewhere in the archipelago. In 1957, another lump of similar coal (sample 1055) was found by V.K. Razin in talus at Cape Washington on Ziegler Island.

Investigations by A.F. Dibner showed that the miospores in these pieces of coal (samples 61 and 1055) are similar to those in the Lower Carboniferous coals of the Russian plate and adjacent regions. These pieces of coal could therefore be assigned to the Lower Carboniferous, probably the Visean (V.D. Dibner 1970, p. 62). Subsequent detailed palynological examinations of the Culm of Spitsbergen (Playford 1962, 1963) and revision of the material from the above-mentioned samples support a more precise age range of late Visean-early Serpukhovian. Thus palynological data from both the borehole and outcrops confirm the presence of upper Visean-lower Serpukhovian deposits in Franz Josef Land.

Koettlitz (1899) had no doubt that flint pebbles which he collected from the surface of an overturned iceberg grounded near the northern end of Bell Island had derived from conglomerates occurring in Jurassic beds on the neighbouring islands. In pebbles of pale-grey chert, Hind found radiolarians (up to 0.2 mm across) of the genera *Cenosphaera, Cenellipsis* and, less commonly, *Xyphostylus*(?) and *Dorysphaera*(?), typical of the lower Culm of Devon, Cornwall and southern Scotland (Koettlitz 1899). This is in good agreement with modern biostratigraphical schemes (R. Lipman, pers. comm. 1994). Similar Palaeozoic radiolarians were also found by Hind in the Upper Triassic-Lower Jurassic sandstones at Cape Gjertrud (Newton & Teall 1897, 1898).

3.2.2 Upper Carboniferous – E.N. Preobrazhenskaya & I.V. Shkola

Stratigraphy and lithology revealed by borehole data

Upper Carboniferous deposits were found at a depth of 1657–1740 m in the Nagurskaya borehole. They are 83 m thick and rest disconformably on Lower Carboniferous coal-bearing rocks, the boundary being marked by a sudden change in lithology revealed by the drilling cuttings and by a change in the character of log curves.

The sequence consists of massive and very hard, light-grey, bioclastic detrital limestones (Fig. 3.2.4) – brachiopod-crinoid packstones and wackestones. Recrystallised fossil fragments dominated by broken crinoid stems and crushed brachiopod valves account for 60–80% of the limestones. Admixed clayey material amounts to 3–6%. Stylolitic sutures, subparallel to the overall horizontal attitude of the rocks, were observed on the outer surface of the core.

Logging suggests that the Upper Carboniferous succession can be divided into two parts. The lower unit (1692–1740 m) consists of relatively compact, fissured water-bearing rock. A bed with a relatively low carbonate content lies at the base of this unit. The upper unit (1692–1657 m) is composed of less compact argillaceous limestone.

Single brachiopods of the species *Spiriferela* ex gr. *turussica* Tscherniak, suggesting a wide age range from Lower Carboniferous to Lower Permian, were identified by V.I. Ustritsky (pers. comm. 1979) at the base of the upper unit (1696–1702 m).

M.F. Solovieva and G.P. Sosipatrova (pers. comm. 1979) gave a more precise age range. They identified a rich assemblage of foraminifers in the same part of the core, including *Fusulinella* cf. *usvae* Dutk., *Fusiella* sp., *Tuberitina maljavkini* Mikh., *Earlandia elegans* Raus., *Tolipammina communis* Lip., *Trepeilopsis* aff. *australiensis* Crespin, *Hemigordus* sp., *Eolasiodiscus* aff. *rectus* Potiev., *Protonodosaria quadrangula* Gerke, *P. parviformis* Gerke, *P. proceraformis* Gerke, *Nodosaria* cf. *braklyi* Mikh., *N.* cf. *galinae* Gerke et Karav., *N. concinna* Potiev., *Paleotextularia tenuise*

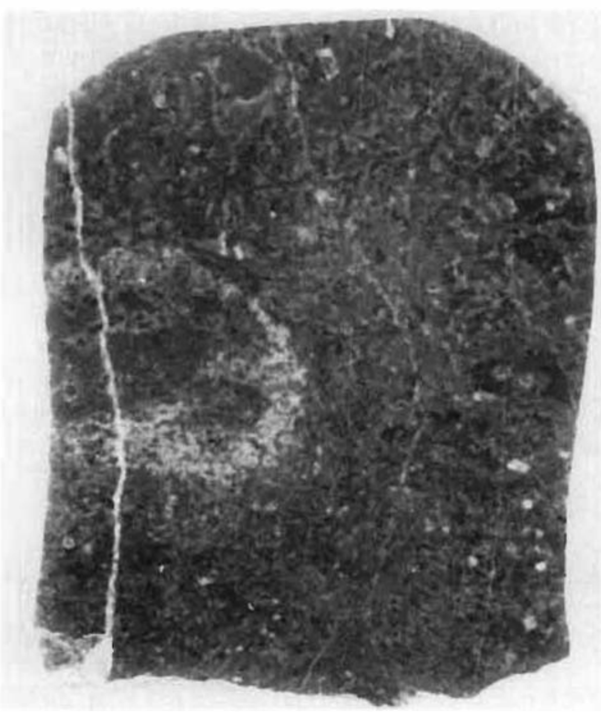


Fig. 3.2.4 Illustrations of the Upper Carboniferous bioaccumulated limestone. Belove: polished surface (x 1.5); Above: photomicrographs (x 250) showing, on the left, limestone composed of echinoderms, brachiopods and algae, and on the right, limestone composed of brachiopod spines. Nagurskaya borehole, interval 1694.3–1696.3 m.

plata Moroz., *Tetrataxis plata* Moroz., *T. postminima* Potiev., *T. minita* Moroz., *T. heminflata* Moroz., *Globivalvulita* cf. *donbassica* Potiev., *G. mosquensis* Reitl., *G. granulosa* Reitl., *Genitzina paratenius* Gerke, *Ammodiscus multivolutus* Reitl., *Endothyra* ex. gr. *bradyi* Mikh., *Orthovertella* sp. and others. This assemblage is readily correlated with those from the uppermost Carboniferous in northeast Russia and the Timan-Pechora province; the lowermost Permian cannot be ruled out. The lower part of the same interval (1696.0–1702.0 m) yielded the following foraminifers: *Protonodosaria praecursor* (Rauser), *Asselodiscus modificatus* (Pot.), *A.* aff. *rectus* (Pot.), *Reitlingerina umbovata* (Rauser) and *R. timanica* (Rauser), *Pseudofusulinella* aff. *usvae* (Dutkevich), *P. kotlovskyi* (Stewart), *P. condense* (Solovieva), *P. bella* (Grozdilova & Lebedeva), *P. delicata* Skinner & Wilde and *P.* cf. *annae* (Grozdilova).

Many of these species are widely developed throughout the Upper Carboniferous and the Asselian (Lower Permian). However, the genera *Asselodiscus* and *Protonodosaria* are known to be confined to the Gzelian and Artinskian. The assemblage is extremely similar to the Gzelian assemblage of the "*Ptotonodosaria praecursor*" zone on Kolguyev Island, which lies between the

Kasimovian and the upper Gzelian beds. Since the position of the zone in the Nagurskaya borehole is not controlled by the ages of immediately underlying and overlying deposits, its younger, Asselian, age cannot be ruled out (V.D. Davydov, pers. comm. 1992).

3.3 TRIASSIC – E.N. PREOBRAZHENSKAYA & I.V. SHKOLA

The full Lower and Middle Triassic succession was found in the Nagurskaya, Hayes and Severnaya boreholes (Figs. 3.3.1 & 3.3.2) and Upper Triassic sediments are present in the Hayes and Severnaya boreholes. The uppermost part (Norian-Rhaetian?) is widely exposed on the islands, and these sections can be correlated with each other and to a composite section based on borehole logs.

The three divisions of the Triassic have mostly been subdivided into stages and substages, the boundaries of which are determined on the basis of changes in fossil assemblages and analyses of sedimentary cycles.

As in other arctic regions, the Triassic macrocycle in Franz Josef Land consists of first-, second- and higher-order cycles, consistent with the stages and substages of the biostratigraphical framework. Within these cycles, there is a gradual upward variation in the composition of the deposits, the fossil assemblages and the facies that is consistent with regression from a sharply defined transgression at the base of each cycle. Index forms of fauna and flora are generally not present throughout a section, but in individual parts, primarily in mainly marine (lower) horizons. Stratigraphical boundaries are drawn at the tops and bases of first- and second-order cycles which are consistent with sedimentation stages and are convenient for section correlation.

Cyclic analysis, based on borehole logs has shown that the Induan(?), Olenekian, Anisian and lower Carnian sediments are represented by marine facies which are most typical for the Triassic macrocycle. Parts of Ladinian and upper Carnian sections are dominated by lagoonal-marine and lagoonal-continental sediments. The Triassic section as a whole exhibits cycles of two orders, namely, major (first-order) cycles that are up to 1000 m thick and minor (second-order) cycles that are 300–700 m thick. Six major and eight minor cycles have been recognised. In some portions of

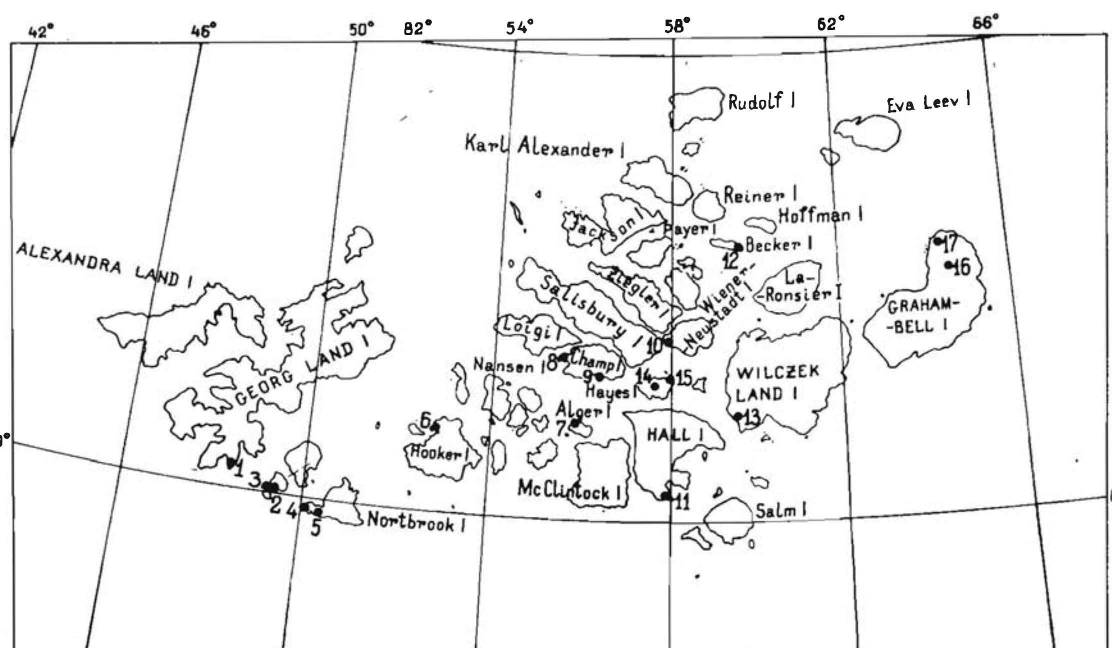


Fig. 3.3.1 Positions of boreholes and outcrops showing Upper Triassic and Lower Jurassic deposits. 1 Cape Steven, George Land, 2 Mabel Island, 3 Bell Island, 4 Cape Flora and 5 Cape Gjertrud, Northbrook Island, 6 Cape Sedov, Hooker Island, 7 Cape Dzegudze, Alger Island, 8 Cape Goristy and 9 Cape Fiume, Champ Island, 10 Cape Vasiliev, Wiener-Neustadt Island, 11 Cape Tegetthoff, Hall Island, 12 Cape Galkovsky, Becker Island, 13 Cape Hansa, Wilczek Land, 14 composite section in outcrops on Hayes Island, 15 Hayes borehole, 16 composite section on Graham Bell Island, 17 Severnaya borehole.

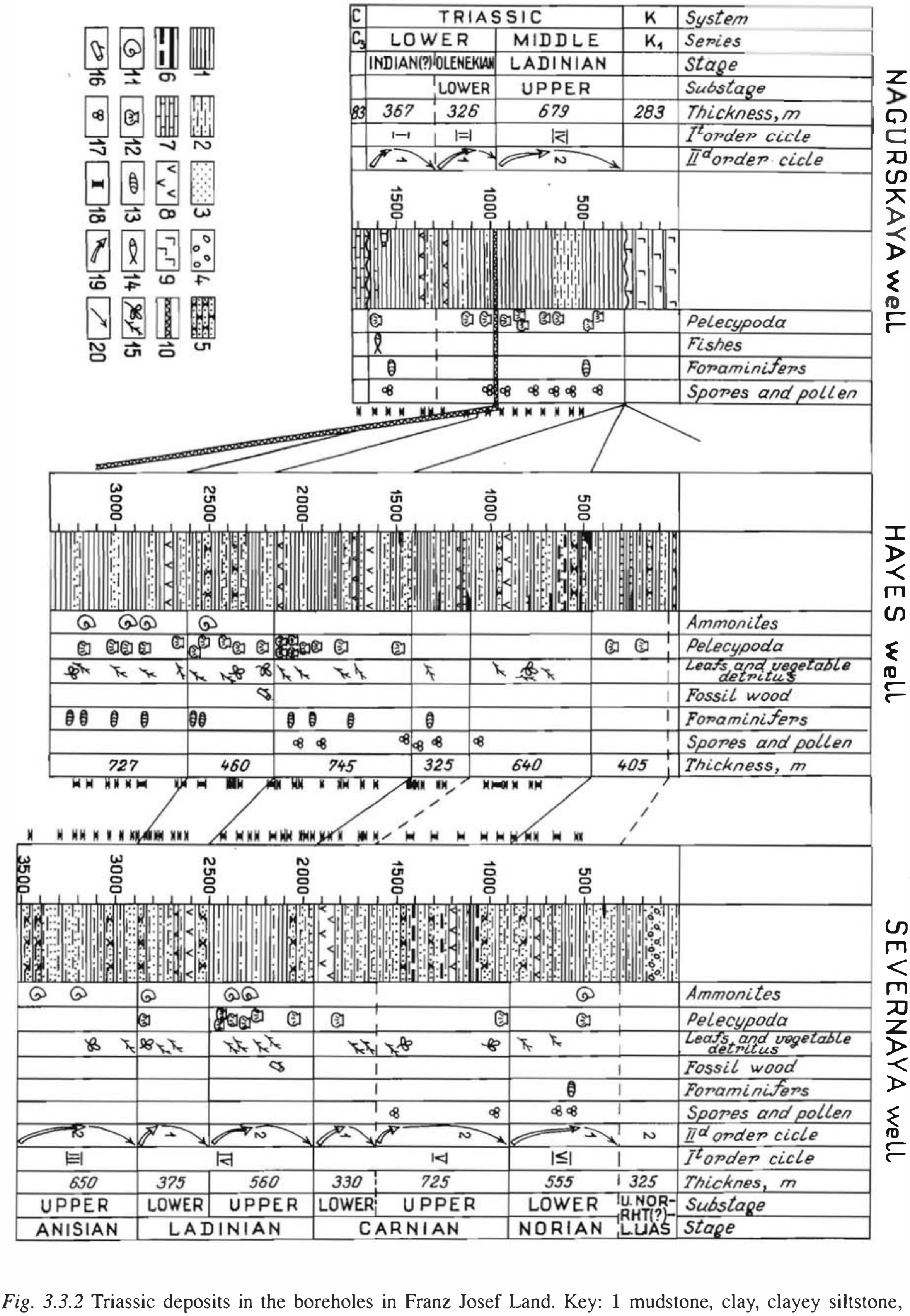


Fig. 3.3.2 Triassic deposits in the boreholes in Franz Josef Land. Key: 1 mudstone, clay, clayey siltstone, 2 siltstone, 3 sandstone, sand, 4 conglomerate, 5 carbonate siltstone and sandstone, 6 coal, carbonaceous rocks, 7 limestone, 8 dolerite (hypabyssal intrusions), 9 basaltic sheets, 10 tectonic contact, 11 ammonoids, 12 bivalves, 13 foraminifera, 14 fish, 15 leaves and vegetable debris, 16 fossilised wood, 17 miospores, 18 coring intervals, 19 transgressive part of the cycle, 20 regressive part of the cycle.

the section, cores and logs permit the recognition of cycles of even higher orders, separate cycles and rhythms being a few hundred metres, tens of metres or metres, and in places only a few centimetres, thick.

The Triassic deposits contain doleritic sills (Figs. 3.3.1 & 3.3.2).

3.3.1 Lower and Middle Triassic – E.N. Preobrazhenskaya, M.N. Korchinskaya & I.V. Shkola

3.3.1.1 Lower Triassic

Induan sediments were tentatively recognised in the Nagurskaya borehole at a depth of 1657–1290 m where it rests unconformably on Upper Carboniferous limestones. Its thickness (excluding intrusions) is 340 m.

The possible Induan sequence is a cycle of mudstone interbedded with limestone and siltstone in its lower and upper parts, respectively. The mudstones are dark grey to black and have lenticular-sinuous, locally horizontal, lamination; they contain pyrite. The limestones are up to 0.6 m thick, argillaceous, light to dark grey, massive, or, less commonly, horizontally laminated. The siltstones are light grey and horizontally laminated.

At a depth of 1610–1615 m, the mudstones yielded fish imprints with well-preserved cephalons. These represent a new genus and species, *Boreichthys shkolai* Selezneva (1982), which according to Selezneva (1982) is similar to specimens of *Parleidus*, an abundant genus in the Lower Triassic of North America and Australia. Somewhat higher up, comparable mudstone contains fragments of foraminifer tests, including *Turitella* aff. *mesotriassica* Koch-Zamnetti, *Psammosphaera* sp., *Dentalina* sp., *Rectoglandulina* sp. nov. (*R. lubrica* Gerke), *Nodosaria* sp., which, according to A.A. Gerke (pers. comm. 1977), indicate the Middle Triassic. The upper part of the cycle yielded only tiny pieces of plant detritus. The deposits were tentatively assigned to the Induan because of their stratigraphical position as the basal cycle of the Triassic.

The lower Olenekian was recognised in the Nagurskaya borehole at a depth of 964–1290 m. Its apparent thickness (excluding intrusions) is about 340 m. Its lower contact was drawn at the top of the siltstones uppermost in the possible Induan cycle. It is composed of black mudstones with rare limestone lenses and clayey siltstone partings. The mudstones contain pyrite cubes or nodules. At a depth of 1126.5 m, the upper part yielded sporadic bivalves, *Posidonia* ex gr. *mimer* Oeberg and *P.* ex gr. *popovi* Bytch., which are abundant in the lower Olenekian almost throughout the Boreal region. The lower Olenekian mudstones are overlain at a depth of 964 m by mudstones yielding upper Ladinian bivalves. This implies a considerable stratigraphical gap, but jointing, brecciation and slickensiding occur at this horizon, suggesting the presence of a tectonic boundary between the lower Olenekian and the Middle Triassic.

3.3.1.2 Middle Triassic

The upper Anisian was encountered in the lower portions of the Hayes (2620–3344 m) and Severnaya (2870–3520 m) boreholes. Its apparent thickness (excluding intrusions) was, respectively, 674 m and 650 m. The deposits represent a large, second-order cycle chiefly consisting of black to dark grey, sinuously to lenticularly laminated mudstones and clayey siltstones and sandstones in the lower part. Third-order cycles were also identified. The number and thickness of silty-sandy beds progressively increase upwards, and the upper portion is mainly composed of grey siltstones and fine-grained sandstones, which are cross bedded or, less commonly, horizontally bedded. The argillaceous beds contain disseminated pyrite and glauconite, as well as ironstone, pyrite and, less commonly, calcareous nodules. In the Hayes borehole, the mudstone yielded remains of ammonoids, bivalves, ostracods, foraminifers, echinoderms, algae and plant detritus. They include typical upper Anisian ammonoids, namely *Frechites* cf. *hevadanus* (Moisisovics) (= *Frechites* cf. *humboldtensis* in Korchinskaya 1985, Plate 2, Figs. 2, 3), *Frechitoides* cf. *migayi* (Kipar.), *Parafrechites sublaqueatum* Bytshkov, *Longobardites* sp. indet., as well as the bivalves, *Daonella dubia* Gabb. and *Mytilus eduliformis* Schloth. This molluscan assemblage characterises the uppermost zone of the Anisian, the *Frechites hevadanus* zone, in northeast Asia.

Possible lower Ladinian sediments were recognised in the Hayes (2495–2870 m) and Severnaya (2160–2620 m) boreholes where their thickness (excluding intrusions) was 460 m and 310 m, respectively. Their lower boundary was drawn at the base of a transgressive unit of mudstones containing beds and lenses of poorly sorted sandy-clayey siltstones. This unit contains a peculiar assemblage mainly consisting of Ladinian bivalves and rests on fine-grained sandstones with plant detritus uppermost in the upper Anisian cycle. The possible lower Ladinian consists of rhythmically intercalated units of various argillaceous rocks, including mudstone containing lenses of poorly sorted rock and sedimentary breccia, alternating with siltstones, sandstones and thin conglomerates. Individual units are a few tens of metres thick. This part of the Middle Triassic sequence is the richest in silty-sandy material and is throughout characterised by poor sorting and an abundance of structures formed by groundwater invasion, bioturbation structures and tracks of mud feeders. Slump structures are also common. A rich assemblage of marine fauna (unidentifiable fragments of ammonoids, bivalves and foraminifers) is present in the lower portion, but the upper part contains only small, stunted bivalves, abundant phytoplankton and remains of higher plants. The bivalves included *Dacryomia scorochodi* Kipar., *Daonella* cf. *densisulcata* Yabe et Schim, *Bakevellia* aff. *lapteviensis* Kurushin, *B.* cf. *ladinica* Kurushin, *Mytilus hayesaensis* Korchinskaya, *Parallelodon* sp. and *Pallaeopharus* sp. The presence of a large *Bakevillia*, similar to *B. ladinica* from eastern Taimyr, *Daonella* cf. *densisulcata* and *Dacryomya scorochodi* suggests a Ladinian age for the deposits. Their position in the sequence and the lack of upper Ladinian forms allow it to be tentatively attributed to the lower Ladinian. Of interest is the presence in the assemblage of specimens of *Palaeopharus*, more typical of the Upper Triassic, and *Parallelodon*, almost unknown in the Middle Triassic. Plant remains include *Schizoneura* cf. *grandifolia* Krysht. et Pryn. and *Tomiostrobus* sp.

The upper Ladinian was recognised in all three boreholes, namely, the Nagurskaya (285–964 m), the Hayes (1415–2160 m), and the Severnaya (1935–2495 m), its thickness (excluding intrusions) being 681 m (apparent), 625 m and 560 m, respectively. Its lower boundary was drawn at the base of a marker mudstone sequence yielding an upper Ladinian faunal assemblage and overlying the silty-sandy rocks which end the lower Ladinian cycle.

The lower part of the upper Ladinian consists of argillaceous rocks, chiefly mudstones, and the upper part is dominated by siltstones and sandstones with scattered lenticules of coal. The bulk of the unit is composed of mudstones that are dark grey, well sorted and lenticularly-sinuously intercalated with silty and calcareous varieties. It contains concretions of pyrite, phosphatic ironstone and carbonate, plant remains and abundant faunal remains such as foraminifers, bivalves, echinoderms and, less commonly, ammonoids and ostracods. Especially characteristic are ubiquitous small specimens of *Daonella*, accumulations of echinoid spines and tiny oolitoid blue-green algae. This argillaceous sequence maintains the same lithologies and peculiar faunal and floral character throughout the three boreholes and is the best Triassic marker horizon in Franz Josef Land. Its thickness ranges from 200 to 400 m.

The uppermost Ladinian is dominated by fine- to medium-grained, light-grey sandstones. Subordinate mudstones are rich in silty and sandy material and yielded rare bivalves, carbonate phytoplankton and plant detritus.

The rich *Daonella* assemblage, chiefly found in the lower-upper Ladinian mudstone sequence, includes typical Ladinian species, such as *Daonella subarctica* Popow, *D. prima* Kipar., *D.* aff. *prima* Kipar., *D. frami* Kittl and *D.* cf. *nitanae* McLearn. Most of them are stunted forms. In addition to these, peculiar little shells identified as a new species, *Daonella parva* Korchinskaya, are abundant in all three boreholes. Along with these *Daonella*, the Severnaya borehole yielded *Nathorstites* cf. *lenticularis* (Whiteaves), an ammonite which is characteristic of the upper Ladinian. The uppermost Ladinian in the Nagurskaya borehole also yielded the following foraminifers: *Glomospira* ex gr. *gordialis* (Park. et Jones), *Haplophragmoides* sp., *Trochaminoides* sp., *Gondryina* aff. *triassica* Trifonova, *Dentalina* aff. *vetustissima* Orb., *Ammodiscus* cf. *filliformis* (Reuss) and others (identified by A.A. Gerke, pers. comm. 1977). This part of the unit is poor in macrofossils, only a few bivalves, such as *Meleagrinella* sp., *Mytilus hauessensis* Korchinskaya and *Myophorigonia* sp., being found. In the Nagurskaya borehole, the entire mudstone unit of the upper Ladinian yielded a rich miospore flora, dominated and subdominated by *Florinites pseudostriatus, Labipollis granulatus, Minutosaccus crenulatus, Osmundacidites senectus, Piceites schatskinskaja, Podosporites amicus, Protohaploxypinus hangri, Raistricida obtusasetosa* var. *triassica, Scopulisporites* sp., *Staurosaccites* sp., *Thuringisaccus multistiatus, Verrucosisporites morulae* and *V. narmianus*. According to V.D. Korotkevich (pers. comm. 1979), this assemblage is characteristic of the Middle Triassic and, probably, the Ladinian.

3.3.2 Upper Triassic

Upper Triassic rocks were encountered in the Hayes and Severnaya boreholes and are frequently exposed throughout the archipelago. The boreholes displayed complete sections through the Carnian, but the youngest beds occur in outcrops. These two sources of stratigraphical information are dealt with separately below. Figure 3.3.3 shows a correlation between various sections and the borehole logs.

3.3.2.1 Upper Triassic in the boreholes – E.N. Preobrazhenskaya, M.N. Korchinskaya, T.M. Pchelina & I.V. Shkola

Lower Carnian

The lower Carnian was recognised in the Hayes (1095–1415 m) and Severnaya (1605–1935 m) boreholes, where its thickness (excluding intrusions) is 282 m and 240 m, respectively. Its lower boundary was drawn at the base of a clayey sequence containing lower Carnian bivalves (see below); this overlies sandstones which complete the Ladinian cycle. The unit is mostly a second-order cycle, largely consisting of silty and clayey rocks. Intercalations of siltstones and sandstones mark the completion of higher-order cycles and often occur in thin, sinuous-lenticular interlaminations with mudstones. The lower portion contains rocks of varied grain size, including sedimentary breccia; slump structures and bioturbation are also encountered. Seams and lenticules of coal appear in the upper part.

Lower Carnian bivalves (*Halobia* cf. *korkodonica* Polub.) were found at the base of the sequence in the Severnaya borehole. According to V.D. Korotkevich (pers. comm. 1979), a Late Triassic age for the deposits is suggested by an omnipresent miospore assemblage dominated by *Piceites* spp., subdominated by *Dictyophyllidites* spp. and *Neoraistricka* spp., and accompanied by *Concavisporites* spp., *Zebrasporites* spp., *Lycopodiumsporites* spp., *Cycadophites* spp., *Diskisporites microdiscus, Florinites* spp. *Podosamites* spp. and *Walchiites* spp.

Upper Carnian

The upper Carnian was tentatively recognised in the Hayes (450–1090 m) and Severnaya (880–1605 m) boreholes in a large, second-order cycle. Its thickness (excluding intrusions) was 640 m and 725 m, respectively. These beds overlie the lower Carnian cycle and contain a Carnian flora. They are transgressively overlain by sediments yielding a lower Norian fauna. The lower boundary of the upper Carnian is drawn at the base of a rhythmic alternation of clayey and silty rocks showing evidence of bioturbation. Poorly sorted material and sedimentary breccias are present. Lenticules and thin seams of carbonaceous rock and coal occur in the upper parts of the cycles. Coal increases upwards. The clayey rocks include mudstones, consolidated clay and clay that is silty and sandy to varying degrees. The rocks contain glauconite, lenses of ironstone, plant detritus and small fragments of bivalve shells. The silty and sandy rocks are poorly sorted, but are dominated by fine-grained varieties, generally calcareous and rich in carbonate phytoplankton. They contain a miospore assemblage in which *Dictyophyllidites* spp., *Nevesisporites* spp., *Striatopiceites* spp. and *Podozamites* spp. are subordinate and *Concavisporites* spp., *Auritulinasporites* spp., *Duplexisporites gyratus, Stereisporites* spp., *Acanthotriletes* spp., *Zebrasporites* spp. and *Vitreisporites* spp. are accompanying species. According to L.A. Fefilova (pers. comm. 1979), such an assemblage suggests a Late Triassic age. A floristic assemblage that included *Neocalamites* sp., *Dictyophillum*(?) sp., *Asterotheca* aff. *merianii* (Brongn.) Stur. and *Strobilites* sp. (cf. *Voltzia novomendensis* Krausel) was found at 740–780 m in the Hayes borehole and at 949–951.4 m and 1411 m in the Severnaya borehole. According to N.D. Vasilevskaya (pers. comm. 1979), the presence of *A.* aff. *meriani* and *Strobilites* sp. (cf. *Voltyzia novomendensis*) suggests the Carnian.

Lower Norian

The lower Norian was encountered in the Hayes (45–450 m) and Severnaya (325–880 m) boreholes, where its thickness was 405 m and 555 m, respectively. Its lower boundary was drawn at the base of a sequence composed of interbedded mudstone, siltstone and sandstone of lagoonal-continental origin which overlies sandstone from the coal-bearing beds in the upper part of the Carnian. A similar gradual transition to the most transgressive stage of the Norian cycle is very characteristic of the lower Norian of Svalbard (Korchinskaya 1980, Pchelina 1980). Both boreholes display a shift in the transgressive facies towards a middle section composed chiefly of very

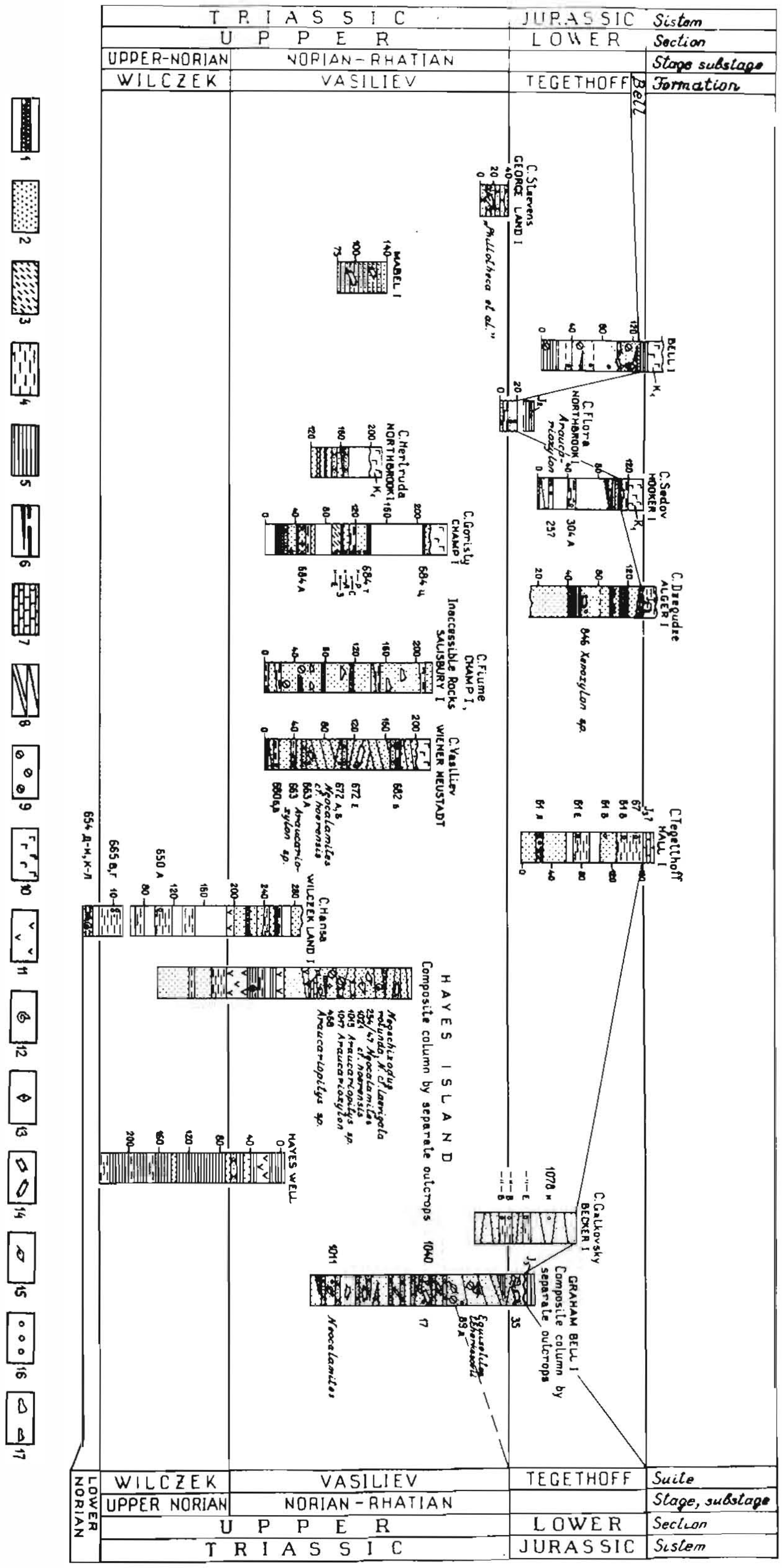


Fig. 3.3.3 Correlation between key sections of Upper Triassic and Lower Jurassic deposits. Key: 1 gravel and conglomerate, 2 siliceous sand and sandstone, 3 micaceous sand and micaceous schistose sandstone, 4 silt and siltstone, 5 clay and mudstone, 6 coal seams and lenses, 7 limestone, 8 cross bedding, 9 pyrite concretions, 10 basaltic sheets, 11 sills of dolerite and coarse-grained dolerite, 12 macrofauna, 13 foraminifera, 14 mineralised wood, 15 macroflora, 16 saurian bones, 17 location of samples yielding spores and pollen.

Fig. 3.3.4 Ice-free Cape Hansa on Wilczek Land (aerial photograph taken in winter) Key: 1 sandy, Holocene raised beaches, 2 hills of subhorizontal Upper Triassic terrigenous rocks, 3 outcrops of faulted lower Norian siltstone and limestone, which form a local dome-shaped structure, 4 doleritic dykes cut by strike-slip faults, 5 glacier, 6 sea ice with icebergs frozen into it.

compact clay containing pyrite, ironstone and calcareous concretions. Siltstone and fine- to medium-grained sandstone bands increase in number and thickness in the upper part.

Higher-order cycles can also be recognised. Their lower parts yielded bivalves, ammonoids and foraminifers, whereas plant debris and coal lenticules were present in their upper parts. Fragments of a whorl of the ammonoid *Pterosirenites* sp. indet. and the bivalve *Halobia* ex gr. *aotii* Kob. et Ichikawa, i.e. forms which are typical of the lower Norian in Arctic regions, were found in the middle of the lower Norian (536.65–546.5 m in the Severnaya borehole). These beds also yielded foraminifers (*Dentalina* sp. (ex gr. *matutina* Orb.), *Nodosaria* sp. (ex gr. *radiata* Terq.), *Marginulina* sp. and *Vaginulinopsis* sp. nov.) which, according to V.A. Basov (pers. comm.), support a Late Triassic age for the rocks.

Post-lower Norian

No core has been taken from beds younger than the lower Norian. The Hayes borehole passed through the basal part of these beds from 0–45 m. Subsequent examination of drilling sludge suggests that this part consisted of argillaceous rocks consistent with the basal part of the upper Norian-Rhaetian(?) beds (Wilczek and Vasiliev Formations – see below).

The same and younger strata were found in the Severnaya borehole, which was located on a northward-plunging monocline. The argillaceous unit was overlain by sandstones with conglomeratic beds, followed by siltstones. The uppermost 65 m of the strata belong to the lower Lias, dated by miospores taken from exposures close to the borehole. Hence, the 325 m thick sequence should be assigned to the upper Norian-Rhaetian(?) – lower Lias (see section 3.3.2.2).

3.3.2.2 Outcropping Upper Triassic

In outcrops (Figs. 3.3.1 and 3.3.3), the Upper Triassic is represented by the lower Norian marine deposits and overlying, mainly continental, deposits which, together, form a continuous Upper Triassic-Liassic sequence.

Lower Norian – V.D. Dibner & M.V. Korchinskaya

At Cape Hansa on Wilczek Land, shaly siltstone with thin interbeds of silty, pelitic and bioclastic limestones, about 20 m in apparent thickness, lies at the base of the section. These are probably exposed here as a result of diapirism (Figs. 3.3.4 & 3.3.5). A rich fauna of ammonoids and pelecypods was found in the rocks and in pyritised calcareous concretions. From samples collected

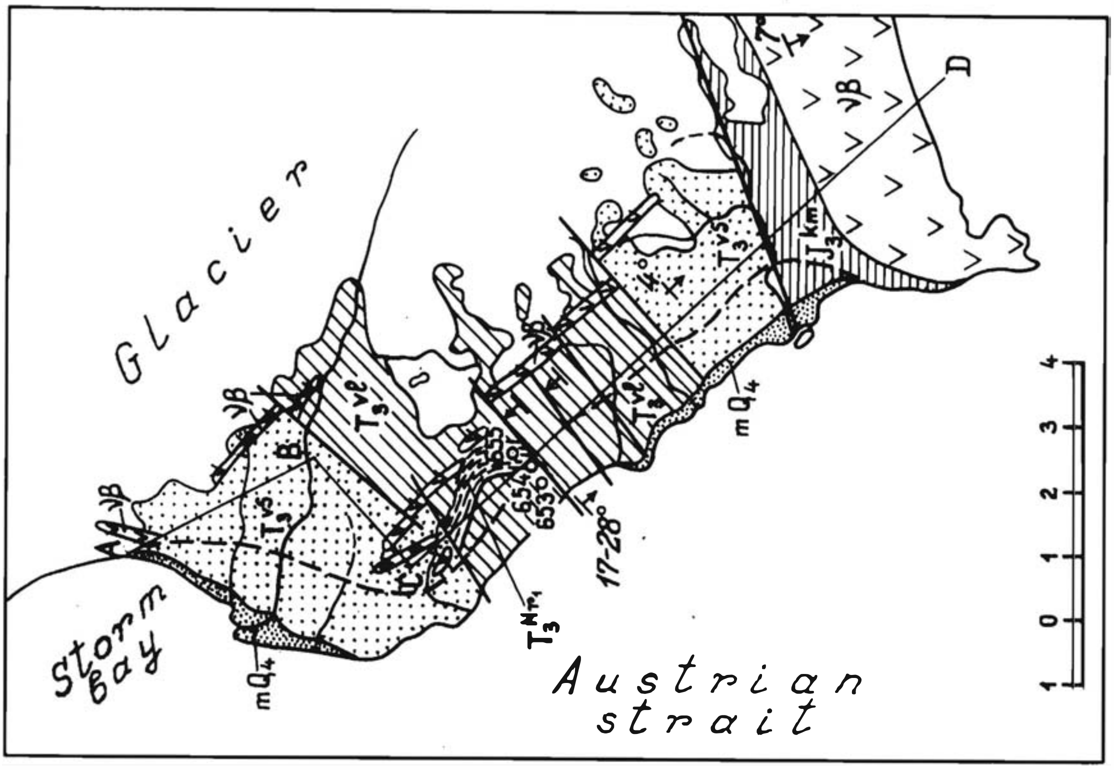


Fig. 3.3.5 Geological sketch map of Cape Hansa. Key: 1 lower Norian siltstone and limestone, 2 Norian siltstone and sandstone, Wilczek Formation, 3 upper Norian-Rhaetian(?) sand, sandstone and conglomerate, Vasiliev Formation, 4 Kimmeridgian siltstone, 5 doleritic dykes and sills, 6 sandy deposits on the present-day beach, 7 upper limit of wave-cut bench, 8 faults, 9 outcrops.

here by Pirozhnikov (1958), Popov (1958) identified the ammonite, *Cyrtopleurites* aff. *strabonis* Mojs., a typical form considered indicative of the *Trachyceras aonoides* zone of the lower Carnian of the Alps. From the same outcrop, Popov (in manus.) also described two new species of ammonites, namely, *Hauerites ganzae* Popow and *Sirenites piroshnikovi* Popow and identified the pelecypods *Palaeonello* cf. *tobieseni* Bohm., *Nucula* cf. *strigillata* Goldf., *Halobia* cf. *zitteli* Lindstr. and *Cardinia* cf. *ovula* Kittl., all of which are Boreal forms found in the Ladinian and Carnian of Ellesmere Land and Bear Island. On the basis of all the evidence, Popov assigned these deposits to the lower Carnian. From the same beds, V.A. Basov (pers. comm.) identified a number of foraminifers, including *Dentalina gladioides* ver. *gladioides* Gerke, *D.* ex gr. *tenuistrata* Terq., *Nodosaria* aff. *mitis* (Terq. et Berth.) and *Neogeinitzina* ex gr. *alaskensis* (Tappan) that are typical for the marine Carnian and Liassic deposits in the Khatanga Bay area of northern Siberia and in Alaska, and O.M. Lev (pers. comm.) identified the ostracod, *Ogmoconcha acuta*(?) Gerke et Lev, also known from the Carnian and Liassic of the Khatanga Bay area. However, more recent data from northeast Asia (Bychkov et al. 1976) and Spitsbergen (Korchinskaya 1980) show that the ammonoids identified as belonging to the genera *Cyrtopleurites, Hauerites* and *Anasirenites*, introduced by Popov, really belong to the genus *Pterosirenites* that is characteristic of the lower Norian in these regions. As mentioned above, a fragment of the ventral side of *Pterosirenites* sp., the lower Norian *Halobia* ex gr. *aotii* and foraminifers reliably dated to the Norian occur at the same level in the Severnaya borehole, at a depth of 536–537 m. Similar foraminifers were also found by Sokolov (pers. comm.) in the "Carnian" (in the sense of Popov) beds at Cape Hansa.

In the bioclastic limestones at the base of the Cape Hansa section, Sedova (Dibner & Sedova 1959) distinguished a spore assemblage dominated by pteridospermaphytes (75%). The dominant morphological groups, *Leiotriletes* (*L. gleichenites* Sed. and others) and *Phylothecites* (*Euryzonotriletes microdiscus* K.-M., *Stenozonotriletes microdiscus* K.-M. and others), are accompanied by rare *Hymenozonotriletes politus* K.-M. and *Azonotriletes itertextus* Naum. var. *triassica* K.-M., as well as *Gibotium, Matonia triassica* K.-M., *Mariattiaceae, Osmundaceae* and *Selaginella*. The pollen spectrum (25%) is represented by *Ginkgoales* and *Bennettitales*, as well as a few *Coniferae, Araucariaceae, Podozamites* and primitive *Pinaceae*.

A similar miospore assemblage was extracted by N.A. Pervuninskaya (pers. comm. 1954) from a diapiric dyke forming a ridge-like outlier of muddy limestone cutting the younger sandstones of the Vasiliev Formation on the northern part of Graham Bell Island. This assemblage is dominated by *Matoniaceae* (52%) which, in substantially lower amounts (14%), is known in the lower part of the Norian-Rhaetian(?) of Cape Hansa and in a few forms (1–3%) in even younger deposits.

Norian and Rhaetian(?): the Wilczek and Vasiliev Formations – V.D. Dibner, A.V. Ditmar† & A.N. Tarakhovsky†

Outcrops of terrigenous deposits, now assigned to the Upper Triassic, were first found by the Jackson Expedition on Cape Steven, at the southern end of George Land. Here, approximately at sea level, Koettlitz found pieces of papery bituminous shale which burnt brightly and were reduced to white ash (Koettlitz 1898, Newton & Teall 1899). The shale contains abundant imprints of leaves among which Nathorst identified *Phyllotheca* cf. *columnaris* Phil. and other cycadophytes of *Pterophyllum* type (Newton & Teall 1897, 1899). Their presence allowed Nathorst (1900) to conclude that these beds are equivalent to the Rhaetian strata in Van Keulenfjorden and the Bellsund area on Spitsbergen. This correlation was confirmed by Vasilevskaya (1985) who studied the Late Triassic flora of Spitsbergen, but she considered it older, determining the age of the flora in both areas as Middle Keuper, i.e. Carnian-Norian.

An extensive development of terrigenous deposits, analogous to those exposed on Cape Steven, was found by Spizharsky (1937a, 1947) on Hooker Island, Nansen Island and many other islands. However, he and Lupanova (1953) correlated the beds, without sufficient reason, with the marine Middle-Upper Jurassic. In his treatise on the geology of the Barents Shelf, Frebold (1950) correctly suggested the presence of continental deposits, older than the marine Aalenian, in Franz Josef Land. New data supporting this were obtained by mapping and stratigraphical investigations carried out in 1953 and 1956–1957. Based on collections examined by N.D. Vasilevskaya (leaf imprints) and I.N. Shilkina (wood), and especially through detailed palynological studies performed by M.A. Sedova, the terrigenous sequence was divided into separate formations (Dibner & Sedova 1959, Dibner 1970). Additional data, particularly on the upper age limit of the sequence, were obtained by Sveshnikova & Budantsev (1969), Yu.Ya. Livshits, A.N. Tarakhovsky (, A.V. Ditmar (pers. comms. 1970's), Dibner (1978) and Mikhailov (1979).

Based on an assessment of all the evidence available, the lower Norian marine beds in Franz Josef Land are thought to be overlain by a terrigenous sequence that has an apparent thickness of about 750 m. It is mainly composed of medium-grained quartzose sandstone and sandstone containing mica and carbonaceous detritus. In the lower part, the arenaceous deposits alternate with silty pelitic sediments containing scattered interbeds of grit and conglomerate, and coal seams. This sequence is widely developed, particularly in the eastern part of the archipelago, and is primarily continental in origin. Based on its content of spores and pollen (290 preparations were examined and 3300 miospores were diagnosed), leaf imprints and lithology, the sequence is differentiated into the Wilczek and Vasiliev Formations, which are Norian-Rhaetian(?) in age, and the lower Liassic Tegetthoff Formation.

Wilczek Formation

The Wilczek Formation was named after Wilczek Land where, together with Hayes Island, the best sections are known. Its total thickness is about 200 m. Lithologically, the formation is characterised by a predominance of well-cemented, fine-grained and silty, cross-bedded sandstone and, especially, siltstone fragments. Overall, the sequence becomes coarser upwards. Clastic grains are almost entirely siliceous (80% quartz and 15% quartz-chalcedony cherts). Instead of consisting only of sandstone with carbonate cement showing Fontainebleau texture, which is typical for the entire terrigenous sequence, the Wilczek Formation also has sandstones with a siliceous cement and these are transitional to quartzitic sandstone. The upper beds of the formation contain thin lenticules of grit composed of small, well-rounded pebbles of quartz, flint and quartzite cemented with fine-grained quartzose sandstone.

According to M.A. Sedova (Dibner & Sedova 1959), the Wilczek Formation differs from the marine deposits, here regarded as lower Norian, by having more pollen and spores. Spores of *Hymnorphyllaceae, Cyatheaceae, Dicksonia, Hausmannia, Onychium, Cheiropleuria, Gleichenia, Todea* and occasional *Calamites* are found. Relatively large numbers of *Matonia triassica* K.-M. (6–17%) and other typical Triassic forms, including *Flebopteris* and *Leiotriletes microdiscus* var.

Fig. 3.3.6 Dissected plateau composed of sand and sandstone of the Vasiliev Formation, Kholmisty Peninsula, Graham Bell Island.

limbata K.-M., characteristic for an assemblage from the Nemtsov Formation of eastern Taimyr (Kara-Murza 1958), has been preserved in places. The amount of conifer pollen, including archaic forms such as *Lebachia, Striatopodocarpites* and *Vittatina*, increases significantly in the Wilczek Formation. The content of pollen from primitive pines and, locally, from *Bennettitales* and *Ginkgoales* also increases. *Caytoniales, Cycadales* and *Podocarpaceae* pollen appears. The overall composition of the miospore assemblage in the Wilczek Formation indicates an Upper Triassic age. Some differences from the assemblage in the lower Norian beds suggests a relatively late Norian age. The Wilczek Formation generally contains no microfauna, macrofossils or coal. This also makes it similar to the lower "barren" beds of the Nemtsov Formation of eastern Taimyr, tentatively assigned to the Norian by Shvedov (1957) and to the Carnian-early Norian by Mogucheva (1982).

Vasiliev Formation

The Vasiliev Formation (Fig. 3.3.6) was named after Cape Vasiliev on Wiener-Neustadt Island, the location of one of its most complete and, palynologically and floristically, well-documented sections. The formation has a total apparent thickness of 550 m and is characterised by its diversity of lithologies, which is especially evident in the middle portion. This includes a 50–60 m thick unit of variegated sand and sandstone with abundant mica, varying in grain size, and locally containing beds composed entirely of mineralised wood remains, leaves of equiseta and araucarians, abundant carbonaceous detritus and pyrite concretions. A particularly interesting lithology on Cape Goristy (Champ Island) is a poorly consolidated sandstone with flakes of bleached biotite accounting for more than 50% of the rock, the remainder being composed of grains of quartz, flint, feldspars and a small amount of very loose, argillaceous(?) cement. Macroscopically, the rock is hardly discernible from mica schist.

The formation as a whole is dominated by fine- to medium-grained sand and, to a lesser degree, sandstone, the light fraction of which is notable for a largely polymictic composition. Along with quartz and flint (together only 58%), it contains fragments of acid plagioclase, potash feldspars, acid effusives, chloritic rocks, graphitic mica schist, coal, etc.

Fig. 3.3.8 Fauna from core material in the Hayes borehole. 1) *Gymnotoceras* sp., spec. I/12354, depth 3132 m, upper Anisian. 2–3) *Frechites* cf. *nevadanus* (Moisisovics & Smith); 2) spec. 3/12354, 3) spec. 5/12354, depths 2853.9 m and 2878.6 m, upper Anisian. 4–5) *Frechitoides* cf. *migayi* (Kiparisova), depths 2847.85 m and 2851.45 m, upper Anisian. 6) *Longobardites* sp., spec. 7/12354, depth 2848.3 m, upper Anisian. 7–8) *Mytilus (Mytilus) eduliformis* Schlotheim; 7) spec. 16/12354, 8) spec. 15/12354, right valves, depth 2851.6 m, upper Anisian. 9–10) *Mytilus (Mytilus) hayesaensis* Korchinskaya; 9) spec. 25/12354, 10) spec. 26/12354, left valves, depths 2045.8 m and 2380.0 m, Middle Triassic. 11) *Daonella dubia* Gabb., spec. 12354, right valve, x 3, depth 3203 m, upper Anisian. 12–13) *Daonella* sp.; 12) spec. 14/12343, depths 3132.4 m and 2940 m, upper Anisian, left valve, x 3, 13) *Daonella* cf. *dubia* Gabb., spec. 13/12354, left valve, x 3, depth 2836.3 m, upper Anisian. 14) *Bakevellia (Maizuria)* aff. *ladinica* Kurushin, spec. 18/12354, left valve, depth 2563.7 m, Middle Triassic. 15–16) *Bakevellia (Maizuria)* aff. *lapteviensis* Kurushin; 15) spec. 19/12354, 16) spec. 20/12354, left valves, depths 2531.8 m and 2778.8 m, Middle Triassic. 17) *Palaeopharus* ? sp., left valve, depth 2557.6 m).

The formation also includes scattered bands and lenses of silt, siltstone, mudstone and muddy limestone, as well as gravel and conglomerate. The last two form beds and lenses up to a few metres thick, primarily within the variegated unit on the islands of Northbrook, Hayes, Wilczek Land and Graham Bell. The psephites are composed of relatively well-rounded pebbles, up to 10 cm in diameter on the eastern islands. Quartz, chalcedony and quartzite account for 90% of the pebbles, the remainder being jasper, radiolarite and chert (with Lower Carboniferous radiolarians in the George Land area), quartzitic sandstone, acid effusives (amygdaloidal porphyry and granite); on the islands of Wilczek Land and Graham Bell they include fine-grained, muddy limestone with Middle Carboniferous foraminifers and leptobiolithic coal of Middle Devonian affinity (Korzhenevskaya 1957).

Beds and lenses of brown coal, 0.3–2.0 m thick, have been found in the upper part of the formation on the islands of Champ, Wiener-Neustadt, Bolshoi Komsomolsky, Wilczek Land and Graham Bell. They consist of thin intercalations of durain, duroclarain and fusain (Dibner & Krylova 1963).

Work undertaken by V.D. Dibner in the 1950's was continued in the 1970's by Yu. Livshits, A.N. Tarakhovsky and A.V. Ditmar. As a result, the Vasiliev Formation has been best studied on the islands of Hayes and Graham Bell (Fig. 3.3.6).

On Hayes Island, A.V. Ditmar (pers. comm. 1979–80) differentiated the following five units, in ascending order: argillaceous, dark-coloured, variegated, siltstone-sandstone and sandstone. The argillaceous unit (50 m thick) is dominated by mudstone. The dark-coloured unit (35 m thick) is composed of beds of clay and sand with large loaves of sandstone and mudstone and pyrite concretions. The variegated unit (40 m thick) had previously been recognised by Dibner (see above). The siltstone-sandstone unit (50 m thick) is characterised by the presence of large pyrite concretions (up to 30 cm) and large trunks of carbonised wood (up to 5 m in length). The sandstone unit (45 m thick) contains thin interbeds and lenses of coal and carbonised wood debris, as well as large ironstone concretions ranging from 0.3 to 1.5 m in size. The variegated unit is a marker horizon. In particular, its equivalent at Inaccessible Rocks on Salisbury Island is the upper part of a 220 m thick terrigenous sequence, and the upper part (Bed 3) of the Eira sequence on Bell Island is a similar lithology (Mikhailov 1979).

On Graham Bell Island, the Vasiliev Formation was divided by Yu. Ya. Livshits (pers. comm. 1973) into two members and by A.N. Tarakhovsky (pers. comm. 1975) into three members. The Lower Vasiliev Member consists of unconsolidated sand and arenaceous silt with pyrite concretions. In the Middle Vasiliev Member, psammites, accounting for 25–40% of the unit, are represented by sandstone which is cross bedded in places and contains pyrite and ironstone concretions, carbonised and silicified wood, and lenses made up of small pieces of coal. The Upper Vasiliev Member is composed of sand with similar concretions, wood and coal.

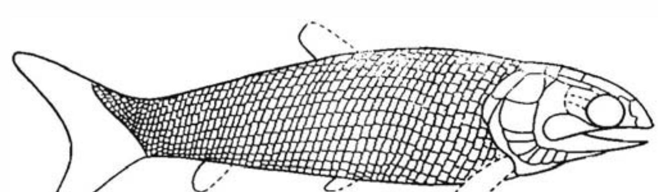


Fig. 3.3.7 *Boreichtys shkolai* sp. nov.: external view, reconstruction, x 2; Lower Triassic, Nagurskaya borehole, Alexandra Land (Selezneva 1982).

Fig. 3.3.8

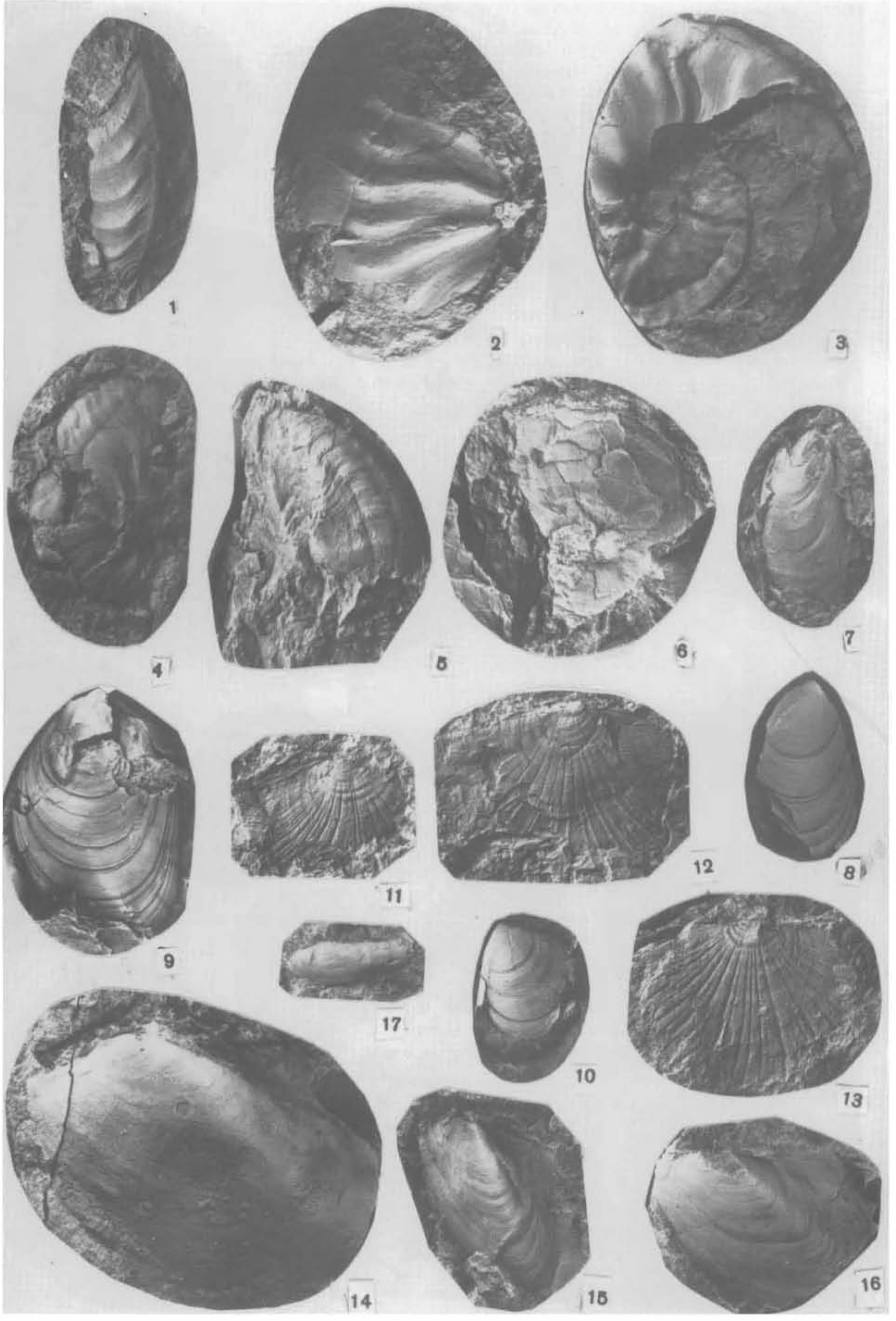


Fig. 3.3.9

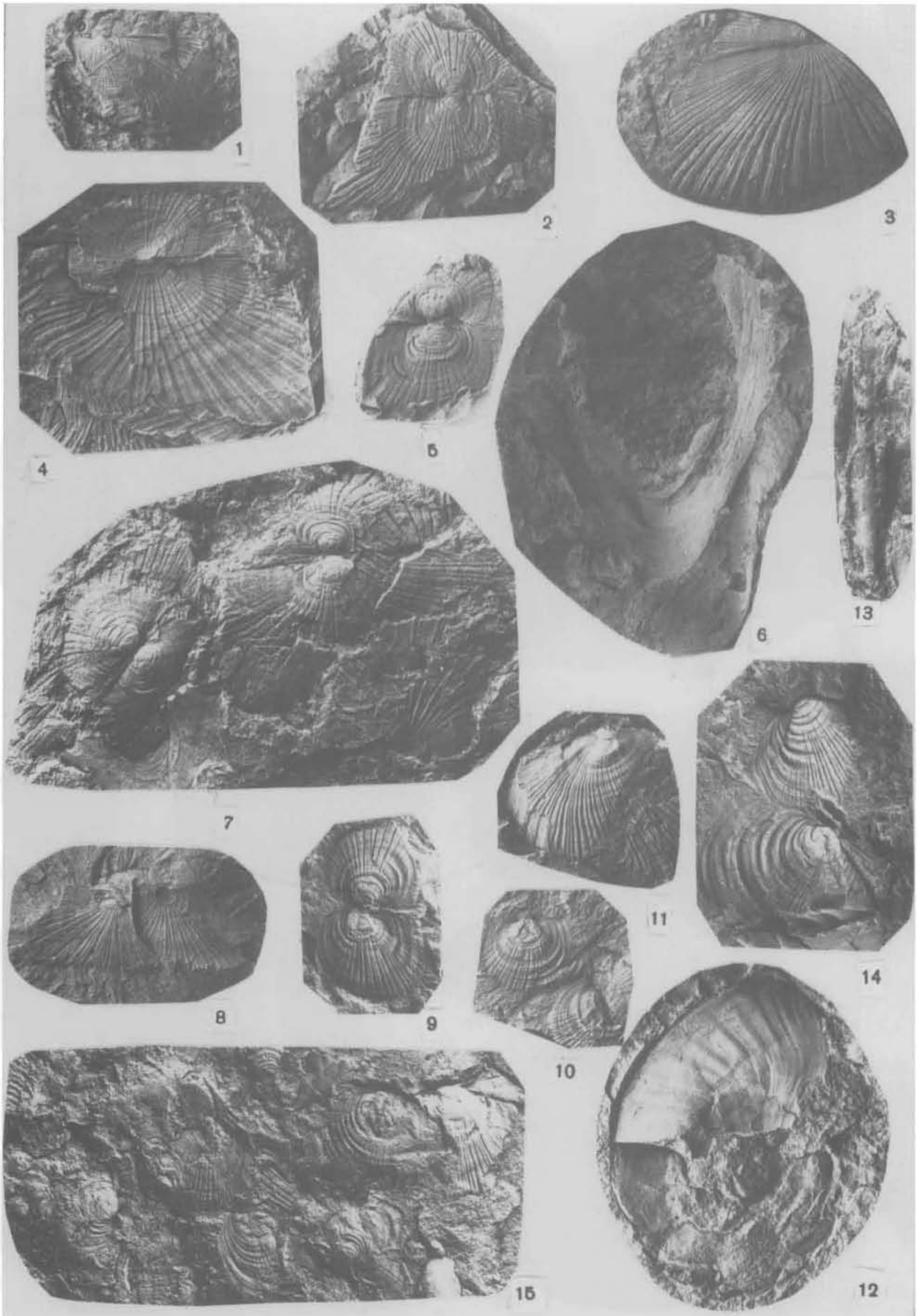


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Fig. 3.3.9 Fauna from core material in the Nagurskaya, Hayes and Severnaya boreholes and from Cape Hansa (outcrops). 1) *Daonella subarctica* Popov, left valve, Severnaya borehole, Graham Bell Island, depth 2275.25 m, Ladinian. 2) *Daonella frami* Kittl., spec. 31/12354, depth 2275.7 m, Ladinian. 3) *Daonella prima* Kiparisova, spec. 33/12354, right valve, Hayes borehole, depth 2043.3 m, Ladinian. 4) *Daonella* aff. *prima* Kiparisova, x 3, spec. 32/12354, Severnaya borehole, depth 2331.3 m, x 3, Ladinian. 5, 9 and 10) *Daonella parva* Korchinskaya; 5) spec. 39/12354, Nagurskaya borehole, Alexandra Land, depth 516.0 m; 9) spec. 44/12354, Severnaya borehole, Graham Bell Island, depth 2276.9 m; 10) spec. 45/12354, left valve, Hayes borehole, depth 1900 m, x 3, Ladinian. 6) *Bakevellia* ex. gr. *ladinica* Kurushin, lower part of the right valve, Hayes borehole, depth 2562.8 m, Middle Triassic. 7) *Daonella dubia* Gabb., x 3, spec. 9/12354, Hayes borehole, depth 2853.8 m, upper Anisian. 8) *Daonella* cf. *nitanae* McLearn., spec. 52/12354, right valve, Hayes borehole, depth 2033.5 m, Ladinian. 11) *Halobia* cf. *korkodonica* (Polubotko), spec. 48/12354, Severnaya borehole, depth 1950 m, Graham Bell Island, lower Carnian. 12) *Nathorstites* cf. *lenticularis* (Whiteaves), spec. 46/12354, Severnaya borehole, Graham Bell Island, depth 2275.7 m, x 3, Ladinian. 13) *Pterosirenites* sp. indet., spec. 51/12354, part of ventral surface, Severnaya borehole, Graham Bell Island, depth 537.2 m, x 3, Norian. 14–15) *Halobia* ex. gr. *aotii* Kobayashi et Islandchikawa; 14 spec. 49/12354; 15) spec. 50/12354, right valves, x 3, Severnaya borehole, depths 537.2 m and 536.7 m, lower Norian. 16) *Pterosirenites* sp. (full size), Cape Hansa, Wilczek Land, lower Norian; collection of L.P. Pirozhnikov, spec. 11056 in the Chernyshev Central Museum of Geology and Exploration, St. Petersburg.

On the islands of Graham Bell, Hayes and Wiener-Neustadt, the Vasiliev Formation has yielded fragments of araucarian wood, including a new species, *Protocedroxylon dibneri* (Shilk.) Shilk. et Chudaib., described by Shilkina (1960, 1967). She also described *P. gregussii* (Shilk.) Shilk. et Chudaib. and *Xenoxylon latiporosum* (Gramer) Gothan from the same deposits; these species were also found in much younger, Lower Cretaceous strata (Shilkina & Chudaiberdiev 1971).

For biostratigraphical purposes, the stems of *Neocalamites* cf. *hoerensis* (Shimp.) Halle, found on the islands of Hayes and Wiener-Neustadt, and the stems of *Equisetites* sp. and fragments of *Dipteridaceae* fronds and of the conifer *Podozamites* sp. collected on Bolshoi Komsomolsky Island (Dibner 1970), are of much greater interest. In 1973, on Graham Bell Island, in the Matusevich Bay area and the northern part of the Kholmisty Peninsula, Livshits collected numerous imprints of arthrophytes of the same type, including *Neocalamites* sp., *Equisetites tcherkesovi* sp. nov. and *Arthropsida* gen, et sp. indet., as well as tiny frond fragments of *Dipteridaceae*. According to N.D. Vasilevskaya, these finds indicate the Late Triassic, *N. hoerensis* being, in particular, typical of the Rhaetian of eastern Greenland (Birkelund & Perch-Nielsen 1976, Vasilevskaya 1985).

Unlike the pollen assemblages of the Wilczek Formation, those of the Vasiliev Formation examined by M.A. Sedova (Dibner & Sedova 1959) (based on 1250 miospores identified in 110 preparations from specimens collected in 1953–1957) are characterised by substantially fewer spores of such typical Triassic ferns as *Leiotriletes gleichenites* Sed., *Clathropteris, Cheiropleuria* and *Osmundaceae*, and a larger percentage of pollen of *Bennettitales, Ginkgoales* and especially conifers, typical Triassic forms of which still survive, although younger (Jurassic) forms dominate.

Pollen assemblages showing identical suites of miospores, such as *Coniopteris, Matoniaspori-*

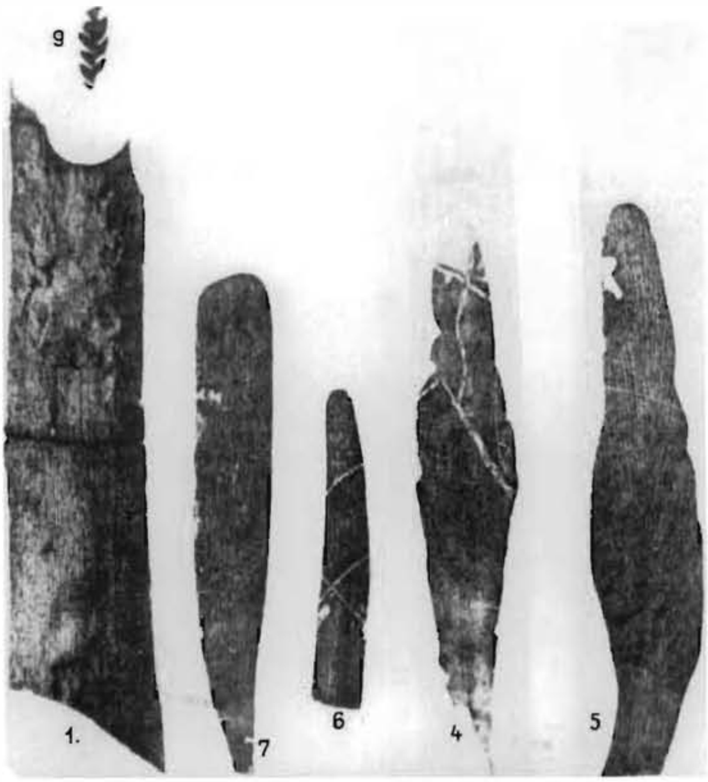


Fig. 3.3.10 Flora collected from Mesozoic beds *in situ* near sea level at Cook Rocks, George Land. 1) *Phyllotheca* cf. *columnaris* Phill.; 4–5) *Zamiopteris* cf. *glossepteroides* Schmalh.; 6–7) *Rhiptozamites* aff. *goepperti*; 9) *Asplenium* cf. *whitbiense* Brongn. (Newton & Teall 1897, Plate XI).

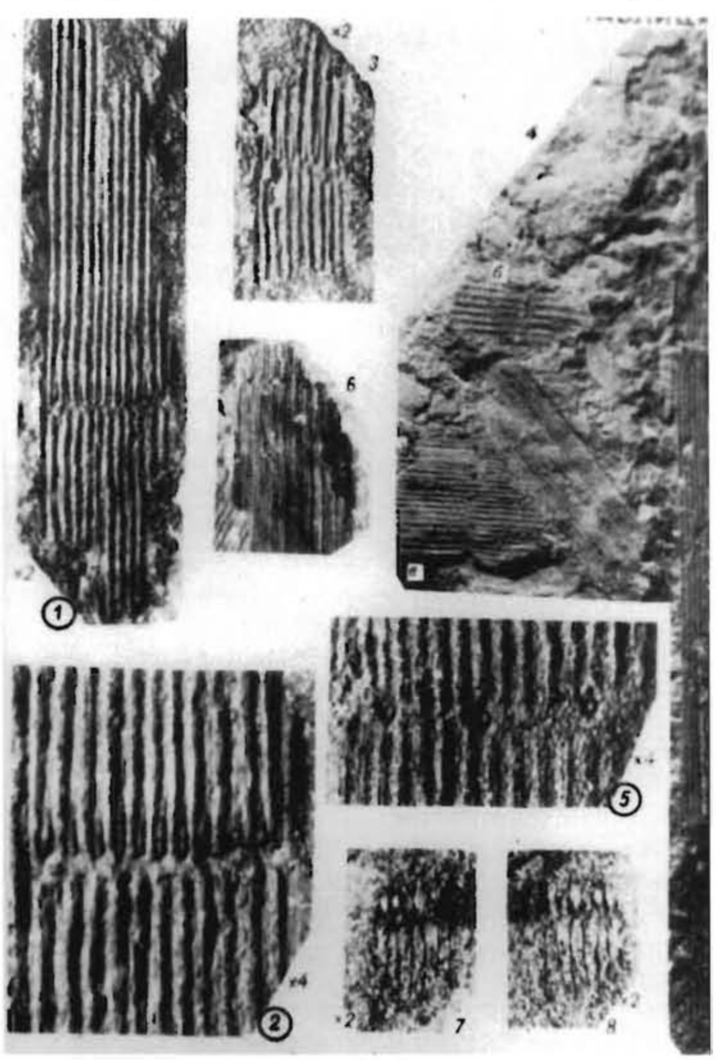


Fig. 3.3.11 Vasiliev Formation (Upper Triassic), Kholmisty Peninsula, Graham Bell Island. Samples 1–3, 4a, *Equisetites tcherkesovii* Vasilevsk., sp. nov., 1–2) holotype, spec. 42/12127; 3–4a) specs. 43, 45/12127, 4b, 5–6) *Neocalamites* sp., specs. 46/12127, 47/12127. 7–8) *Equisetites* sp., specs. 48/12127, 49/12127. The specimens are housed in the Chernyshev Central Museum of Geology and Exploration, St. Petersburg (Vasilevskaya 1985, Plate I).

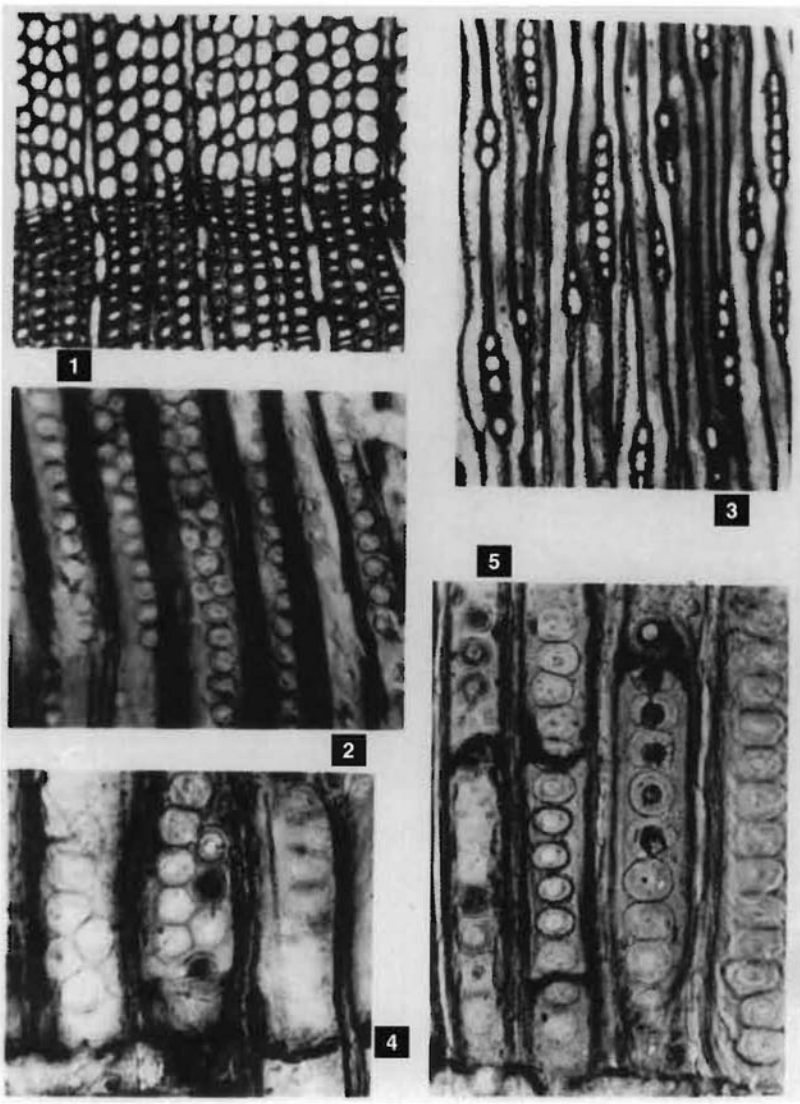


Fig. 3.3.12 Sections of Upper Triassic wood. 1–3) *Protocedroxylon dibneri* (Shilk.) Shilk. et Chudaib. Coll. 570, spec. 60; 1) lateral section, x 110, 2) radial section, x 300, 3) tangential section, x 110. 4–5) *Protocedroxylon gregussi* (Shilk.) Shilk. et Chudajb. Coll. 570, spec. 49, radial section showing pore type in tracheids and different stages of pore degradation, x 450 (Shilkina 1967, Plate I).

tes, Phlebopteris, Calamitaceae, Marattiaceae, Cyatheaceae and *Podocarpaceae*, primitive conifers (*Piceites, Pinites* and *Striatopinites*), *Vittatina, Caytonipollenites, Bennettitales* and *Ginkgoaceae*, were distinguished from additional collections made by Yu.Ya. Livshitz (pers. comm. 1974), A.N. Tarakhovsky (pers. comm. 1975), V.D. Dibner (V.D. Korotkevich, pers. comm. 1977), A.V. Ditmar (pers. comm. 1980) and Mikhailov (1979) on the islands of Graham Bell, Hayes, Bell and Wilczek Land (Cape Hofer). According to V.A. Korotkevich, these indicate an Upper Triassic-Lower Jurassic age for the strata on Graham Bell Island and an Upper Triassic (Norian-Rhaetian) age for those on the islands of Hayes and Bell and at Cape Hofer on Wilczek Land.

On Hayes Island, the siltstone at the base of the Vasiliev Formation (specimens 1009/1957) yielded the foraminifer *Frondicularia brisaeformis* Born. (a single test) and abundant *Ammodiscus* sp. (ex gr. *asper* Tarq.) which, according to V.A. Basov (Dibner 1970, p. 70), have no value for dating purposes, but indicate locally alternating deposits of a predominantly continental, and otherwise coastal, nature. This is also shown by an ichthyosaurus vertebra found in the middle of the formation, which cannot be more precisely identified (A.K. Rozhdestvensky, pers. comm. 1958).

In the central part of Hayes Island, near locality 285 (psammites of the Vasiliev Formation), E.G. Bro and A.V. Ditmar (pers. comm. 1980) collected numerous ironstone concretions that were scattered on the surface. These yielded bivalves (*Neoschizodus rotunda* (Alb.) and sparse *N.* cf. *laevigata* (Ziet.) and *Unionites* sp.). According to a preliminary conclusion made by I.V. Polubotko, they suggested an Upper Triassic age, but when she re-examined the fauna (pers. comm. 1992) she expressed a doubt about this age, concluding that the *Neoschizodus* more closely resembled species known from the Lower Jurassic of northern Europe. However, the manner in which the concretions occurred allows them to derive from erosion of Lower Jurassic beds that

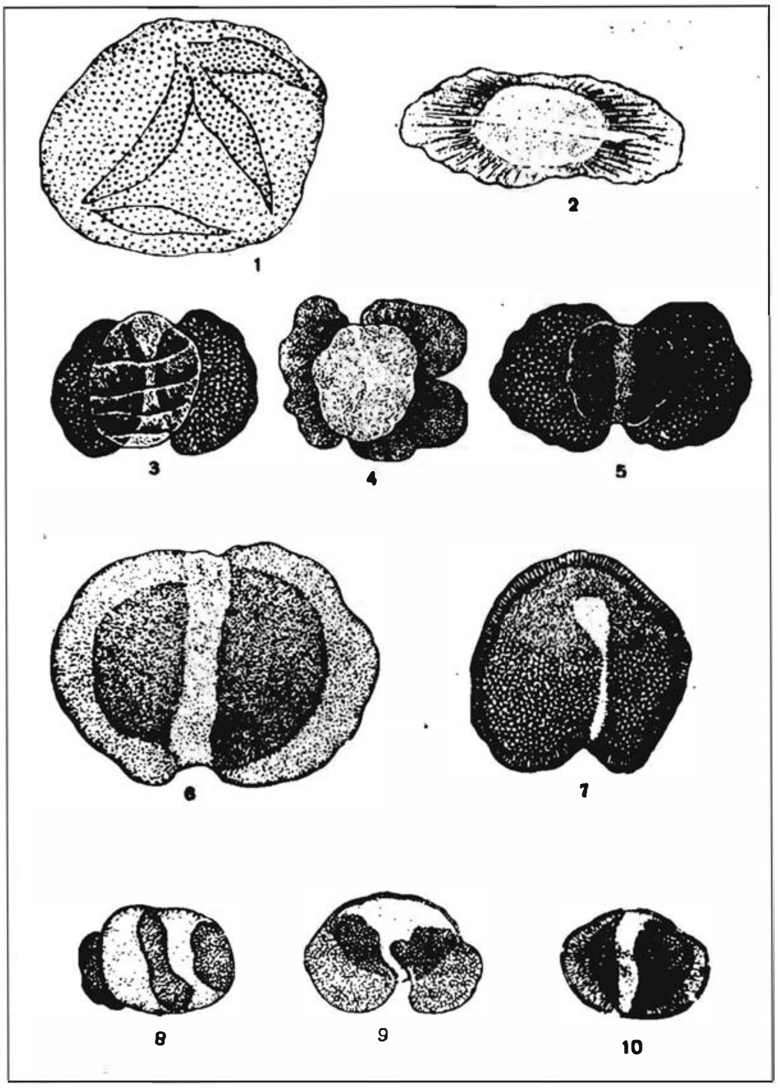


Fig. 3.3.13 Miospores from the Vasiliev Formation (Norian-Rhaetian), x 700. Cape Goristy, Champ Island (specs. 684c/448, 1957). Samples 1–10.
1) *Araucariaceae*,
2) *Lebachia*,
3) *Striatopinites* Sed.,
4) *Podocarpus* cf. *dacrydioides* A. Rich.,
5) *Podocarpaceae*,
6) *Pinaceae*,
7) *Cedrus*,
8) *Coniferae*,
9–10) *Pinus*, x 700 (Dibner & Sedova 1959, Plate III).

once overlay the Upper Triassic deposits that are well documented by their typical Neocalamite flora, and spore and pollen spectra.

3.4 JURASSIC

3.4.1 Lower Jurassic (Lias) – V.D. Dibner

The Lower Jurassic rocks comprise the upper third of an unbroken sequence of Upper Triassic-lower Lias terrigenous deposits named the Tegetthoff Formation after a peninsula on Hall Island. This formation has been described from the islands of Bell, Hooker, McClintock, Alger, Becker and Graham Bell (Figs. 3.3.4 & 3.3.5). Its total apparent thickness is about 180–200 m.

Dibner & Sedova (1959) described the following section on the west side of Cape Tegetthoff, in ascending order:

1. Sand with low-angle cross bedding, inequigranular, light grey; apparent thickness 1 m
2. Pebbles, polymict, with arenaceous groundmass; apparent thickness 3 m Break in outcrop 36 m
3. Quartzose sandstone, inequigranular; cleavage at 45° to horizontal bedding; apparent thickness 15 m Break in outcrop 15 m
4. Greenish grey siltstone, readily breaking into fragments; apparent thickness 15 m
   Break in outcrop 20 m
5. Sand, clayey and greyish yellow with small coal fragments, alternating with similar sandstone interbeds (0.5–1.0 m); apparent thickness 15 m
6. Flaggy siltstone, dark grey, with bands (0.2 m) of polymict conglomerate; thickness 30 m.

Fig. 3.4.1 Cape Galkovsky, Becker Island, locality 1070 (1957). Lower Jurassic silt, sandstone and, uppermost, quartzitic sandstone, up to 180 m thick. Photo: V.K. Razin.

The total thickness is about 150 m.

Muddy limestone, probably belonging to the Middle to Upper Jurassic marine sediments, overlies this sequence.

On the whole, the lithology of the Tegetthoff Formation is characterised by the presence of (i) inequigranular, mainly quartzose sand with concretions of pyrite and ironstone and some siltstone, and (ii) sandstone interbeds, usually with carbonate and, in places (Becker Island), siliceous cement. As in the Wilczek Formation, beds of quartzitic sandstone also appear in the sequence. Scattered beds and more continuous thicknesses of siltstone are found and, less commonly, muddy limestone or, in places, numerous interbeds of grit and conglomerate. Seams and beds of coal also appear in the Tegetthoff Formation on the islands of Alger and Northbrook (Horn 1932, Sveshnikova & Budantsev 1969).

From five samples taken from Beds 6, 5, 3, 2 and 1 in the type section described above, M.A. Sedova (Dibner & Sedova 1959) determined a rich miospore assemblage characterised by various fern spores. It contained abundant *Osmundaceae* (10–22%), smaller numbers of fern spores, such as *Gleichenia* and *Coniopteris*, and a few *Onychium, Cheiropleura* and *Cibotium*. The pollen spectrum was mainly represented by pollen from archaic pines (24–42%), along with *Bennettitales, Cycadaceae* and *Ginkgoales*, the percentage of which decreased from 23–29 to 8% upwards. There was a little pollen of *Podocarpus* and *Araucariaceae*, including that of *Podozamites*, in the assemblage. The samples from the upper portion yielded little pollen. This resembled *Taxodium* or *Cupressaceae*, and some forms similar in morphology to the pollen of angiosperms (*Juglandaceae*).

An instructive section found at the foot of the coastal terrace on Cape Flora, 200 m from the ruins of the Jackson Expedition's winter quarters, was described by Nansen (Pompecky 1900) and Dibner (1957a, b). Based on field observations by Budantsev (pers. comm. 1960) and pollen analytical data from samples which he collected, the sequence is, in ascending order:

1. Sandstone, fine-grained and micaceous, with large and small argillaceous loaves. Apparent thickness 0.5 m. A pollen spectrum was dominated by archaic conifers, including Permian relics such as *Striatoconiferites, Lebachia* and *Vittattina*. *Bennettites, Cycadales, Ginkgos, Podozamites, Araucariaceae* and archaic *Pinaceae* were also observed. Spores are mainly represented by *Osmundaceae* and *Pterydophyta*, including some determined on the basis of their morphology, namely, *Leiotriletes, Lophotriletes, Periplecotriletes, Camptotriletes, Acanthotriletes* and *Hymenozonotriletes*. A few spores of algae (*Hystrichospheridae*), equisetums and ferns (*Hyme-*

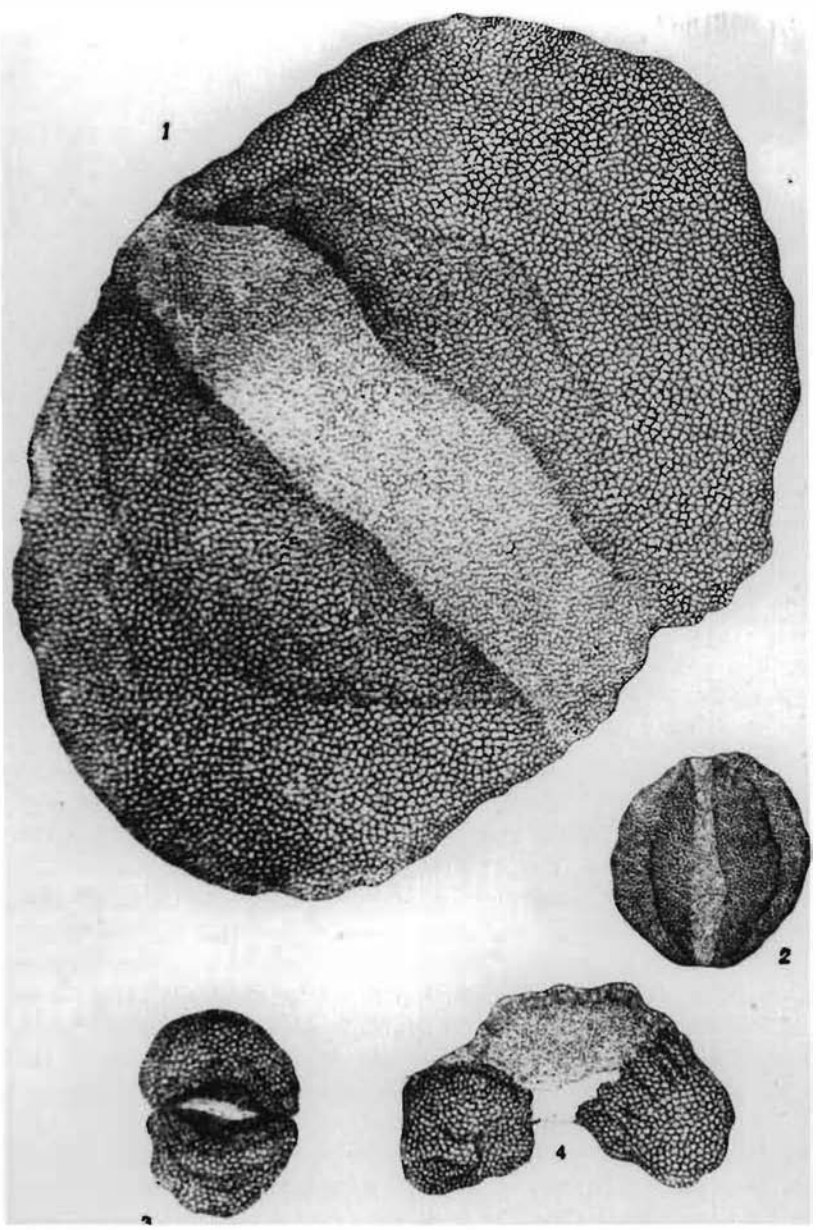


Fig. 3.4.2 Tegetthoff Formation (Lower Jurassic), Cape Sedov, Hooker Island, (spec. 304a, 1957), x 700. 1–3) *Pinaceae*, 4) *Pinus*, x 700 (Dibner & Sedova 1957, Plate VI).

nophyllaceae, *Cibotium* and *Marathiaceae*) were also found. M.A. Sedova (Sedova & Dibner 1959) suggested a probable Upper Triassic age for the assemblage.

2. Sand, fine-grained, quartzose, horizontally and sinuously bedded, in places ocherous, containing pebbles of metamorphic rocks, ubiquitous carbonaceous detritus sometimes forming bands up to 0.5 cm thick, and lenses of brown coal. The bed is 10.0 m thick. M.A. Sedova (Sedova & Dibner 1959) studied the pollen spectra of three samples, which are similar to each other and differ from the assemblage in Bed 1. Although conifer pollen is locally abundant (up to 50–75%), that of the Permian relics was missing. Some of the most ancient spores, such as *Lophotriletes triassica* K.-M., *Camptotriletes curvus* K.-M. and *Hymenosonotriletes* were also absent. There is somewhat less Bennettites pollen. Pollen of ancient pines increases slightly to dominate the assemblage. All told, the data probably indicate the lower(?) Lias.
3. Siltstone, greenish-grey, flaggy, with marly(?) nodules and abundant Aalenian belemnites and pelecypods (see below). Apparent thickness 8.0 m.

Thus, the Upper Triassic/Lias boundary occurs within this section. The Lias (Bed 2) is probably very reduced (perhaps due to erosion) and is sandwiched between the Upper Triassic deposits (judging by spores and pollen) and the marine sediments, reliably dated as Aalenian.

Another locality where pollen analysis revealed the lowermost beds of the Tegetthoff Formation is situated at the northern end of Graham Bell Island, near Lake Severnoe (north) and the Severnaya borehole. A sample (no. 35) collected by L. Govorukha in 1961 yielded abundant miospores of (percentages in brackets): *Matonia* sp. (23), *Phlebopteris* (11), *Coniopteris* sp. (10), *Stenozonotriletes* (10), *Leiotriletes gleichenites* Sed. (5), *L. calamitaeformis* K.-M. (3), *Lophotriletes* sp. (4), *Phyllotheca* (3), *Calamitaceae* (1), *Cibotium* sp. (1), *Hymenozonotriletes* sp. (1) and unidentified (5). Pollen was represented by *Picea* sp. (11), *Paleopicea glaesaria* Bolch. (4), *Podocarpaceae* (2), *Pinaceae* (2), *Ginkgoaceae* (1), *Conifereae* (1), *Pseudowalchia cocea* Bolch. (1) and *Quadraeculina limbata* Mal. (1). V.D. Korotkevich (pers. comm. 1963) concluded that this pollen spectrum is similar to that determined by M.A. Sedova (Dibner & Sedova 1959) in the Tegetthoff Formation. The lack of ribbed pollen and the presence of very large conifer pollen suggest that sample 35 should be attributed to the Lower Jurassic.

Data on the age of the uppermost beds of the Tegetthoff Formation were obtained on Bell Island, where Mikhailov (1979) recognised the Bell unit, a 25 m thick sandstone with interbeds of silt and ironstone concretions. This rests on the palynologically dated Vasiliev Formation sandstone (see section 3.3.2.2). The middle part of the unit, which (as shown by lithofacies) undoubtedly belongs to the Upper Triassic-Lower Jurassic sequence, yielded an assemblage of foraminifers dominated by *Ammodiscus pseudoinfimus* Gerke et Sossip., *Recurvoides* sp., *Trochamina* aff. *inusitata* Schleif., Tr. aff. *lupidosa* Gerke et Sossip. and *Gaudryina* sp. According to A.A. Gerke (Yu.A. Mikhailov, pers. comm. 1979), the assemblage indicates the Pliensbachian-Toarcian, or, more probably, the Toarcian. This is consistent with the conclusions of M.A. Sedova (Dibner & Sedova 1959) who thought that the palynologically dated, chiefly continental, part of the Tegetthoff Formation was probably lower Lias.

Summary

The palynological studies (Dibner & Sedova 1959, V.D. Korotkevich, pers. comm. 1963) thus show that the pollen assemblage in the Tegetthoff Formation on the islands of Northbrook, Hall, McClintock, Hooker and Becker is consistent with the pattern found in the Wilczek and Vasiliev Formations. Triassic (ribbed) pollen has almost completely disappeared, to be replaced by more Jurassic forms of ferns (*Osmundaceae* and others), lycopods and equisetum. The pollen (*Podocarpus*, *Bennettitales*, *Ginkgoales*) is more and more dominated by conifers. Very characteristic is the appearance of extremely large pollen from ancient *Podocarpaceae* and *Pinaceae* (Fig. 3.4.2), not known anywhere else from earlier than the Lias. The assemblage is similar to that described by Pervuninskaya (1958) from the lower Lias of the Anabar-Khatanga depression, which is also notable for an absence of ribbed pollen and an increase in the proportion of *Osmundaceae*. Moreover, the *Podocarpus* and conifer pollen grains show morphological similarity with those in the Tegetthoff Formation. On the other hand, a probable Toarcian age for the uppermost beds on the coast of Bell Island and the fact that they are unconformably overlain by the faunally correlated Aalenian on Cape Flora suggest that the Tegetthoff Formation accumulated throughout the Lias. Large pollen from conifers typifies the Lower Jurassic deposits in the Vilyui syncline and in Aldan in eastern Siberia (Bolkhovitina 1956). Extremely large forms of ancient pine pollen were also reported by Rogalska (1956) from the Lias of Silesia.

The substantial palynological data outlined above (more than 1600 forms of miospores were identified by M.A. Sedova in the Tegetthoff Formation) indicate a Liassic age for the Tegetthoff Formation and clearly demonstrate the quantitative and qualitative differences in the miospore assemblages of this and the Vasiliev Formation. This rules out their coevality. However, within the Lias, the lower age limit of the Tegetthoff Formation, i.e. the time when the large conifer pollen was produced, remains uncertain. It is also necessary to determine the appearance, synchronous to this age limit, of lithofacies features which would be easily discernable when mapping the Tegetthoff Formation and correlated formations. Solution of these problems would bring us closer to determining the Triassic-Jurassic boundary within the unbroken Upper Triassic-Lower Jurassic terrigenous sequence.

3.4.2 Middle and Upper Jurassic – V.D. Dibner & N.I. Shulgina

Middle to Upper Jurassic marine silty and clayey rocks and occasional carbonates are only patchily preserved in Franz Josef Land (Figs. 3.4.3 & 3.4.4), because of deep denudation which antedated volcanic activity in Barremian-Albian time. They yield a rich fauna of molluscs, ammonoids, belemnites, foraminifers and other fossils which allow the beds to be correlated between key sec-

Table 3.5.1

(■ = shaded cell)

Stage	Sub-stage	Zones and Beds \ Islands	North-brook I. Cape Flora	Hooker I. Bear and Sedov capes, Rubini Rock	Mount Ciurlio-nis foot	Champ I. Cape Fiume	Rainer I. West Coast	Berghaus I.	Wilczek Land I. Cape Hansa	Wilczek Land I. Cape Lamont	Wilczek Land I. Cape Hofer	Graham Bell I. Cape Kohlsaat	Klagen-fuhrt I.
Hauterivian		Cyrena spp. Beds									■		
Valanginian	upper										■		
	lower	Temnoptichites diptichus											■
Berriasian/Valanginian boundary beds of continental origin										■			
Berriasian	lower	Buchia unschensis, B. uncitoides Beds								■			
Volgian	middle	Laugeites ex.gr. stschurowskii Beds						■					
		Dorsoplanites spp. Beds								■	■		
	middle-lower	Buchia mosquensis, B. rugosa, B. gracilis, B. mniovnikensis Beds										■	
Kimmerigian	upper	Amoeboceras decipiens and A. kochi							■		■	■	
	lower	Amoeboceras kitchini and Rasenia spp.						■	■		■		
Oxfordian	upper	Amoeboceras ravni									■		
		Amoeboceras alternans									■		
	middle	?											
	lower	Cardioceras corddatum				■					■		
		Cardioceras percaelatum				■							
Callovian	upper	Quenstdtoceras lamberti	■	■							■		
		Longaeviceras keyserlingi		■		■					■		
	middle	Rondiceras tschefkini Beds	■										
	lower	Cadoceras elatmae	■	■		■					■		
Bathonian	upper	Arcticoceras ischmae Beds		■									
	middle			■									
	lower	Arctocphalites elegans Beds	■			■							
Bajocian	upper												
	lower	Tugurites ex.gr. festigatus Beds				■							
Aalenian	upper	Tugurites ludwigia (?) Beds	■	■	■	■	■						
	lower	Pseudollioceras maclintoki	■	■		■	■						
Sources of biostratigraphic data			*Nansen 1900, Pomecky 1900, Dibner & Shulgina 1960, Dibner 1970*	*Samoilovich & Bodylevsky 1933, Spizharsky 1937, Dibner & Shulgina 1960, Dibner 1970*		*Yefremova et al. 1983 a,b*	*Dibner & Shulgina 1960, Pirozhnikov 1961, Dibner 1970, Shulgina & Burdykina 1992*			*Shulgina & Mikhailov 1979, Meledina et al. 1979, Mesezhnikov & Shulgina 1982, Shulgina & Burdykina 1982*		*Livshitz & Markelova 1973 unpublished*	*Kirillov 1974 unpublished*

Table 3.5.1.
Biostratigraphical scheme for Middle to Upper Jurassic and Lower Cretaceous marine deposits of Franz Josef Land.

tions, to the internationally recognised chronostratigraphical zones (Table 3.5.1) and to other parts of the Arctic (Shulgina & Burdykina 1992).

3.4.2.1 Middle Jurassic

Lower Aalenian

The lower Aalenian has only been found at Cape Fiume on Champ Island (Figs. 3.4.4 and 3.4.5). Rhythmically intercalated clays and silt, 20--35 m thick, are exposed on the western part of the cape. These, as well as younger Middle Jurassic deposits are flat-bedded and dip very gently westwards. Ammonites and belemnites are uncommon (usually in calcareous clay concretions, but well-preserved bivalves form lenses of coquina. The presence of the ammonite *Pseudolioceras* cf. *maclintocki* (Haugh.) indicates the lower Aalenian zone of the same name. *Oxytoma jacksoni* Pomp., *Propeamussium* ex gr. *olenekense* (Bodyl.) and *Arctica* aff. *humiliculminata* Schur., which are characteristic for the whole of the Aalenian (Yefremova et al. 1983a), may also be mentioned.

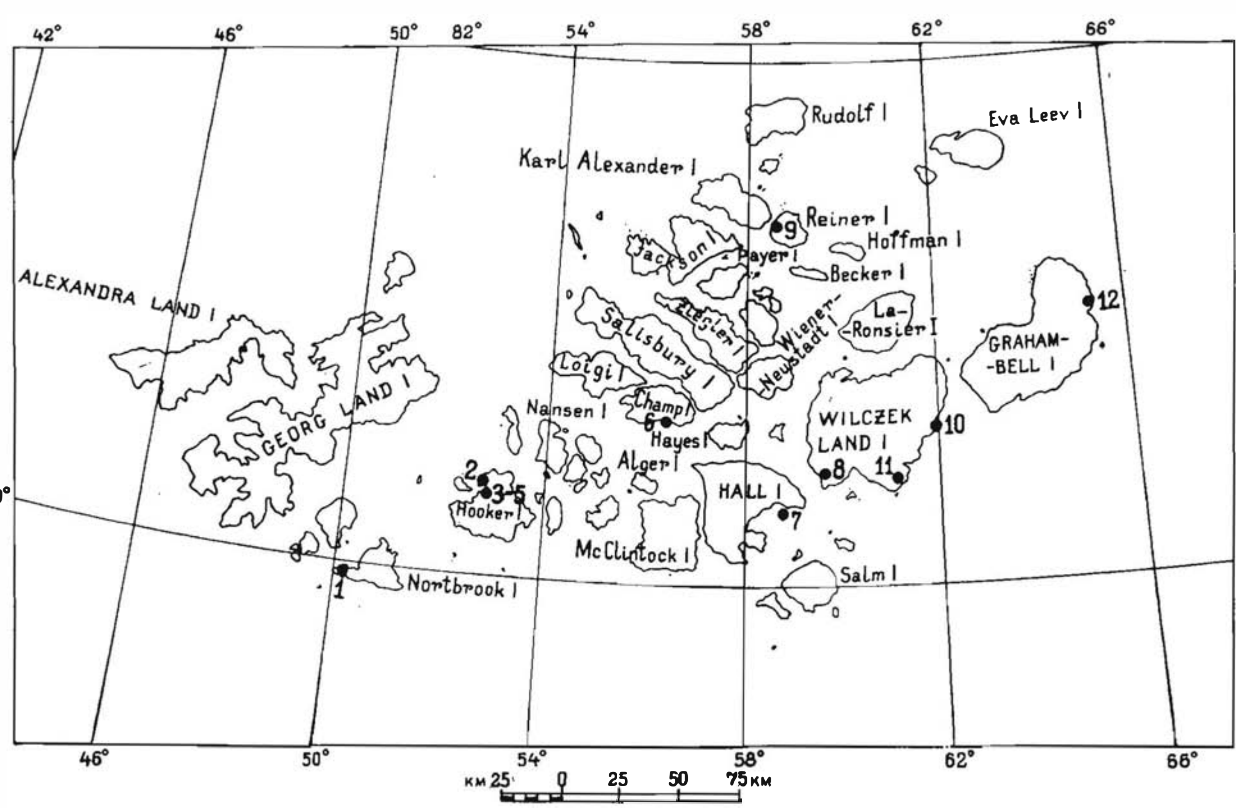


Fig. 3.4.3 Location of key sections of Middle and Upper Jurassic deposits. 1 southwest end of Northbrook Island, 2 Cape Sedov, 3 isthmus near Rubini Rock, 4 Mount Ciurlionis and 5 Cape Medvezhy, Hooker Island, 6 Cape Fiume, Champ Island, 7 Berghaus Island, 8 Cape Hansa, Wilczek Land, 9 west coast of Rainer Island, 10 Cape Lamont and 11 Cape Hofer, Wilczek Land, 12 Cape Kohlsaat, Graham Bell Island.

Upper Aalenian
An outcrop of dark grey clay, 25 m in apparent thickness, with abundant nodules of fossiliferous, cryptocrystalline limestone, was found in 1957 by V.D. Dibner at the foot of Mount Ciurlionis, on the south coast of Tikhaya Bay on Hooker Island. A fragment of an ammonite was identified by N.I. Shulgina (Dibner & Shulgina 1960) as *Ludwigia* sp. indet. (cf. *murchisonae* Sow.). S.V. Meledina (Yefremova et al. 1983b) subsequently revised the identification as *Tugurites* sp. Both these ammonites belong to the late Aalenian. *Propeamussium olenekense* (Bodyl.), *Oxytoma jacksoni* Pomp. var. *kelimiarense* Bodyl., *Hibolites*(?) cf. *beirechi* Opp., *Discina reflexa* Sow. and *Lingula beani* Phill. are also present. The presence of *Tugurites* sp. in the assemblage suggests the upper Aalenian (Shulgina & Burdykina 1992).

Undifferentiated Aalenian
Aalenian beds are also known from Cape Flora on Northbrook Island, the north coast of Tikhaya Bay on Hooker Island, and the west coast of Rainer Island.

On Cape Flora, at the foot of the strandline terrace on which the ruins of the winter quarters of the Jackson Expedition are located, the Tegetthoff Formation sandstone (see section 3.4.1) is overlain by flat-bedded, greenish-grey, flaggy shale with marly nodules, 8–10 m in apparent thickness. Probably the same unit outcrops a few hundred metres to the northwest, where the beds are at sea level. Here, in 1953, V.D. Dibner collected the bivalves *Oxytoma jacksoni* Pomp. var. *kelimiarense* Bodyl. and *Pecten* (*Variamussium*) *oleneki* Bodyl. (= *Propeamussium olenekense* Bodyl.) and unidentifiable belemnites. According to V.I. Bodylevsky, the fauna suggests an Aalenian age (Dibner & Shulgina 1960). Nansen (1900) noted that somewhat younger beds are exposed up-dip, east of the first exposure, at 7–10 m a.s.l. They consist of clay with abundant interlayers of sandy-marly nodules (up to 30 cm across), cut by calcite veins and containing disseminated pyrite. The nodules and clay are crammed with fossil fragments among which Pompeckj (1900) identified *Oxytoma jacksoni* Pomp., *Lingula beani* Phill., *Discina reflexa* Sow. and *Hibolites* cf. *beyrichi* Opp. The presence of *Oxytoma jacksoni* reliably associates the assemblage with the Aalenian, although Pompecky (1900) assigned the deposits to the lower Bajocian.

A.V. Ditmar (pers. comm. 1988) found that the Upper Triassic psammites on the north coast of Tikhaya Bay are overlain by alternating, 5–20 cm thick, layers of grey clay, yellowish-grey siltstone and dark-grey mudstone, along with lenses of calcareous siltstone and limestone. The sequence has an apparent thickness of 25 m and is abundantly fossiliferous, especially the carbonates. Bivalves dominate, with smaller numbers of brachiopods and gastropods, and sporadic belemnites and crinoids. E.S. Yershova (pers. comm. 1981) identified the bivalves *Oxytoma jacksoni* (Pomp.) and *Propeamussium olenekense* (Bodyl.) and the brachiopods *Discina reflexa* (Sow.) and *Lingula beani* Phill., which are typical for the Aalenian of Franz Josef Land. She also identified for the first time in the archipelago *Arctotis lenaensis* (Lah.), *Camptonectes* (*Boreionectes*) aff. *giganteus* Arkell and *Dacryomyo gigantea* Zakh. et Schur. The first and last species are typical of the Aalenian in northern Siberia. Because of the lack of ammonites, she was unable to propose a more precise age than Aalenian.

A slab of dark-grey siltstone containing a fragment of *Oxytoma* sp. indet, similar to the reliably dated Aalenian species *Oxytoma jacksoni* found at the foot of Mount Ciurlionis, was collected on the west coast of Rainer Island. The siltstone is about 5 m thick and along with an overlying dolerite sill dips 40° NW (Dibner & Shulgina 1960).

Lower Bajocian(?)
Evidence suggesting the presence of the Bajocian was first obtained at Cape Fiume on Champ Island where V.A. Basov (pers. comm.) found an assemblage including *Ammodiscus pseudoinfimus* Gerke of possible Bajocian age in the lower part of the middle unit, composed of "banded shale". As mentioned above, the ammonite *Tugurites* sp. (ex gr. *fastigatus* West.), a reliable index species for the lower Bajocian, was found in talus below this part of the sequence (Yefremova et al. 1983a, b).

Bathonian
At Cape Fiume on Champ Island (Fig. 3.4.5), the upper part of the middle unit, composed of banded clay (185–210 m a.s.l.), contains fragments of the ammonite *Arctocephalites* cf. *elegans* Spath, suggesting the lower Bathonian beds of the same name. This agrees with finds of rostra of

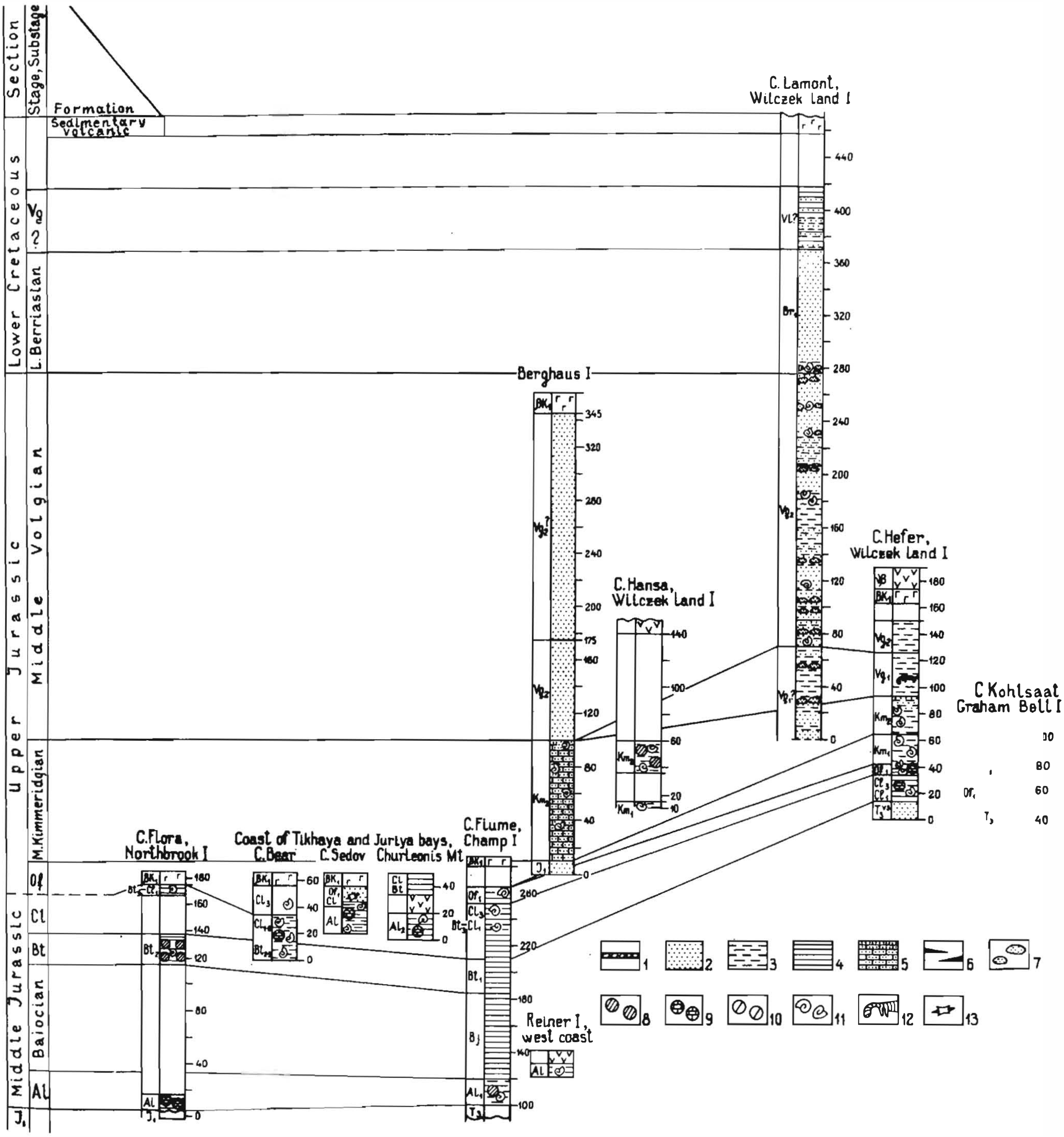


Fig. 3.4.4 Sections of Middle Jurassic deposits. 1 conglomerate, 2 sand and sandstone, 3 silt and siltstone, 4 clay and mudstone, 5 arenaceous limestone, 6 lenses of brown coal, 7 sandstone loaves, 8 phosphatic nodules, 9 calcareous and marly concretions, 10 pyrite nodules, 11 invertebrate fauna, 12 saurian skeleton, 13 saurian vertebra.

Fig. 3.4.5 Cape Fiume, Champ Island. 0–100 m Upper Triassic sand and sandstone; 100–280 m flat-bedded mainly clayey deposits, Aalenian-Callovian; above 280 m Lower Cretaceous basaltic sheets. Photo: V.K. Razin.

the belemnites *Paramegateuthis nescia* Naln. and *P. pressa* Naln. there. Its thickness is 25 m (Yefremova et al. 1983a).

From Cape Flora on Northbrook Island, above talus which probably covers the upper Aalenian and the Bajocian, Koettlitz (1898) and Nansen (1900) described flat-bedded clays abounding in phosphatic nodules and fragments of sandy marl. The nodules are fossiliferous, mainly pelecypods and smaller numbers of ammonites and belemnites. The ammonites, originally identified by Pompecky (1900) as lower Callovian, were later revised by Spath (1932) as upper Bathonian *Arctocephalites koettlitzi* Pomp., *A. pilaeformis* Spath and *A. ellipticus* Spath. According to recent data (Shulgina & Burdykina 1992), ammonites of this genus suggest the lower Bathonian.

A dinoflagellate assemblage composed almost solely of *Stephanelytron redcliffense, Lithodinia jurassica, Pareodinia ceratophore, Gonyaulacysta jurassica* and *Tubotuberella eisenackii* was found in three phosphoritic nodules collected by Nansen from talus, but definitely belonging to the same Bathonian beds. According to Smelror (1986), this assemblage suggests middle to upper Callovian-lower Oxfordian, thus conflicting with the evidence from the ammonoid fauna.

From the south coast of Yury Bay, midway along the north coast of Cape Medvezhy on Hooker Island (Fig. 3.4.6), Dibner & Shulgina (1960) described an 18–20 m thick unit of greenish-grey, thinly laminated and flaggy, silty claystone with numerous nodules of cryptocrystalline limestone, disseminated pyrite and secondary gypsum exposed in unstable scree consisting of overlying basalts and tuffs. The claystone and nodules are packed with fossils, chiefly belemnites. The lower part yielded the ammonite *Arcticoceras ishmae* (Keys.) already known from non-systematic collections made there by R.L. Samoilovich and I.M. Ivanov (Ognev 1933, Samoilovich & Bodylevsky 1933). The beds containing the *Arcticoceras* are now dated as upper-middle to lower-upper Bathonian, whereas *Arcticoceras ishmae* was previously thought to be typical of the lowermost zone of the Callovian. Unfortunately, because of landslips of the fossiliferous rock at Cape Medvezhy, precise bed-by-bed collection of the fauna was not possible. *A. ishmae* was therefore collected together with ammonites that suggested different Callovian substages and zones (see below).

Callovian

The Callovian is exposed on Cape Hofer and Cape Fiume (where all three Boreal Callovian zones were first recognised), as well as at Tikhaya Bay, Jury Bay and Cape Flora.

At 15–35 m a.s.l. on Cape Hofer, Wilczek Land (Figs. 3.4.7–3.4.9), the sands of the Vasiliev Formation are disconformably overlain by "brown clays" whose base yielded the ammonite *Cadoceras* (*Paracadoceras*) *anabarensis* Bodyl., indicating the lower Callovian *Cadoceras elatmae* zone. The overlying 10–12 m of rock yielded the ammonite *Longaeviceras* ex gr. *keyserlingi*, an

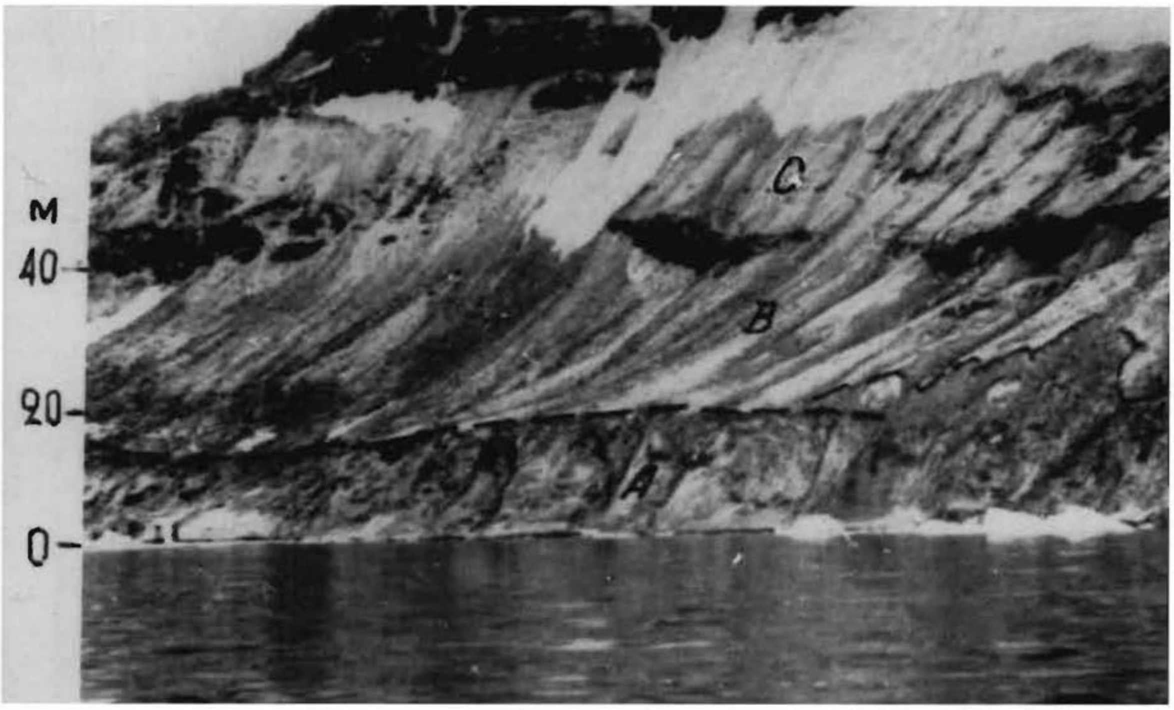


Fig. 3.4.6 Cape Medvezhy, Hooker Island. A middle-upper Bathonian-Callovian flaggy sandy-clays, B talus probably covering Upper Jurassic strata, C Lower Cretaceous basalts and tuffs. Locality 298, 1957. Photo: V.D. Dibner.

index fossil of the lower-upper Callovian, and the ammonites *Quenstedtoceras holtedahli* Salf. and *Eboraciceras mologae* (Nik.), suggesting the uppermost Callovian, i.e. *Quenstedtoceras lamberti*. The Callovian part of the "brown clays" abounds in large disc-shaped nodules (up to 0.5 m across) of dark grey cryptocrystalline limestone showing cone-in-cone structure and transected by calcite veinlets. In this respect, the unit strongly resembles the Callovian clay at Tikhaya Bay and Yury Bay (Shulgina & Mikhailov 1979, Shulgina & Burdykina 1992).

At Cape Fiume on Champ Island, the uppermost part of the "banded clay" (235–237 m a.s.l.) consists of massive, greenish-grey clay with sporadic nodules of calcareous mudstone yielding, not least, the ammonite *Pseudocadoceras* aff. *nanseni* (Pomp.), which is known from the uppermost Bathonian and lower Callovian of northern Siberia. Its position in the section at Cape Fiume indicates lower Callovian. The lower-upper Callovian index fossil, *Longaeviceras* cf. *keyserlingi* (Sok.), was found above, at a height of 248–255 m a.s.l. The Callovian beds are about 20 m thick (Yefremova et al. 1983a, Shulgina & Burdykina 1992).

On the coasts of Tikhaya Bay and Yury Bay on Hooker Island, along with *Arcticoceras ishmae* which was found in collections made by R.L. Samoilovich at the base of the Cape Medvezhy section, V.I. Bodylevsky identified *Pseudocadoceras nanseni* (Pomp.), suggesting the lower Callovian, *C.* (*Longaeviceras*) ex gr. *nikitini* (Sok.), indicating the lower-upper Callovian zone, and *Quenstedtoceras* sp., pointing to the uppermost Callovian zone (Samoilovich & Bodylevsky 1933). Moreover, in a collection made by I.M. Ivanov 2–14 m a.s.l., Ognev (1933) identified *Cadoceras elatmas*, an index species of the lower Callovian, and the Callovian belemnites *Cylindroteuthis tschernyschewi* Krimh. and *C. tornalites* Phil., as well as *Pachyteuthis* cf. *panderi* Orb. which suggests the Callovian-Oxfordian. Ognev also cited partly dubious evidence for a younger, Upper Jurassic and Valanginian, fauna (see below).

In 1980, Cape Medvezhy was investigated by L. Petrunin. Although his collection of belemnites and, in part, ammonites is poor as regards state of preservation and composition, an interesting item is the ammonite *Camptonectes* cf. *borealis* Geras., which is unknown from earlier collections. According to O.V. Cherkesov, it suggests the lower-middle Callovian (Ditmar et al., pers. comm.

1982). Thus, even though the strata (and fossils) on Cape Medvezhy suffer from landslips, the faunal composition clearly points to the presence of outcrops (variably concealed by landslides and talus) of middle to upper Bathonian, and lower and middle Callovian age.

The belemnites *Pachyteithis panderi* Orb. and *P. borealis* Orb., and the ammonite *Arcticoceras* sp. indet. were identified in collections made on the tombolo between Rubini Rock and Mount Ciurlionis by R.L. Samoilovich and N.P. Lupanova. According to V.I. Bodylevsky, the belemnites belong to the upper Callovian and the ammonite to the lower Callovian (Samoilovich & Bodylevsky 1933). Nowadays, the genus *Arcticoceras* is placed in the middle-upper Bathonian (Shulgina & Burdykina 1992). In a sample collected here by V.D. Dibner in 1953, G.M. Romanovskaya found a spectrum with a high content of conifer pollen (51%) and large amounts of *Bennettitales* and *Ginkgoales* (14%). Spores, accounting for 34% of the assemblage, are mainly represented by ferns of the *Osmundaceae* and *Sellaginella* (11%) families (Dibner & Shulgina 1960, Dibner 1970).

At 70–80 m a.s.l. on Cape Sedov, in talus under the lower basalt sheet, Spizharsky (1937a, b) found a large sandy-gritty concretion in sandy clays and sands; it contained a cervical of the short-

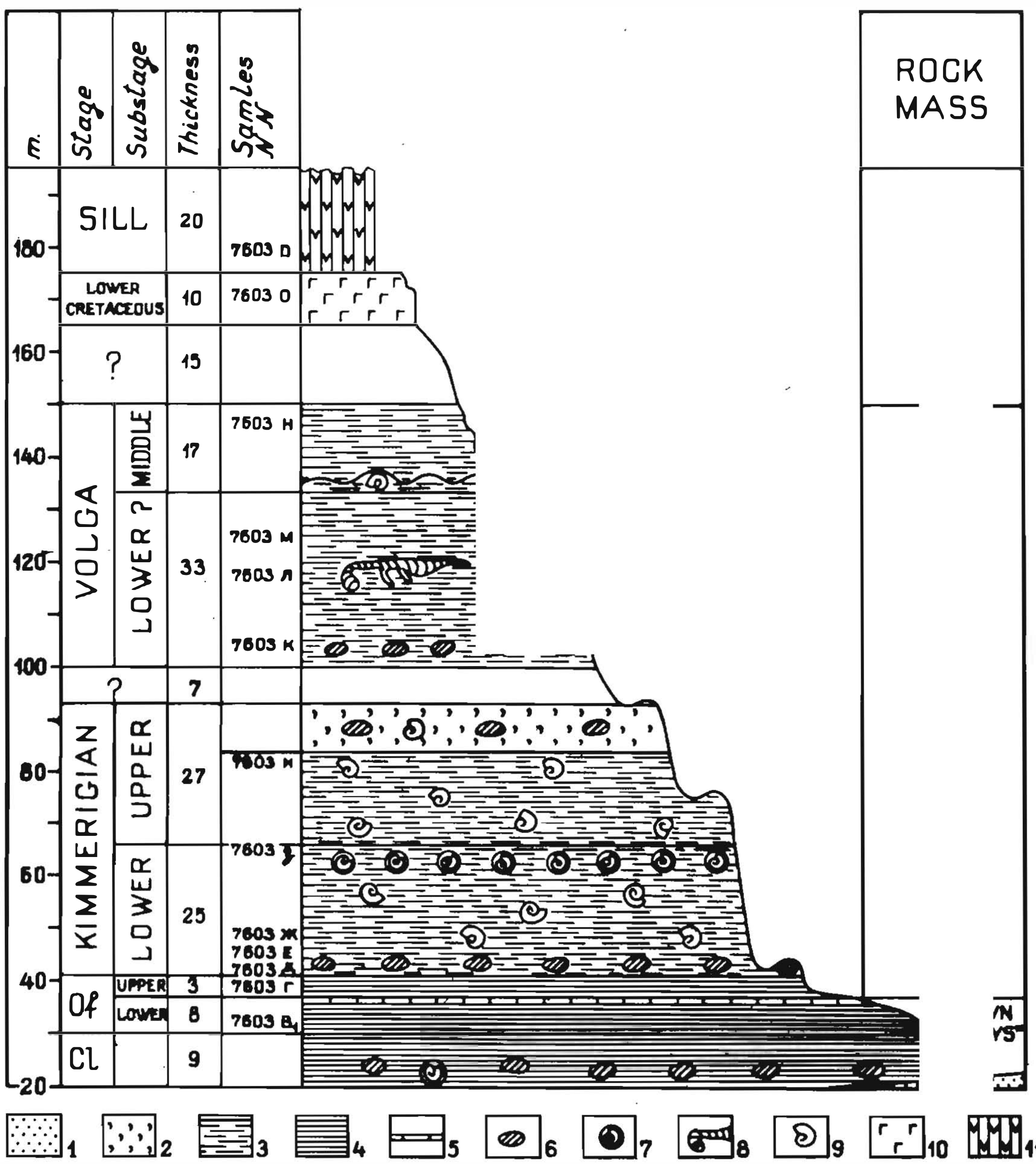


Fig. 3.4.7 Section of Upper and Middle Jurassic deposits at Cape Hofer, Wilczek Land. 1 sand, 2 chloritic sand, 3 laminated siltstone, 4 clay, 5 limestone, 6 nodules, 7 nodules with faunal remains, 8 saurian skeleton, 9 remains of invertebrates, 10 basalt, 11 dolerite.

Fig. 3.4.8 Cuesta made up of Upper Triassic, Callovian and Upper Jurassic deposits. Cape Hofer, Wilczek Land. Photo: V.D. Dibner.

necked plesiosaurus *Peloneustes* cf. *philarchus* (Seeley). According to Ryabinin (1936), it is typical of the upper Callovian-lower Oxfordian. Not far from here, also below the basalt, V.D. Dibner in 1953 observed an outcrop of silty clays (7 m in apparent thickness), similar to the upper Bathonian-Callovian deposits of Cape Medvezhy and unconformably overlying sand and sandstone with poorly preserved plant remains that probably belongs to the Upper Triassic Vasiliev Formation.

At Cape Flora on Northbrook Island, 150–172 m a.s.l., above talus covering the Bathonian deposits, Koettlitz (1898, 1899) and Nansen (1900) found outcrops of clay with abundant cone-in-cone structures and interbeds abounding in large argillaceous sandstone nodules packed with remains of pelecypods, ammonites and belemnites. Recent revisions of Pompecky's original identifications of various bivalves and ammonites collected at 168 m a.s.l., along with biostratigraphical data, show that different ammonites indicate different stages (Shulgina & Burdykina 1992). Thus, *Pseudocadoceras nanseni* (Pomp.) suggests the upper Bathonian-lower Callovian, *Rondiceras tschefkini* the middle Callovian and *Eboraciceras stenolobum* (Nik.) the middle-upper Callovian. Higher up, at 175 m a.s.l., in talus near the overlying basalt sheets, Koettlitz and Nansen found *Quenstedticeras vertumnum* (Sintz.), which belongs to the uppermost Callovian *Quenstedticeras lamberti* zone (Shulgina & Burdykina 1992).

Oxfordian

The Oxfordian occurs on Cape Fiume (most completely) and on Cape Hofer and Cape Kohlsaat, where only the lower Oxfordian was found.

At 32–40 m a.s.l. on Cape Hofer, Wilczek Land, the 8 m thick upper part of the "brown clay" yielded *Cardioceras (Cardioceras)* cf. *cordatum* (Sow.), *C. (C.)* cf. *percaelatum* Pavl. and *C. (Scotticardioceras)* cf. *excavatum* (Sow.)), suggesting two zones of the lower Oxfordian, the *Cardioceras percaelatum* and the *Cardioceras cordatum* zones, although these are not clearly dif-

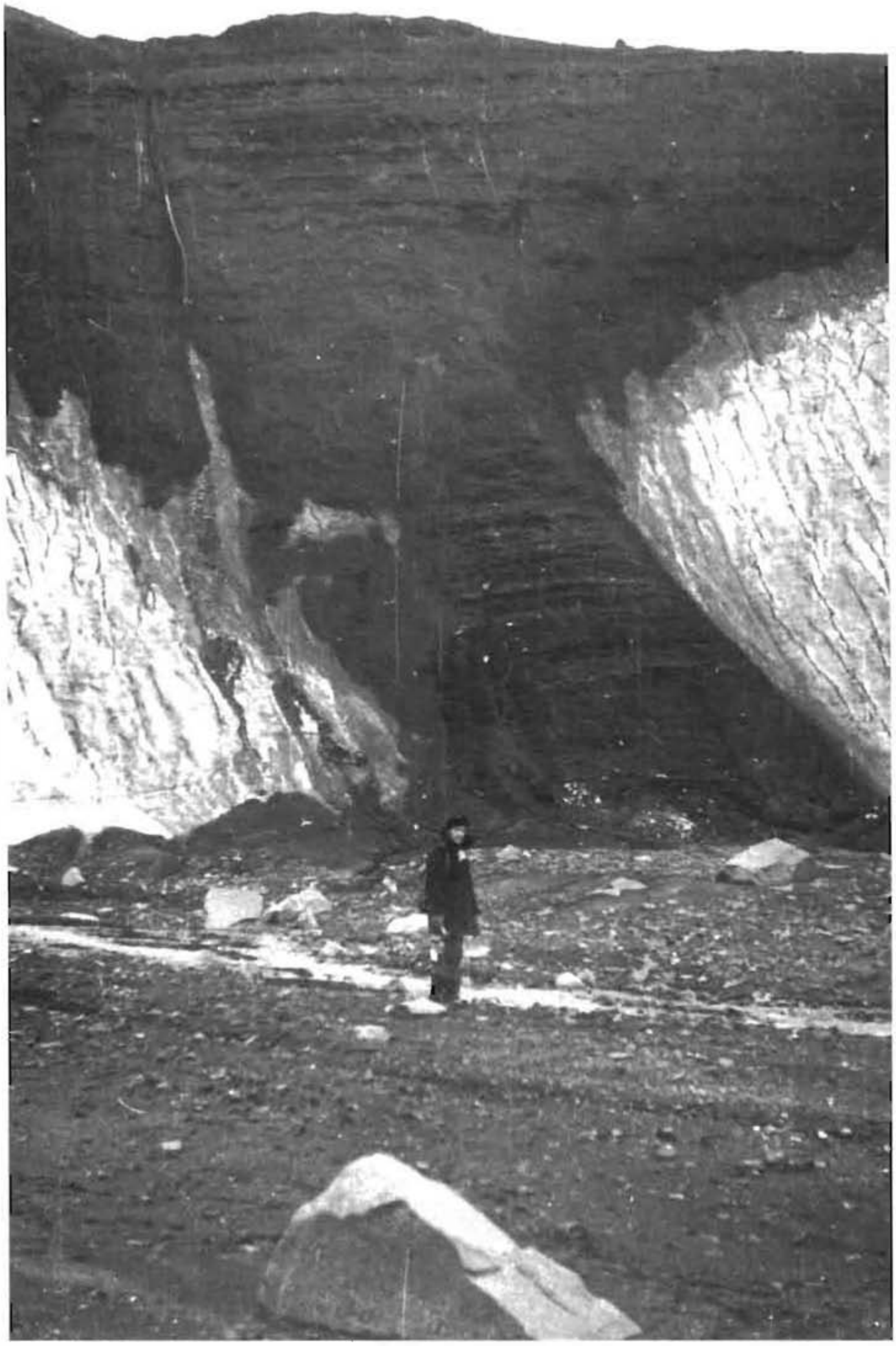


Fig. 3.4.9 Callovian sandy-silty deposits at Cape Hofer, Callovian cuesta scarp (see Fig. 3.4.8). Photo: V.D. Dibner.

ferentiated. Like the Callovian, the lower Oxfordian abounds in disc-shaped argillaceous sandstone concretions (Shulgina & Mikhailov 1979, Shulgina & Burdykina 1992).

At Cape Kohlsaat on Graham Bell Island, siliceous grit and sand of the Upper Triassic Vasiliev Formation is overlain by an 8.5 m thick unit of fine- to medium-grained grey sand with interbeds of phosphatic nodules. Near the top is silicified wood, bones (of saurians?), ammonites and belemnites (*Cardioceras (Cardioceras) arcticum* Pavlow, *C. (C.) praecordatum*, *C. (C.) jacuticum*, *C. (Scotticardioceras) delicatum* (Buchman) and *Pachyteuthis* cf. *panderianum* (Orb.)) which, according to E.S. Yershova (pers. comm. 1981), suggest the lower Oxfordian *Cardioceras cordatum* zone. From the same section, I.A. Shilkina (pers. comm. 1973) identified fragments of trunks of *Protocarpoxylon* and *Sahnioxylon* collected by Yu. Livshits (Livshits & Markelova, pers. comm. 1973).

At Cape Fiume on Champ Island, a 10 m thick unit uppermost in the "massive clay" sequence yielded the ammonite *Cardioceras* sp. juv., suggesting the lower Oxfordian (Yefremova et al. 1983a).

The upper Oxfordian was found only at Cape Hofer on Wilczek Land, where a 3 m thick unit occurs at the base of "black clay" which extends up to the middle Volgian (= lower-upper Tithonian). The basal unit is overlain by a thin horizon of calcareous nodules and is dated by the ammonite *Amoeboceras (Amoeboceras) alternans* Buch, an index species of the lower-upper Oxfordian zone. The ammonites *Amoeboceras (Prionodoceras) freboldi* Spath and *A. (P.)* cf. *ravni* Spath, which indicate the uppermost Oxfordian *Amoeboceras ravni* zone, were found above that horizon (Shulgina & Mikhailov 1979, Shulgina & Burdykina 1992).

Lower Kimmeridgian

Kimmeridgian strata have been found at Cape Hofer and Cape Hansa on Wilczek Land, on Berghaus Island and at Cape Kohlsaat on Graham Bell Island.

The lower Kimmeridgian at Cape Hofer occurs 40–63 m a.s.l., where laminated siltstone with glauconite-rich intercalations rests conformably upon the Oxfordian clay. It yielded the ammonites *Amoeboceras (Amoebites) kitchini* (Salf.), *A. (A.) subkitchini* Spath and *Rasenia (Rasenia)* aff. *inconstans* Spath, indicating the *Amoeboceras kitchini* and *Rasenia* spp. zone, equivalent in range to the lower Kimmeridgian (Yefremova et al. 1983a).

On the southeastern extremity of Cape Hansa (Fig. 3.3.5), at 10–60 m a.s.l., Pirozhnikov (1958) observed small outcrops of poorly cemented, laminated siltstone dipping 25° SE. Overlying sedimentary strata are concealed beneath talus originating from dolerite sills outcropping from 140 m a.s.l. From 10–15 m a.s.l., the siltstone (with calcareous nodules) contains *Buchia concentrica* (Sow.) and *Entolium demissum* (Phill.), as well as the ammonites *Amoeboceras (Amoebites) spathi* Shulg. and *Rasenia* sp., suggesting the lower Kimmeridgian (Dibner & Shulgina 1960).

Upper Kimmeridgian

At Cape Hofer, the lower Kimmeridgian siltstone is overlain at 63–85 m a.s.l. by similar siltstone containing the ammonites *Amoeboceras (Haplocardioceras) decipiens* Spath, *A. (Euprinoceras) kochi* Spath and *A. (E.) sokolovi* Bodyl., all of which are characteristic of the upper Kimmeridgian (the lower part of the Tithonian, after Harland et al. (1982, chart 2.10)).

From 85–94 m a.s.l., the laminated siltstone is interbedded with leptochloritic sands. These beds are devoid of macrofossils, but V.A. Basov found an assemblage of foraminifers (*Kutsevella* ex gr. *minutissima* and *Trochamina tosacca*) which is developed over a wide age range from Callovian to Kimmeridgian inclusive (Shulgina & Mikhailov 1979, Shulgina & Burdykina 1992).

At Cape Hansa on Wilczek Land, Pirozhnikov (1958) found that the laminated siltstone between 35 and 60 m a.s.l. contained *Aucella bronni* Reitl., but this was later re-identified (Shulgina 1960, 1986) as *Buchia concretica* (Sow.). *Amoeboceras (Haplocardioceras) decipiens* Spath and *A. (Euprinoceras) kochi* Spath, which are now index species for the zone corresponding to the upper Kimmeridgian, were also found.

Samples collected in 1956 on the small Berghaus Island (Fig. 3.4.10) from a sequence of thinly intercalated ferruginous sandstone, arenaceous limestone, siltstone and mudstone contained upper Kimmeridgian bivalves, ammonoids and belemnites. One ammonite (sample 79/35), originally identified by N.I. Shulgina (Dibner & Shulgina 1960) as *Amoeboceras (Amoebites) bodylevskii* sp. nov. and subsequently re-identified by M.S. Mesezhnikov as *A. (Euprionoceras) kochi* Spath, was collected from talus at 35 m a.s.l. *Amoeboceras (Haplocardioceras) decipiens* Spath (sample 79/50) was collected 15 m higher up. At first, these species were referred to the lower Kimmeridgian (Spath 1936), but numerous studies later confirmed a suggestion made by Shulgina (Dibner & Shulgina 1960) of an upper Kimmeridgian age. Thin slabs of limestone and siltstone from 75 m and 100 m (samples 79/75 and 79/100) display imprints of Oxfordian-Kimmeridgian *Aucella* ex gr. *bronni* Rouill, now revised as *Buchia concentrica* (Sow.). Hence, the upper Kimmeridgian beds seem to extend up to a height of 100 m (Dibner 1970, Mesezhnikov & Shulgina 1982, Shulgina & Burdykina 1992).

Undifferentiated Kimmeridgian

At Cape Kohlsaat on Graham Bell Island, a thin unit of lower Oxfordian sand is overlain by 25 m of laminated, black bituminous clay and mudstone, succeeded by 3.5 m of the same rock types in-

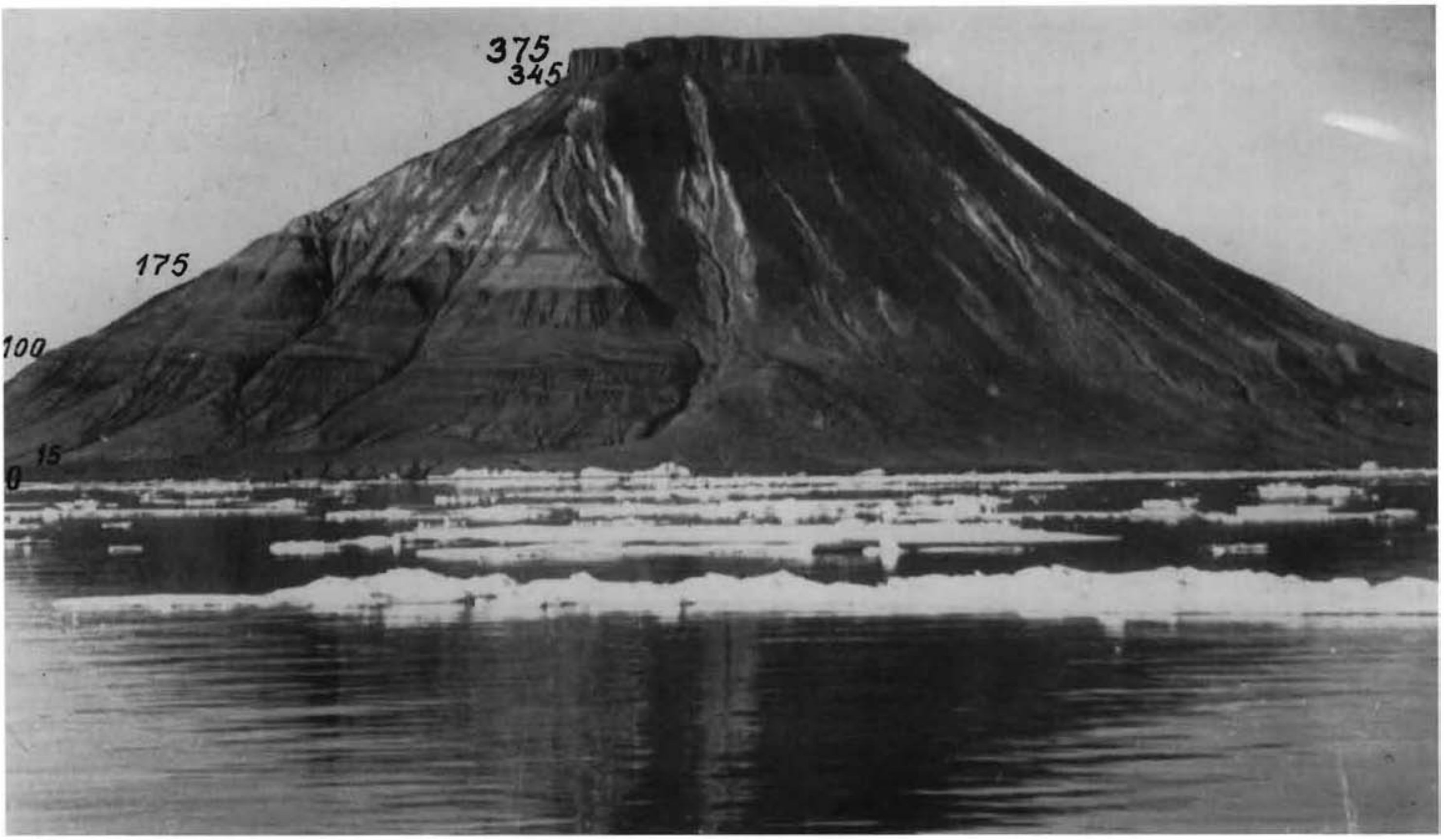


Fig. 3.4.10 Upper Jurassic deposits, Berghaus Island. From the base up: A 0–15 m Lower Jurassic (Tegetthoff Formation), B 15–100 m Kimmeridgian, C 100–175 m middle Volgian(?) "dark sand" facies, D 175–345 m middle Volgian(?) "light sand" facies, E 345–375 m Lower Cretaceous basaltic sheet (or doleritic sill). Photo: Yu.P. Chernokaltsev.

terbedded with grey medium-grained sand. The clay contains *Amoeboceras (Amoebites)* juv. sp. indet., *Buchia* ex gr. *concentrica* (Sow.) and *B. tenuistriata* (Lah.), indicating the Kimmeridgian (E.S. Yershova, pers. comm. 1993).

Volgian

The Volgian (defined as the upper Tithonian or Portlandian according to the chronostratigraphic scale of Harland et al. (1982, chart 2.10)) has been recognised on the Hofer, Lamont and Kohlsaat peninsulas and on Berghaus Island.

At 126–143 m a.s.l. on Cape Hofer (Wilczek Land), the uppermost part of the "black clay" unit, here represented by laminated siltstone, yielded *Dorsoplanites* sp. (cf. *aldingeri*). Spath, *D.* sp. (aff. *triplex* Spath) and *Buchia* ex gr. *fisheriana* (Orb.). Beds containing *Dorsoplanites* spp. suggest the lower-middle Volgian. Thus, the interval 94–126 m a.s.l. remains undated. It is made up of thinly flaggy, sooty siltstone and poorly indurated siltstone locally rich in glauconite and containing an interbed of cryptocrystalline limestone concretions some metres above the base. A saurian skeleton (preserved length about 3.0–3.5 m) was found 106 m a.s.l. It is highly deformed, probably by diapirism, since it was accompanied by foreign fragments of massive siltstone differing greatly from the poorly consolidated, laminated varieties that make up this "black clay" sequence. Based on a photograph (Fig. 3.4.11), L.A. Nesov (pers. comm. 1993) believes this to be a plesiosaur. Unfortunately, vertebrae and other bones are still awaiting expert examination at the Palaeontological Institute of the Russian Academy of Science in Moscow. This 94–126 m interval, separating the upper Kimmeridgian and the middle Volgian, is tentatively assigned to the lower Volgian on the basis of a microfaunal assemblage containing *Evolutinella emelianzevi* and *Haplophragmium elongatum* (Shulgina & Mikhailov 1979, Shulgina & Burdykina 1992).

The lower part (0–70 m a.s.l.) of Cape Lamont on Wilczek Land is made up of the "dark sand" unit consisting of alternating, cross-bedded, dark (in places slightly carbonaceous) sand and flat-bedded silt. These beds are unfossiliferous except for rare fragments of belemnite rostra. The upper part of the "dark sand" (70–120 m a.s.l.) consists of alternating bands of grey, brown and yellow, fragmented siltstone and thinly flaggy, semi-consolidated calcareous sand, which also forms large (up to 2–3 m) loaves. In places, these strata are crammed with fossils, such as *Dorsoplanites* sp. (?cf. *gracilis*), *D.* sp. (aff. *maximus*), *Buchia* cf. *andersoni* (Pavl.), *B.* sp. (cf. *lahuseni* Pavl.) and *B.* ex gr. *fisheriana* (Orb.). They are succeeded by a sequence comprised of a "light grey sand" unit and light yellow sand interbedded with calcareous sandstones, with large loaves at the base. From 120–180 m a.s.l., these strata contain, in addition to the above-mentioned fauna, *Buchia stantani* (Pavl.), *B. terebratuloides* (Lah.) and *B. lahuseni* (Pavl). The presence of *Dorsoplanites* spp. in this sequence (70–275 m a.s.l.) proves a lower-middle Volgian age. The occurrence of *Buchia unschensis* (Pavl.) in the light-coloured sand from 280–400 m a.s.l. indicates that these beds may be upper Volgian-Berriasian (Shulgina & Mikhailov 1979, Shulgina & Burdykina 1992).

In 1973, on the upper part of Cape Kohlsaat on Graham Bell Island, Yu.Ya. Livshitz discovered the bituminous shale of the Kimmeridgian overlain by a thin (1–2 m) siliceous mudstone succeeded by 7–8 m of grey arkose with interbeds of medium-grained, yellow sand containing lenses of sooty, dull coal. The uppermost part of this unit contains fragments of belemnites and *Buchia mosquensis* Buch., *B. rugosa* (Fish.), *B. gracilis* (Pavlov) and *B. mniovnikensis* (Pavl.), an assemblage which, according to E.S. Yershova (pers. comm. 1972), suggests the lower-middle Volgian.

On Berghaus Island, above the suggested upper limit (100 m a.s.l.) of the Kimmeridgian deposits, *Laugeites* aff. *stschurowskii* (Nikit.), *Buchia russiensis* (Pavl.), *B. gracilis* (Pavl.) and *B.* cf. *mosquensis* (Buch.) were collected by Pirozhnikov (1961b) at 106 m a.s.l. N.S. Voronets (pers. comm. 1960) assigned this assemblage to the lower Volgian "epivirgatite" beds which occur on the Russian plate and in Siberia; according to the recent Arctic biostratigraphical scheme (Shulgina & Burdykina 1992), this corresponds to the upper part of the middle Volgian beds. Figure 3.4.10 shows a significant change in colour at a height of 175 m which, by analogy with Cape Lamont

Fig. 3.4.11 Skeleton of plesiosaur possibly transported by diapirism into middle Volgian silt. Photo: V.D. Dibner.

Fig. 3.4.12 Selection of Middle Jurassic ammonites and belemnites. 1) *Pseudolioceras* cf. *maclintocki* (Haughton), spec. 489–440, sample 309–12, mould of imprint, side view, Cape Fiume, Champ Island, lower Aalenian *Pseudolioceras maclintocki* zone. 2) and 3) *Tugurites* sp. (ex gr. *fastigatus* West.); 2) spec. 489–443, sample 309–18, side view of a fragment; 3) spec. 489–444, sample 309–18, side view of half a whorl, Cape Fiume, Champ Island; the sculpture resembles that of the lower Bajocian species *Tugurites fastigatus* (West.). 4 and 5) *Pseudocadoceras nanseni* (Pomp.), Cape Flora, Northbrook Island, middle Bathonian-lower Callovian (from Pompecky 1900, Plate II, Figs. 1, 5). 6a, b) *Arctocephalites* cf. *elegans* Spath., spec. 489–446, sample 309–19a, side view, a) imprint, b) mould; Cape Fiume, Champ Island, lower Bathonian *Arctocephalites elegans* zone. 7a, b) *Cadoceras (Paracadoceras) anabarense* Bodyl. spec. 489–400, a) side view, b) apertural view; Cape Hofer, Wilczek Land, lower Callovian *Cadoceras elatmae* zone. 8a, b) *Arctoteuthis (Microbelus)* cf. *pseudo-lateralis* Gust., spec. 87–405, sample 475–4, a) ventral view, b) side view; Cape Fiume, Champ Island, lower to middle Callovian. Middle Jurassic ammonites and belemnites from Cape Fiume, Champ Island (Yefremova et al. 1983) and Callovian and Oxfordian ammonites (Meledina et al. 1979) are housed in the Museum of the Institute of Geology and Geophysics, Siberian Branch, Russian Academy of Sciences.

(only 65 km from Berghaus Island), can be interpreted as the change from the dark sand to the overlying light-coloured sand. If this is the case, this light-coloured sand right up to the overlying basaltic sheet, i.e. to 345 m, is probably also middle Volgian in age (Fig. 3.4.4).

Inferred Middle to Upper Jurassic deposits

In addition to the deposits described above, there are isolated outcrops of marine deposits which, until studied in detail, can only be tentatively assigned to undifferentiated Middle to Upper Jurassic deposits.

On the islands of Bell and Mabel, in the clay underlying the basaltic sheet, J. Grant, a member of Leigh Smith's Expedition in 1880, found belemnites which were tentatively assigned to the Oxfordian (Markham 1881) or the Callovian by Newton & Teall (1897). Unfortunately, deposits of this age were not confirmed on Bell Island (Mikhailov 1979) or on Mabel Island, mapped by A.V. Ditmar in 1980.

Horn (1932) found belemnites in sandy clay exposed from 150 to 190 m a.s.l. on Alger Island, above the Lower Jurassic continental deposits, but did not give their age. The general stratigraphical situation suggests a Middle to Upper Jurassic age for these deposits.

M.G. Groswal'd (pers. comm. 1957) observed outcrops of siltstone with abundant belemnites below basaltic sheets on the Pila (Saw) nunatak on the east coast of Hooker Island. This siltstone probably represents the Callovian silt described above, which is also rich in belemnites on Cape Medvezhy on the west coast of Hooker Island.

Belemnites which cannot be definitely identified, but are clearly Jurassic in age (V.I. Bodylevsky, pers. comm. 1958), have been found on the beach on the east coast of Brice Island and at the foot of Cape Frankfurt on Hall Island. These may be Kimmeridgian or Volgian beds extending from neighbouring Berghaus Island. Fragments of cryptocrystalline limestone, i.e. probably the same rock which forms large disc-shaped concretions in the Callovian and lower Oxfordian "brown clay", were collected by A.S. Davydov (NIIGA), a geologist who briefly visited the southwest coast of MacNulty Island, 2–3 km south of the southern tip of Cape Hofer, during a cruise by the "Nikolai Kolomeitsev" in 1976.

Correlation of the sections of Middle to Upper Jurassic deposits (Fig. 3.4.4) allows us to estimate their total thickness as 550 m. However, inadequate data are so far available on the structural geology of Franz Josef Land, including sections that have been studied (such as Berghaus Island and Cape Hansa), and the complex faulting of relatively recent age implies that further studies would provide not only more precise data on the stratigraphy and thicknesses of such sections, but also permit us to discover unknown sections of Middle to Upper Jurassic deposits.

3.5 CRETACEOUS

Both Lower and Upper Cretaceous deposits occur on Franz Josef Land. The Lower Cretaceous consists of (i) mainly terrigenous marine and continental deposits of Berriasian-Barremian age, and (ii) a sedimentary-volcanic sequence divided into the Barremian-lower Aptian Tikhaya Bay

Fig. 3.4.12

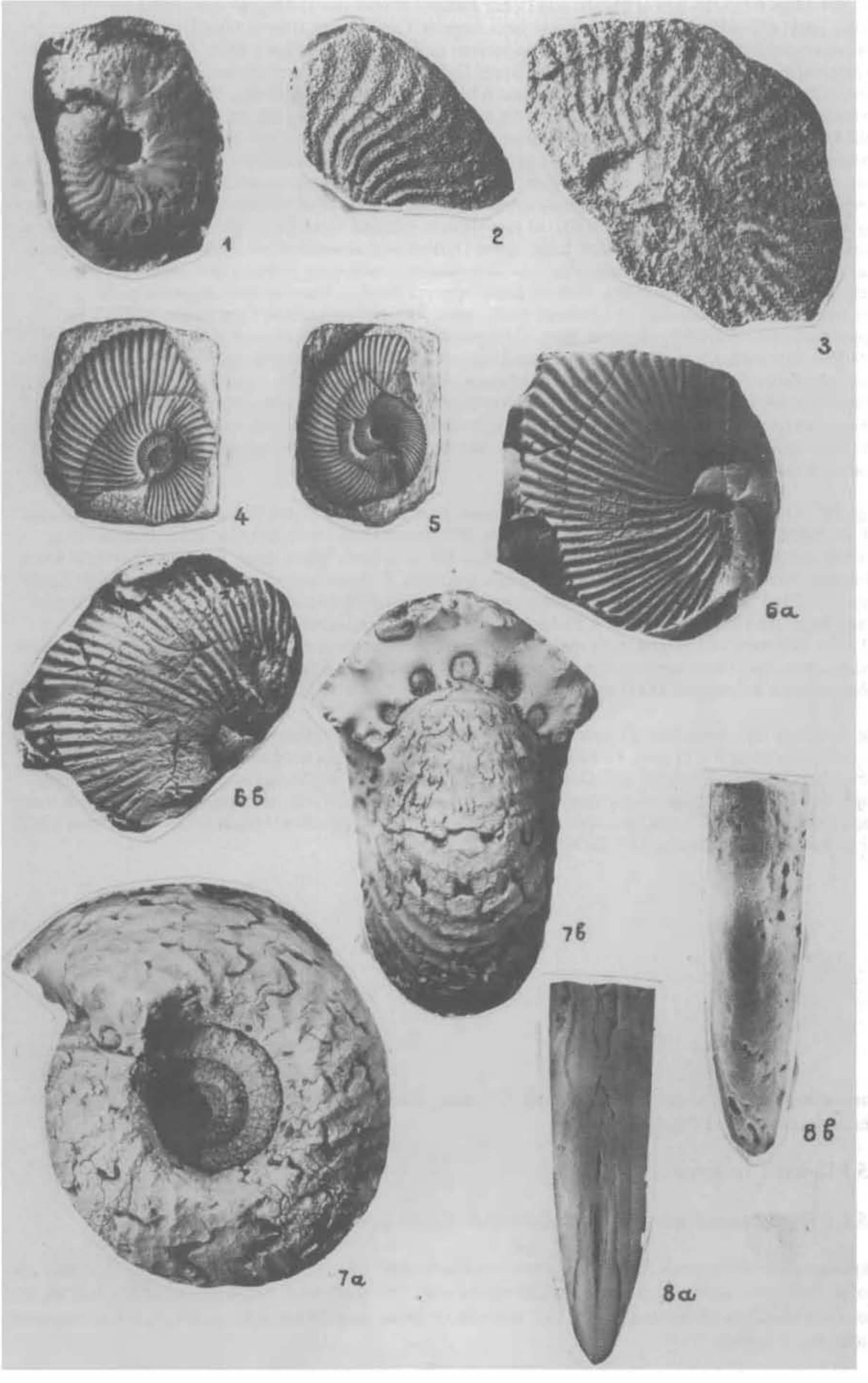


*Fig. 3.4.13 (p. 67).*Selection of Middle and Upper Jurassic ammonites 1) *Longaeviceras* cf. *keyserlingi* (Sok.), spec. 489–452, sample 309–15, side view, imprint, Cape Fiume, Champ Island, upper Callovian *Longaeviceras keyserlingi* zone. 2a, b) *Longaeviceras* ex gr. *keyserlingi* (Sok.), spec. 489–409, a) side view, b) external view, Cape Hofer, Wilczek Land, upper Callovian *Longaeviceras keyserlingi* zone. 3) *Cardioceras (Cardioceras)* cf. *percaelatum* Pavl., spec. 489–411, side view, Cape Hofer, Wilczek Land, lower Oxfordian *Cardioceras percaelatum* zone. 4–5a, b) *Cardioceras (Cardioceras)* cf. *cordatum* (Sow.); 4) spec. 480–432, side view, 5a, b) spec. 489–410, a) side view, b) apertural view, Cape Hofer, Wilczek Land, lower Oxfordian *Cardioceras cordatum* zone. 6a, b) *Quenstedtoceras (Quenstedtoceras) holtedahli* (Salf. et Freb.), spec. 489–405, a) side view, b) external view, Cape Hofer, Wilczek Land, upper Oxfordian *Quenstedtoceras lamberti* zone of western Europe or *Eboraciceras subordinarium* zone of Siberia. 7a, b and 8a, b) *Eboraciceras mologae* (Nik.); 7a, b) spec. 489–402. a) side view, b) external view, 8a, b) spec. 489–404, a) side view, b) external view, Cape Hofer, Wilczek Land, upper Oxfordian *Quenstedtoceras lamberti* zone or *Eboraciceras subordinarium* zone. 9a, b) *Amoeboceras (Amoeboceras) alternans* (Buch.), spec. 489–419, a) side view, b) external view, Cape Hofer, Wilczek Land, upper Oxfordian *Amoeboceras alternans* zone. 10) *Amoeboceras (Prionodoceras) freboldi* Spath., spec. 489–425, side view, Cape Hofer, Wilczek Land. Upper Oxfordian *Amoeboceras ravni* zone. 11) *Amoeboceras (Prionodoceras)* cf. *ravni* Spath., spec. 489–416, side view, Cape Hofer, Wilczek Land, upper Oxfordian *Amoeboceras ravni* zone. 12a, b) *Amoeboceras (Amoebites) alticarinatum* Mesezhn. et Romm., spec. 4/12049, a) side view, b) external view, Cape Hofer, Wilczek Land, lower Kimmeridgian *Amoeboceras kitchini* and *Rasenia* spp. beds. Middle Jurassic ammonites from Cape Fiume, Champ Island (Yefremova et al. 1983) and Callovian and Oxfordian ammonites (Meledina et al. 1979) are housed in the Museum of the Institute of Geology and Geophysics, Siberian Branch, Russian Academy of Sciences.

Fig. 3.4.14 (p. 68). Selection of Upper Jurassic ammonites from Cape Hofer, Wilczek Land. 1a, b) *Zonovia* aff. *sachsi* Mesezhn., spec. 12/12049, a) side view, b) external view, lower Kimmeridgian *Amoeboceras kitchini* and *Rasenia* spp. beds. 2) *Rasenia (Rasenia)* aff. *inconstans* Spath., spec. 6/12049, side view, lower Kimmeridgian *Amoeboceras kitchini* and *Rasenia* spp. beds. 3) *Amoeboceras (Euprionoceras) kochi* Spath., spec. 11/12049, side view, upper Kimmeridgian *Amoeboceras decipiens* and *Amoeboceras kochi* zones of Franz Josef Land and Spitsbergen. 4, 5) *Amoeboceras (Hoplocardioceras) decipiens* Spath.; 4) spec. 8/12049, side view of a fragment, 5) spec. 9/12049, side view, upper Kimmeridgian *Amoeboceras decipiens* and *Amoeboceras kochi* zones of Franz Josef Land and Spitsbergen. Kimmeridgian ammonites (Mesezhnikov & Shulgina 1982) are deposited in the Museum of VNIGRI.

Fig. 3.4.15 (p. 69). Selection of Upper Jurassic (Tithonian/Middle Volgian) ammonites. 1, 2) *Dorsoplanites* sp. (aff. *triplex* Spath.); 1) spec. 13/12049, side view, Cape Hofer, Wilczek Land, 2) spec. 14/12049, side view, Cape Lamont, Wilczek Land, *Dorsoplanites* spp. beds. 3) *Dorsoplanites* sp. indet., spec. 15/12049, Cape Hofer, Wilczek Land, *Dorsoplanites* spp. beds. 4) *Crendonites*(?) sp. indet., spec. 16/12049, side view, Cape Lamont, Wilczek Land, *Dorsoplanites* spp. beds. Volgian ammonites (Mesezhnikov & Shulgina 1982) are deposited in the Museum of VNIGRI.

Formation and the upper Aptian-Albian Salisbury Formation. The Upper Cretaceous consists of Cenomanian marine deposits.

3.5.1 Lower Cretaceous

3.5.1.1 Terrigenous sequence – V.D. Dibner & N.I. Shulgina

Exposures of terrigenous strata of Berriasian-Barremian age are known from Capes Lamont and Hofer (Wilczek Land), Cape Fiume (Champ Island), the southwest coast of Salisbury Island, and the islets of Klagenfuhrt and Alger. Comparison of these limited sections suggests a total apparent thickness of 150 m.

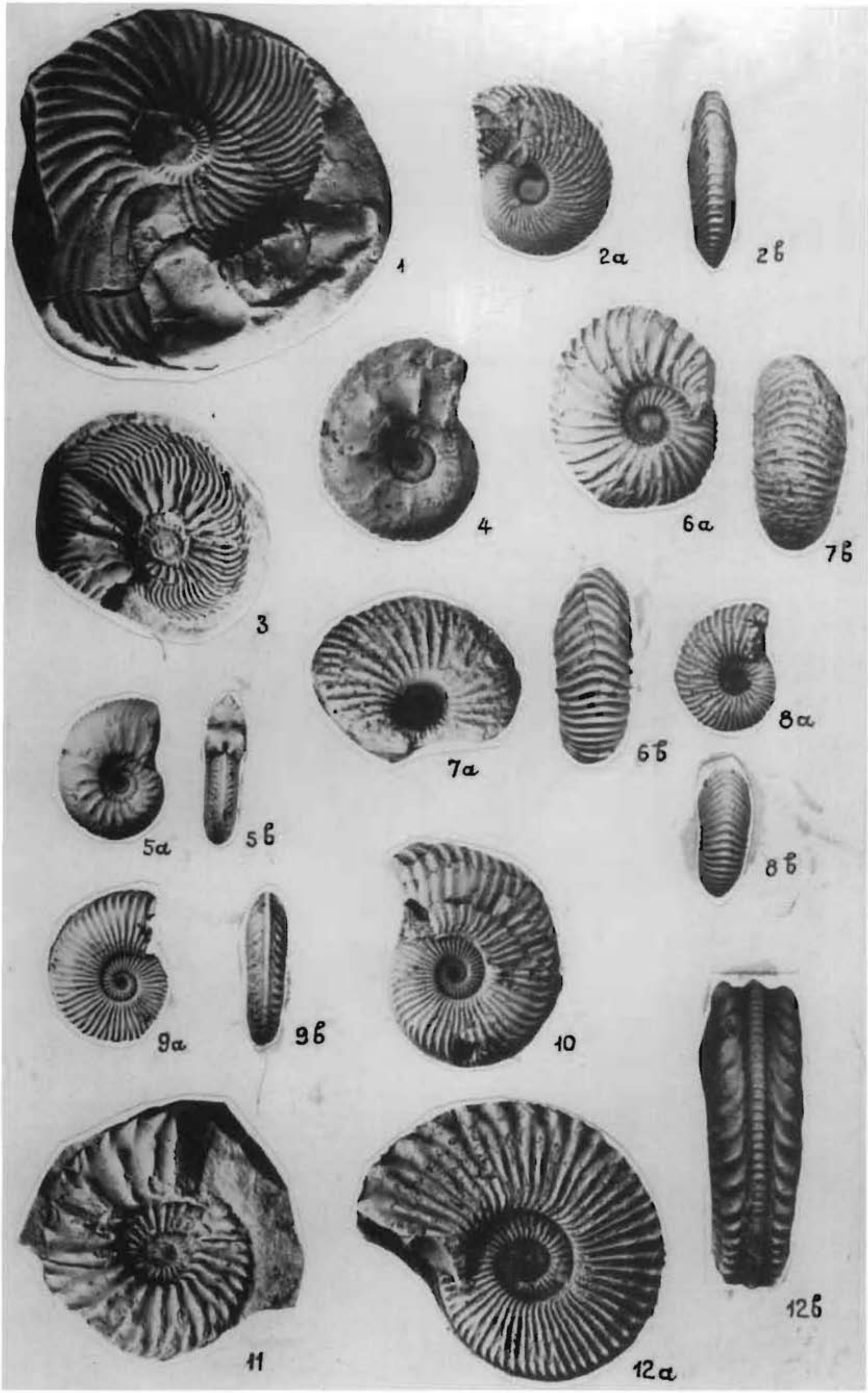


Fig. 3.4.13

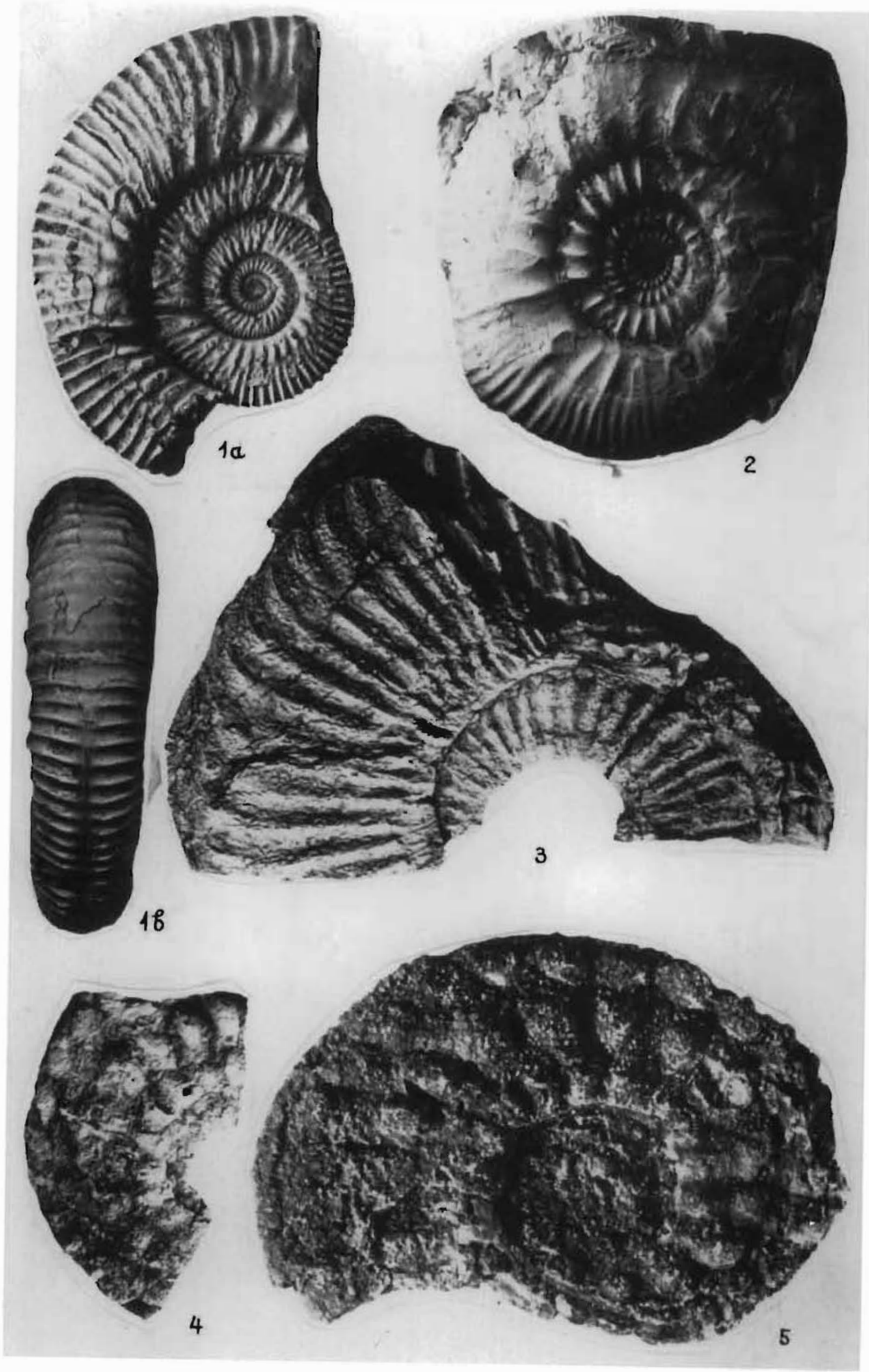


Fig. 3.4.14

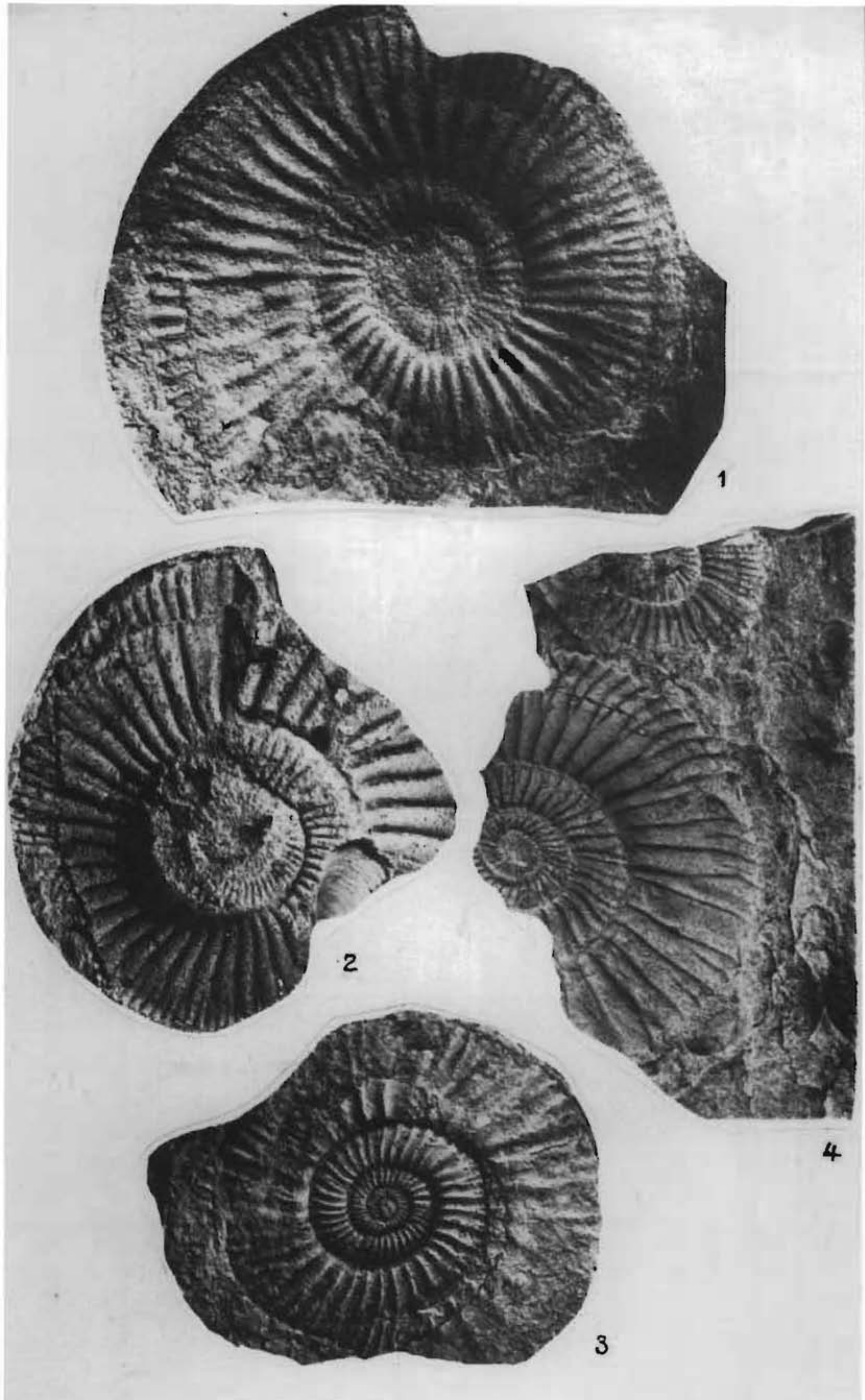


Fig. 3.4.15

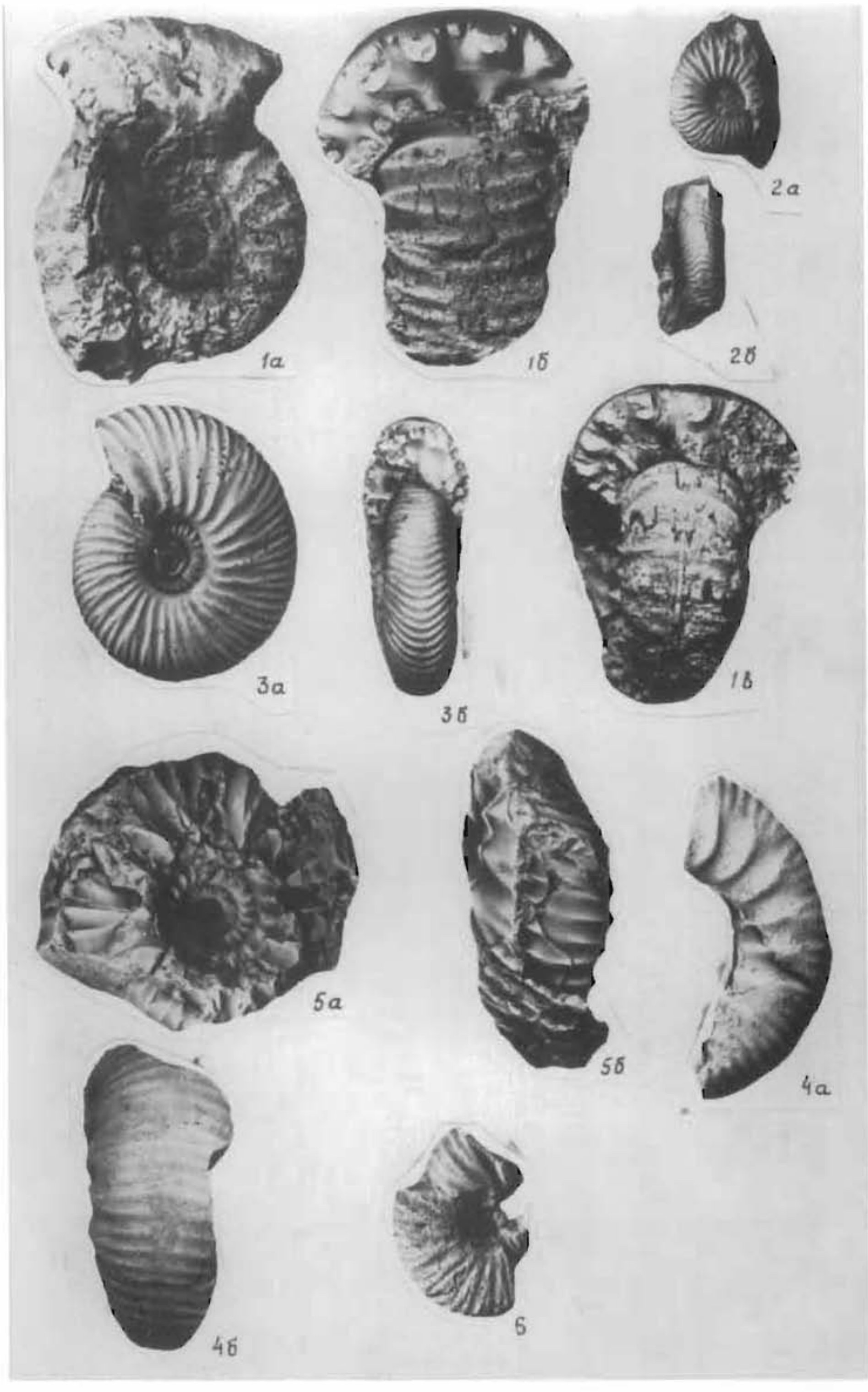


Fig. 3.4.16 Selection of Lower Cretaceous ammonites from Klagenfuhrt Island collected by O.V. Kirillov (unpubl. manus.). 1a, b) v. *Temnophychites* (Russanova) cf. *diptychus* (Keys.), spec. 20/12049, a) side view, b) apertural view, lower Valanginian, probably *Temnoptychites syzranicus* zone of Siberia. 2a, b) *Surites* sp. juv., spec. 21/12049, a) side view, b) external view, Berriasian. 3a, b) *Borealites antiquus* (Jeletzky), spec. 22/12049, a) side view, b) apertural view, Berriasian. 4a, b) *Temnoptychites (Temnoptychites)* aff. *triptychiformis* (Nik.), spec. 23/12049, a) side view, b) external view, lower Valanginian. *Temnoptychites syzranicus* zone of Siberia. 5a, b) *Temnoptychites* (Russanovia) aff. *diptychus* (Keys.), spec. 24/12049, a) side view, b) external view, lower Valanginian *Temnoptychites syzranicus* zone of Siberia. 6) *Surites* sp., spec. 25/12049, side view, fragment, Berriasian. Berriasian and Valanginian ammonites (Shulgina & Burdykina 1992) are housed in VNII Okeangeologia.

Lower Berriasian

At Cape Lamont on Wilczek Land, the middle Volgian "light sand" is disconformably overlain by the uppermost part of this sequence, which begins with an 8 m thick unit of silt with large loaves of calcareous sandstone. This is overlain by light-grey and light-yellow sands, which locally show horizontal lamination. The total thickness is 95 m (Shulgina & Burdykina 1992). The basal silt yielded *Buchia unschensis* (Pawl.) and *B. uncitoides* (Pawl.), indicating the Buchia beds, corresponding to the lower half of the Berriasian. This may equate with the *Hectoroceras kochi* zone recognised on the Russian plate and in the northern Urals and Siberia, as well as in England and east Greenland. The silt and sand have also yielded a miospore assemblage with typical Lower Cretaceous spores, such as *Lycopodiaceae, Selaginellaceae, Osmundaceae*, *Pelletieria* sp. and *Coniopteris* sp., as well as pollen of *Ginkgo elongata* K.-M., *Pinuspollenites* sp. and *Taxodiaceae* (*Cupressaceae*) identified by V.V. Pavlov.

Berriasian-Valanginian(?)

Berriasian-Valanginian(?) strata have been recognised at Cape Lamont, Cape Fiume and Inaccessible Rocks.

At Cape Lamont, this unit consists of variegated clay and silt which disconformably overlie the lower Berriasian rocks. It is composed of thinly interbedded, variegated, carbonaceous clay and silt which readily becomes fragmented and has thin lenses of coal, sand coated by a sooty film, and sandstone with intercalations of conglomerate (Shulgina & Mikhailov 1979, Shulgina & Burdykina 1992). The apparent thickness is 50 m. The deposits have yielded miospore assemblages, including spores of *Lycopodium* sp., *Selaginella* sp., *Osmunda jurassica* K.-M., *Anemia* sp., *Pelletiera* sp. and *Coniopteris* sp. of Early Cretaceous appearance, and pollen of *Ginkgo elongata* K.-M. and *Taxodiaceae* (*Cupressaceae*). According to V.V. Pavlov (pers. comm. 1978), this poor assemblage probably corresponds to the Berriasian-Valanginian.

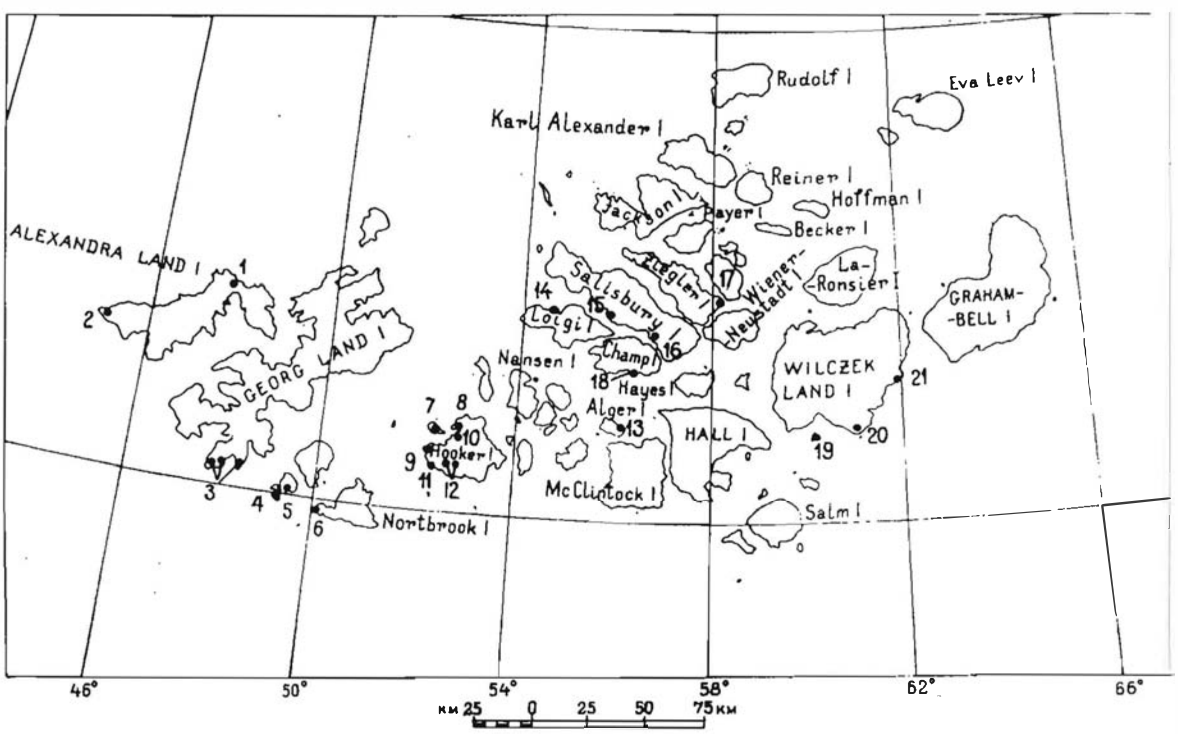


Fig. 3.5.1 Location of Lower Cretaceous sections described in the text. 1 Nagurskaya borehole and 2 Cape Mary Harmsworth, Alexandra Land, 3 southern capes of George Land, 4 Bell Island, 5 Mabel Island, 6 Cape Flora, Northbrook Island, 7 Scott-Keltie Island, 8 Cape Sedov and Mount Ciurlionis, 9 Cape Dundy, 10 Cape Medvezhy, 11 Cape Ugolny, 12 Kirov and Tass Nunataks, Hooker Island, 13 Cape Dzegudze, Alger Island, 14 Cape Petigaks, Luigi Island, 15 Cape Kavagli, 16 Inaccessible Rocks, Salisbury Island, 17 Cape Washington, Ziegler Island, 18 Cape Fiume, Champ Island, 19 Klagenfuhrt Island, 20 Cape Hofer and 21 Cape Lamont, Wilczek Land.

At Inaccessible Rocks on Salisbury Island, the base of the unit lies below sea level. Otherwise, both there and at Cape Fiume on Champ Island, the unit consists of a moderately variegated alternation of terrigenous and tuffaceous deposits, which at Cape Fiume can be seen to disconformably overlie the Oxfordian clay. The unit is composed of intercalated sand, clay and mudstone. Subordinate clayey tuffite and lithoclastic tuff form sporadic beds, up to 10–15 m thick. The mudstone and tuff contain fragments of charred wood, and the tuffite includes lenses of hard coal, up to 1.0 m thick. From these deposits, V.V. Pavlov separated similar miospore assemblages to those found in the equivalent strata on Cape Lamont (A.V. Ditmar, pers. comm. 1981).

A section on the northeast coast of Klagenfuhrt Island was examined in 1974 by O.V. Kirillov (pers. comm. 1975). At the base of the sea cliff, he observed an apparent thickness of 25–30 m of sand with concretions of arenaceous limestone (up to 0.5 m across) containing ammonoids, belemnites and pelecypods. Among these, N.I. Shulgina identified *Cylindroteuthis* ex gr. *antiquus* Jeletzky and *Surites* spp., indicating the beds of the same names in the lower half of the Berriasian (these directly overlie the beds containing *Buchia incitoides* and *B. unschensis*). *Temnoptychites (Russanovia)* cf. *diptychus* (Keys.), *Buchia keyserlingi* (Lah.) and *B. sibirica* were also found, indicating the lower Valanginian *Temnoptychites diptichus* beds. This sandstone was overlain by basaltic sheets interlayered with coal-bearing deposits of the sedimentary-volcanic sequence.

Valanginian-Hauterivian

At Cape Hofer on Wilczek Land, fragments of siltstone were found by L.P. Pirozhnikov in 1957 in talus below outcrops of basalt. The siltstone had been contact metamorphosed by an underlying basaltic sheet and bore imprints of the brackish-water pelecypods *Cyrena* cf. *venulina* Martins. and *C.* cf. *uvatica* Dunk. which, according to G.G. Martinson (pers. comm. 1958), indicate the Valanginian-Hauterivian (Dibner 1961c, d, 1970).

Hauterivian-Barremian

At Cape Dzegudze on Alger Island, terrigenous deposits occur from 234 to 269 m above sea level, where they are overlain by basaltic sheets. They overlie beds with belemnites (which cannot be precisely dated, but which, as shown above, are known to occur in beds no younger than the Valanginian in Franz Josef Land). The unit consists of a 35 m thick bed of partly red sand and sandstone with a thin seam of brown coal at the base. The sandstone contains imprints of leaves, among which Florin (1936) identified *Sphenobaiera* sp., a ginkgoaceous plant typical of the Hauterivian-Barremian assemblage of plant fossils studied by Florin from deposits interlayered with basaltic sheets on the islands of Northbrook, George Land and Bell.

3.5.1.2 Sedimentary-volcanic sequence – V.D. Dibner

The sedimentary-volcanic sequence rests with a major unconformity on dissected Triassic-Jurassic rocks and, in places, on Neocomian beds. More or less complete marker sections occur on Alexandra Land, the southern capes of George Land, the islands of Bell and Mabel (southwest coast), the Cape Flora area on Northbrook Island, the islands of Hooker, Scott-Keltie and Brady, the capes of Petigaks (Luigi Island), Fiume (Champ Island) and Washington (Ziegler Island), and at Cape Kavagli and Inaccessible Rocks (Salisbury Island).

Tikhaya Bay Formation Barremian-lower Aptian

From 0 to 283 m in the Nagurskaya borehole (drilled for coal) on Alexandra Land, tuffaceous and terrigenous deposits alternate with nine sheets (10–71 m thick) of porphyritic plagioclase and plagioclase-pyroxene basalts. They rest with a major unconformity on the upper Ladinian terrigenous beds. The drilling confirmed the earlier assumption by I.V. Shkola that the two upper and thickest basaltic bodies (intervals 0–71 and 74–114 m) were formed by a series of thin sheets lying directly one upon the other. This is shown by drilling sludge which contains fragments of vesicular basalt, typical of the upper, scoriaceous margins of basic lava. Terrigenous beds were found in the intervals 71–74, 114–118, 135–138, 160–164, 192–195, 214–215 and 252–256 m where drilling sludge contained pieces of basalt and tuff alternating with pieces of mudstone and smaller fragments of coaly shale and, less commonly, coal. A K-Ar age determination on one of the uppermost basaltic sheets (sampled at a depth of 49 m) gave 120 ± 8 m.y., indicating late Barremian (Kovaleva & Piskarev 1977, Tarakhovsky et al. 1983). Neither macroscopic plant remains nor miospores were found in the sludge.

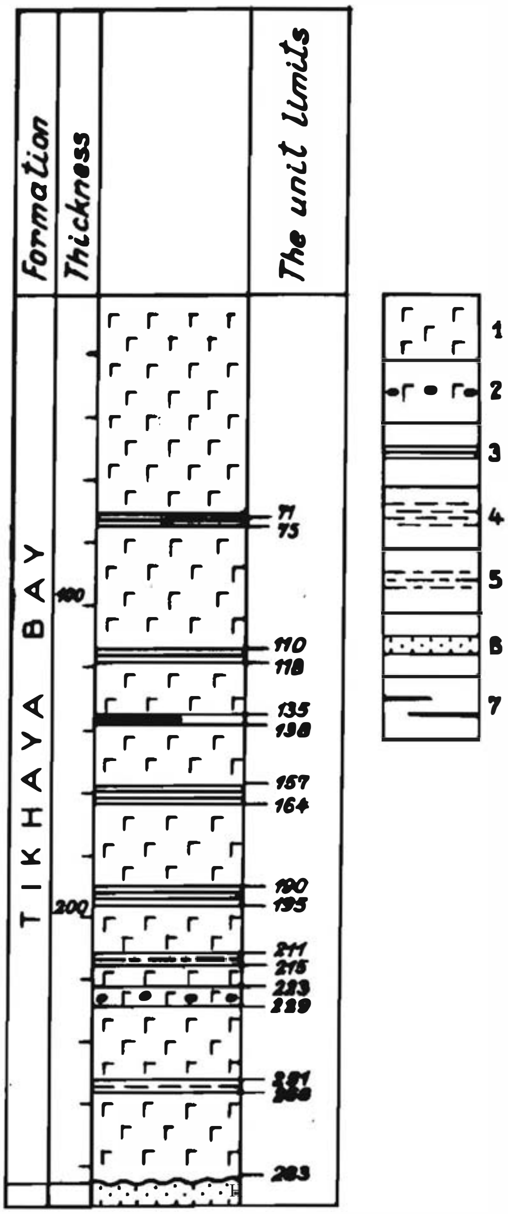


Fig. 3.5.2 Lower Cretaceous rocks in the Nagurskaya borehole on Alexandra Land (according to I.V. Shkola).
1 basalt, 2 coarse-grained quartz dolerite, 3 mudstone, 4 silty mudstone, 5 clayey siltstone, 6 sandstone, 7 brown coal.

At Cape Mary Harmsworth, the western point of Alexandra Land, Spizharsky (1937a, 1947) found a fossilised fir cone, wood and trihedral needles, typical of firs, in a fragment of silicified coal in rock debris weathered from basaltic sheets. Fedin (1943) identified the cone as a new species, *Papaninia involucrata* Fedin, and the wood as *Pityoxylon eiggense* (Whit.) Krischt. Taking into account that three related conifers could not have grown together, Fedin believed that the cone, wood and needles belong to a single species, resembling *Elatides curvifolla* (Dunk.) Nath. of Hauterivian-Barremian age. This agrees with the Barremian age determined radiometrically for the upper sheet.

Depressions, about 50–60 m deep, mainly eroded in Liassic sand and sandstone were observed by V.D. Dibner on the north coast of Tikhaya Bay in 1957. They were filled by 8–10 basaltic flows separated by beds of silty-psammitic tuff ranging in thickness from 1–2 to 10–15 m. A trunk of charred and unevenly burnt (xylainised and locally vitrinised) wood was exposed when part of the lowest tuff bed was removed. Similar thin flows occur on the surface of Upper Jurassic deposits at the foot of Cape Medvezhy (south coast of Yury Bay), at Cape Frankfurt on Hall Island, and elsewhere. About 10 basaltic sheets, locally separated by beds of silty-psammitic and agglomeratic tuff, generally directly overlie an erosion surface of pre-Cretaceous rocks whose depressions are levelled off by basaltic flows. Beds of normal sedimentary rocks (silt, clay, carbonaceous shale, brown coal, etc.) are also present from the lowermost part of the sequence, gradually replacing the tuffaceous rocks as the interbasaltic beds upwards. In many places, the sheets occur one upon the other, in which case the boundaries between them are drawn at amygdaloidal and scoriaceous surfaces, at weathering crusts at the top of the sheets, and on their chilled, near-basal part which commonly contains fragments of fossilised wood.

On Cape Sedov and Cape Medvezhy, these basaltic flows are overlain by basaltic sheets which are locally interlayered with 5–15 m thick beds of silt, clay, carbonaceous shale, brown coal and basaltic tuff (Fig. 3.5.3). At Cape Medvezhy, weathering crusts define the boundaries between some sheets.

The following is a composite section (from the base up) based on partial sections measured at Cape Medvezhy by V.D. Dibner in 1953 and 1957 at a number of localities separated by faults:

1. Thin basaltic flows, separated by similar sills. Apparent aggregate thickness 15 m. Numerous fragments of carbonised Lower Cretaceous wood, *Keteleerioxylon arcticum* Shilkina (Shilkina 1960, 1967), found at an adjacent locality on the cape, were probably derived from this part of the section.
2. Talus, 30 m
3. Porphyritic basaltic sheet; 32 m
4. Fragmented, chocolate-coloured siltstone; 3 m
5. Talus, 10 m; fragments of calcinised wood and debris of silty tuff with charred plant detritus were found in the upper part
6. Porphyritic basaltic sheet; apparent thickness 8 m. The upper part is heavily weathered to a depth of 1 m
7. Talus, 9 m
8. Compact, bright yellow clay with relict basaltic textures representing the uppermost part of the weathering crust that began in the upper part of Bed 6; apparent thickness 2 m (total thickness of the weathering crust, including the part hidden by talus, is 12 m)
9. Brown seat-earth and dull coal, passing into silty carbonaceous shale; 2 m
10. Carbonaceous silty shale, 0.5 m; contains poor imprints of leaves, as well as miospores. According to V.D. Korotkevich (pers. comm. 1958), the pollen is dominated (72%) by conifers (*Podozamites* sp., *Protopicea mesophytica* Pokr., *P. biangulina* (Mal.) *arctica* K.-M. and *Pinus* of the subgenus *Diploxylon*, etc.); spores (22%) are solely of ferns, mainly from the families *Cyatheaceae* and *Osmundaceae*, which she thought indicated the Aptian.
11. Basaltic tuff; 1 m
12. Porphyritic basaltic sheet; 30 m
13. Sedimentary and tuffaceous deposits; 5 m
14. Porphyritic basaltic sheet; 20 m
15. Sedimentary and tuffaceous rocks; 3 m
16. Basaltic sheet; 17 m
17. Basaltic sheet; apparent thickness 15 m.

The total thickness of this section is 195 m.

The thin flows in the lower part permit this section on Cape Medvezhy to be correlated with the Cape Sedov section, also on Hooker Island, and with sections on Mount Ciurlionis and near the Voronin glacier studied by N.P. Lupanova in 1932 (Lupanova 1953), as well as with outcrops in the Cape Dundy area (Fig. 3.5.2).

In 1980, A.N. Tarakhovsky showed that the Tikhaya Bay Formation on Cape Dundy is composed of three units consisting mainly of basaltic lava, which overlie Upper Jurassic clay. The lower unit starts with a 2.5 m thick tuffitic breccia which is usually rich in silicified wood, and this is followed by several basaltic sheets with an aggregate thickness of 25 to 65 m. The middle unit starts with carbonaceous mudstone, up to 3.5 m thick, which is succeeded by five basaltic sheets, partly separated by terrigenous beds, one of which yielded fossilised wood, *Keteleerioxylon arcticum* Shilk. (Shilkina 1960, 1967). The middle unit is 25–90 m thick. The upper unit starts with tuff (3.0 m), which is overlain by a sheet of porous basalt. The aggregate thickness for all three units varies from 75 to 180 m (Tarakhovsky et al. 1980). In agglomeratic tuff (apparent thickness 1.5 m) underlying the lowermost basaltic sheet at Cape Dundy, Lupanova (1953) found (in 1932) plant remains in which V.D. Prinada (in 1933) identified imprints of fern fronds (*Polypodites arctica* Pryn. and *Cladophlebis haiburnensis* (Lindl. et Hutt.) Brongn., the conifer, *Pityophyllum staratschini* Heer, and the *Ginkgoales*, *Phoenicopsis angustifolia* Heer. These, as well as *Pityophyllum longifollum* Heer, *Ginkgo lepida* Heer, identified by V.D. Prinada in 1925 from M.A. Pavlov's collection, are stored at the Chernyshev Central Geological Museum, St. Petersburg. These identifications were confirmed by Sveshnikova & Budantsev (1969). These plant fossils are in samples of silty tuffaceous shale, probably collected by M.A. Pavlov in talus at Cape Sedov where the Russian Polar Expedition overwintered in 1913–1914. A fragment of calcinised wood, assigned by Shilkina (1960, 1970) to *Cupressinoxylon diskoense* Walton, was found here on Mount Ciurlionis by V.D. Dibner.

At Cape Flora on Northbrook Island a section from the lower part of the sedimentary-volcanic sequence, reliably identified by its content of ferns, *Ginkgoales* and conifers, was described by Nansen (1900). It overlies the Callovian marine deposits and occurs 172–330 m above sea level.

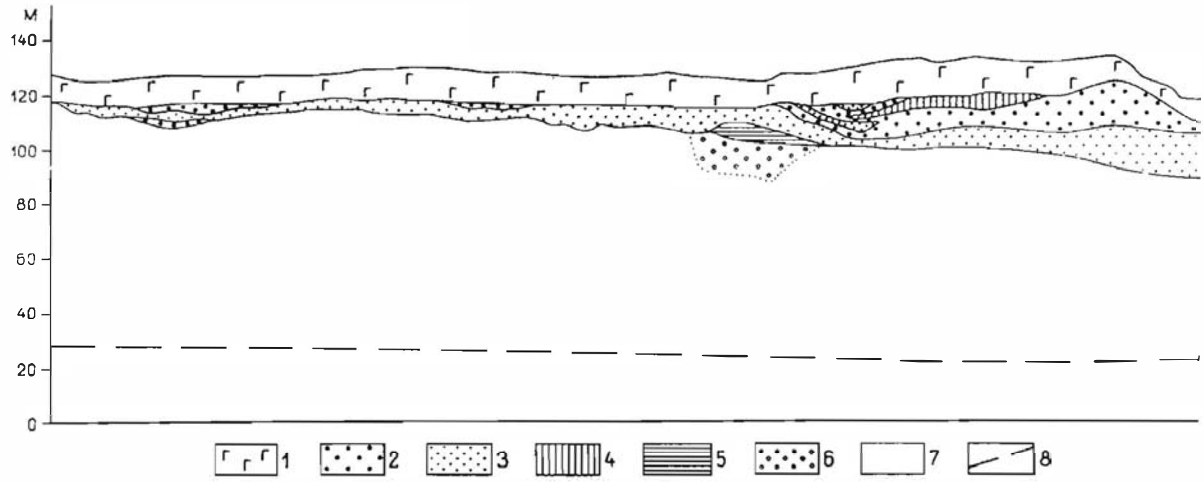


Fig. 3.5.3 North coast of Tikhaya Bay where the base of the Tikhaya Bay Formation is exposed (locality 307, 1957). 1 basaltic sheets, 2 basaltic flows, 3 volcanic tuff, 4 Lower Cretaceous silty clay, 5 Callovian silty clay, 6 Lower Jurassic psammite, 7 talus, 8 rear edge of 30 m terrace.

From the base up it consists of:

1. First basaltic sheet; 2 m
2. Clay, highly baked in its upper part, transforming it into shale to a depth of 0.25 m; 1 m
3. Second basaltic sheet; 24 m
4. Shale, 2 m. Imprints of the ferns *Cladophlebis* sp., *Thyrsopteris* sp., *Asplenium petrushinense* Heer and *Onychiopsis* sp. and leaves of *Ginkgoales*, first identified by A. Nathorst (in Nansen 1900) and later revised by Florin (1936) as *Ginkgo polaris* Nath., *Czekanowskia rigida* Heer and *Culgoweria mirabilis* Florin. Thin slabs of shale with imprints of leaves may also have been collected here by I. Vogan; Whitfield (1906) referred the leaves to *Stephanophyllum*(?), *Podozamites*(?), *Ginkgo polaris* Nath. and *G. sibirica* Heer. Judging by the height above sea level, a seam of brown coal, 0.5–1.0 m thick, found by the Fiala Expedition (1907) 200 m above sea level, also belongs to this horizon.
5. Third basaltic sheet; 42 m
6. Brown sandstone (0.6 m thick) with leaves of *Thyrsopteris* sp. and *Ginkgo* cf. *polaris* Nath. (according to A. Nathorst (in Nansen 1900) and with fragments of wood *Cupressinoxylon koettlitzi* Seward (identified by A. Seward). Imprints of *Ginkgoales* leaves found by G. Horn in talus of sandstone, probably also derived from here. Among these, Florin (1936) identified, *G.* cf. *polaris* Nath., *Czekanowskia rigida* Heer, and *Sphenobaiera horniana* Florin which was a new genus and species.
7. Fourth basaltic sheet; 16 m
8. Fifth basaltic sheet; 13 m
9. Micaceous quartz sand with fossilised wood; 1.0 m
10. Sixth, seventh and eighth basaltic sheets, 12, 17 and 19 m thick, respectively.

Sheet 8 is overlain by ice. The aggregate apparent thickness of the section is 158 m.

Sample C.P.3, collected by Nansen about 200 m above sea level from talus of grey-green mudstone from the bed separating the first and second basaltic sheets, was analysed for miospores by Smelror (1986). The spectrum is dominated by bisaccate pollen (75%). By analogy with an assemblage characterising association F of the Helvetiafjellet Formation in Kong Karls Land (Bjærke 1977), a combination of bisaccate pollen with rare spores suggests the Barremian. Miospore spectra from samples C.P.2 and C.P.1 characterise the shale between the basalts exposed at 210 m above sea level. These spectra are also dominated by bisaccate pollen (80–85%), but the lack of characteristic spores prevents a dating that is more precise than Lower Cretaceous.

On the southern capes of George Land and Bell Island, the Leigh Smith (1880–82) and especially Jackson (1894–97) Expeditions found a Ginkoaceous flora in talus. From these collections, initially examined by E. Newton (Newton & Teall 1899), Florin (1936) distinguished four new species and genera of *Ginkgoales*, namely, *Arctobaiera fletti, Stephenophyllum solmsi, Windwardia crookallii* and *Sphenobaiera paucinervis*, and the conifer, *Elatides curvifolia* (Dunk.) Nath. (pine family), a characteristic form for the Hauterivian-Barremian of Spitsbergen.

On Mabel Island, Upper Triassic sand is disconformably overlain by twelve basaltic sheets varying in thickness from 5 to 45 m (apparent thickness of the uppermost sheet). The sheets alternate with thin (4–10 m) beds of terrigenous deposits, such as sandstone, sand and laminated, locally carbonaceous siltstone with carbonised remains of trunks and branches, and imprints of leaves. A miospore spectrum from these deposits contains:

1. dominants: *Osmundaceae* (28%)
2. subdominants: *Podocarpus* sp. (10%), *Lygodium* sp. (9%), *Ginkgo* sp. (6%), *Pseudopicea* (6%)
3. accessories: *Plicifera* sp. (4%), *Bennettitales* sp. (4%), *Picea exilioides* Bolch. (4%), *Coniopteris* sp. (3%), *Dicksonia densa* Bolch. (3%), *Podozamites* sp. (3%), *Paleopicea* sp. (3%)
4. sporadic: *Selaginella rotundiformis* K.-M., *Cibotium junctum* K.-M. and *Cheiropleura compacta* Bolch.

By analogy with the assemblage he found in the variegated unit at Cape Lamont, V.V. Pavlov (pers. comm. 1982) assigned this assemblage to the Berriasian-Valanginian. Unfortunately, this conclusion conflicts with the stratigraphical position of the samples, which definitely belong to a younger sedimentary-volcanic sequence. The aggregate thickness of its lower part, tentatively placed in the Tikhaya Bay Formation by V.D. Dibner, is 207 m (Tarakhovsky et al. 1980).

At Cape Fiume on Champ Island and Inaccessible Rocks on Salisbury Island, basaltic sheets with interbedded terrigenous rocks, equivalent to the Tikhaya Bay Formation, rest conformably on variegated tuffaceous-terrigenous rocks. Basaltic sheets, 3 to 12 m thick, dominate. The lowest one is fine grained. The other five sheets consist of plagioporphyritic basalt with amygdaloidal margins accounting for 10% of each sheet. The terrigenous beds alternating with the basalts mainly occur in the northwestern part of Inaccessible Rocks where, in the upper part of the formation, they form units up to 20 m thick consisting of yellow-grey, locally cross-laminated sand, silt, clay and mudstone with lenses (up to 0.7 m) of thinly flaggy coal. The deposits contain silicified and pyritised fragments of trunks up to 0.4 m across. Sixteen samples taken from both sections yielded sporadic spores of *Coniopteris* sp., *Leiotriletes* sp. and *Plicifera* sp. (family *Gleicheniaceae*), and pollen of

Fig. 3.5.4 Basaltic sheets forming the coast of Geographers Bay, George Land. Photo: V.D. Dibner, April 1953.

Picea sp., *Pinus sacculifera* (Mal.) K.-M., *Podocarpus* sp. and *Araucariaceae*, typical of the Lower Cretaceous. The thickness of the formation here varies, reaching a maximum of 130 m (A.V. Ditmar, pers. comm. 1981).

From talus under the lower basaltic sheet at Cape Washington on Ziegler Island, V.K. Razin in 1957 collected thin slabs of siltstone showing imprints of long, narrow leaves. These were assigned by N.D. Vasilevskaya (pers. comm.) to *Ginkgoales* of the *Phoenicopsis* type, similar to *Windwardia crookallii*. As stated above, this and other species of *Ginkgoales* on the southern capes of George Land and Bell Island were found together with the conifer *Elatides curvifolia*, which is typical for the Hauterivian-Barremian of Spitsbergen (Florin 1936).

Based on data from the Nagurskaya borehole and Cape Flora, the Tikhaya Bay Formation is estimated to be about 380 m thick.

Salisbury Formation Aptian-Albian

The top of an up to 50 m thick, regionally developed sill is the tentative lower boundary of the Salisbury Formation. On Hooker Island and other central and westerly islands in Franz Josef Land, this formation consists of sand, sandstone, siltstone, clay, carbonaceous mudstone, brown coal and other sedimentary rocks interlayered with basaltic sheets which resemble those in the underlying formation. The terrigenous deposits differ from similar beds in the Tikhaya Bay Formation by being still thicker (up to 60 m) and having a higher coal content.

Cape Kavagli on Salisbury Island has a type section which was first investigated in 1957 by V.K. Razin (Dibner 1961c, d, 1970) and then studied in detail in 1960 by two palaeobotanists (Sveshnikova & Budantsev 1969). From the base up, this type section consists of:

1. Talus of basalt; 30–50 m
2. Doleritic sill; apparent thickness 60 m
3. Small outcrops of coarse-grained tuffitic sandstone, partly concealed by talus; apparent thickness 16 m
4. Carbonaceous shale with poorly preserved leaf imprints; apparent thickness 0.5 m
5. Sandstone, light grey, fine grained, with abundant leaf imprints; apparent thickness 1.5 m
6. Talus of basalt and sandstone with abundant fossilised wood and coal fragments; 8 m
7. Brown, semi-lustrous coal with two siltstone partings (0.1 m each); apparent thickness 1.2 m
8. Talus of basalt; 60 m
9. Basaltic sheets (seen from a distance)

Fig. 3.5.5 Basaltic sheets of the Tikhaya Bay Formation crowning the southeast coast of Ziegler Island. Photo: V.K. Razin, 1957.

The total apparent thickness is about 120 m.

The light-grey sandstone of unit 5 contains various plant remains. V.K. Razin collected leaf imprints, assigned by V.D. Vasilevskaya (pers. comm. 1958) to *Taeniopteris*, a new species similar to *T. junboana* Krysht. from the Lower Cretaceous of the southern part of the Primorski area in southeastern Siberia, the Aldan River basin, the Ogoner-Yuryakh Formation of the lower Lena River basin, and the Lena-Khatanga basin where the species is typical for the lower Aptian. Very rich collections were made from the same horizon in 1960 by Sveshnikova & Budantsev (1969). They identified and described, in particular, the following species (including several new ones): *Nilssoniopteris polymorpha* Sveshn., *Tyrmia solsberiensis* Budants. et Sveshn., *Heilungia*(?) cf. *aldanensis* Samoyl., *Podozamites* cf. *angustifolius* (Eichw.) Heer, *Cephalotaxus microphylla* Sveshn. et Budants., *Florina borealis* Sveshn. et Budants., *F. brewifolia* Sveshn. et Budants., and *Pityophyllum lindstoemi* Nath. etc. They considered the assemblage to be Aptian-Albian. A spore-pollen assemblage was separated by M.A. Sedova from two samples from the same unit. Conifer pollen dominated, but it also included pollen of *Taxodium, Bennettitales, Cycadaceae* and *Ginkgoales*, sporadic *Cedrus* and *Caytoniales*, spores of *Sphagnum*, *Lycopodium*, *Selaginella* (film-like perispores), *Coniopteris, Gleichenia* and various specimens of the family *Schizaceae* (*Anemia, Mofria, Lygodium*). In her opinion (Dibner & Sedova 1959, Sveshnikova & Budantsev 1969), the assemblage indicates the Lower Cretaceous.

At Cape Petigaks on Luigi Island a similar section was described by V.K. Razin (Dibner et al. 1962) 20 km west of Cape Kavagli where the following was found, in ascending order:

1. Talus of basalt and sandstone; 60 m
2. Composite bed of brown coal containing a 15 cm siltstone intercalation; apparent thickness 1.1 m; the bed is probably coeval with that at Cape Kavagli (unit 8)
3. Talus; 8 m
4. Vitrinised brown coal; apparent thickness 0.5 m
5. Talus; 4.5 m
6. Brown coal; apparent thickness 0.4 m
7. Talus; 5.0 m
8. Brown coal; apparent thickness 0.3 m
9. Talus; 20 m
10. Basaltic sheets (seen from a distance); apparent thickness 200 m.

These two sections suggest that the apparent thicknesses of separate units of the coal-bearing sedimentary deposits in the Salisbury Formation reach 20 m, whereas judged by talus they are probably 60 m. The total apparent thickness of the formation is between 240 and 300 m.

On Cape Ugolny and Cape Kirov on Hooker Island, Ivanov (1935) and Spizharsky (1937a, 1947) reported exposures of basalts and sedimentary rocks which are tentatively considered coeval with the rocks at Cape Kavagli and Cape Petigaks. At Cape Ugolny (= Coaly), the following beds occur above the sill:

1. Basaltic sheet; 12 m
2. Dark grey and brown, thinly platy clay and shale containing silicified wood and imprints of *Asplenium* sp., *Equisetum* sp., *Phoenicopsis angustifolia* Heer and *Podozamites gramineus* Heer leaves; a 3 m thick seam of brown coal, whose upper 20 cm is altered to ash, occurs in the lower part of the unit; total thickness 10 m
3. Basaltic sheet; apparent thickness 9 m

Unit 2 is probably also exposed to the north at Cape Kirov where Spizharsky (1937a, 1947) described 12 m of slate containing a seam of brown coal (0.5 m) and located between two basaltic sheets. This outcrop also contains a younger, brown coal seam (1.5 m) and underlying clay (0.3 m).

In "Central Land" on Alexandra Land, three basaltic sheets occur which seem to be younger than the above strata, as suggested by their content of organic remains. Their total thickness is about 60 m and they dip very gently northwestwards, the uppermost sheet gradually passing below sea level. The best outcrops occur in the south, on the east coast of Dezhnev Bay. Thin slabs of marly slate preserved in hollows eroded in the scoriaceous amygdaloidal margin are found in debris eroded from the capping basaltic sheet. Near the north coast, a few metres of sand occur above the basalts. A spore and pollen assemblage of Aptian-Albian age, including conifer pollen

(64%) represented by *Pinus* subgen. *Haploxylon* sp., *P. sacculifera* (Mal.) K.-M., *Protopicea mesophytica* Pokr. and *P. biangulina* (Mal.) var. *arctica* K.-M., and spores of ferns (*Coniopteris* and *Hausmannia*) (16%), was discovered by V.D. Korotkevich in the lower part of the sand. Fragments and entire trunks of vitrinised and silicified wood, i.e. relics of a forest destroyed by an even younger volcanic sheet, now removed by erosion, also occur in the block field. From the collection made here by V.D. Dibner, Shilkina (1960, 1967) described new genera and species that are characteristic for the Lower Cretaceous (*Keteleerioxylon arcticum* Shilk., *Paleopiceoxylon arcticum* Shilk. and *Podocarpoxylon sciadopityoides* Shilk.), as well as *Xenoxylon barberi* (Seward) Krausel, dated to the Lower Jurassic, and *X. latiporosum* (Cramet) Gothan and *Protocedroxylon gregussii* Shilk., that are known to appear in the Upper Triassic.

On Scott-Keltie Island, two basaltic sheets with a total apparent thickness of about 50 m form the youngest part of the Salisbury Formation. A large fragment of compact, yellowish-brown saprolite with abundant imprints of long, narrow leaves of the conifer *Pityophyllum lindstroemi* Nath. was found in 1957 by V.D. Dibner on a beach ridge at the eastern end of Scott-Keltie Island. According to N.D. Vasilevskaya (pers. comm. 1958), the species is characteristic of the Ogoner-Yuryakh Formation of the Bulun area (lower Lena River basin) and the Uky Formation of the lower Olenek River basin. Since the Ogoner-Yuryakh Formation was deposited in the period covering the second half of the Aptian to the beginning of the Albian, this *P. lindstroemi* occur-rence probably suggests the same age range.

The aggregate apparent thickness of the Salisbury Formation is about 250 m, and that of the entire Barremian-Albian sedimentary-volcanic sequence is about 530 m.

Summary of the biostratigraphy of the sedimentary-volcanic sequence

Sveshnikova & Budantsev (1969) believed that the flora of the Tikhaya Bay Formation was Neocomian, characterised in Franz Josef Land by a predominance of pteridophytes and *Ginkgoales*, an abundance of conifers and a complete absence of cycadophytes. Based on their own collec-

Fig. 3.5.6 Basaltic sheets and interlayered sandy deposits of the Salisbury Formation at Cape Kavagli. Photo: V.K. Razin.

tions, and revision of specimens studied by Nathorst, Florin and Prinada, they listed the following Neocomian plants: *Polypodites arctica* Pryn., *Cladophlebis haiburnensis* (Lindl. et Hutt.) Brongn., *Ginkgo polaris* Nath., *G. lepida* Heer, *Stephenophyllum solmsii* Florin, *Windwardia crookallii* Florin, *Culgoweria mirabilis* Florin, *Czekanowskia rigida* Heer, *S. horniana* Florin, *Pityophyllum longifolium* (Nath.) Moell, best seen on the islands of Northbrook, Hooker and Bell and the southern peninsulas of George Land. Although Sveshnikova and Budantsev believed that these plants characterise the entire Neocomian, the finds of the conifer *Elatides curvifolia* at Cape Mary Harmsworth and the accompanying, coeval *Ginkgoales* (*Windwardia crookallii* and others) allow us to leave out the Berriasian and Valanginian, the more so because, as shown in section 3.5.1.1, only marine deposits of this age are found in Franz Josef Land. Moreover, the radiometric age of 120 m.y. obtained on the uppermost sheet in the Nagurskaya borehole corresponds to the Barremian. This, together with the Aptian spore and pollen assemblage from the terrigenous bed within the thick series of basaltic sheets at Cape Medvezhy, suggests a Barremian-Aptian age range for the Tikhaya Bay Formation. According to Sveshnikova & Budantsev (1969), the flora from the Salisbury Formation is Aptian-Albian. This period is noted for a dramatic enrichment in large-leaved cycadophytes (until recently only known from southern regions), as well as large-leaved conifers, together forming a conifer-cycadophytic forest formation. In their monograph, Sveshnikova & Budantsev (1969) presented a list of Aptian-Albian plants, mostly from collections they made at Cape Kavagli (see above). The same age is suggested by a miospore assemblage from a thin sand overlying the upper basaltic sheet in "Central Land" on Alexandra Land, and by the *Pityophyllum lindstroemi* Nath. leaves (late Aptian-early Albian) from basaltic talus on Scott-Keltie Island. An Aptian-Albian age for the Salisbury Formation needs no special discussion.

3.5.2 Upper Cretaceous

Lower Cenomanian – V.D. Dibner
An outcrop of Upper Cretaceous deposits on the south coast of Hoffmann Island, so far the only definite one known in Franz Josef Land, was measured by V.D. Dibner in 1957 giving, from the base upwards:

1. Medium to thickly flaggy quartzitic sandstone with muscovite, ranging from medium- to coarse-grained varieties at the base of the visible section to fine-grained rocks at the top. The lower part contains unidentifiable twigs and leaves, as well as a rich fauna of bivalves in which N.I. Shulgina identified the Cenomanian form, *Oxytoma pectinata* Sow., and distinguished a new species, *Nuculana* sp. nov. Apparent thickness 15 m.
2. Poorly cemented siltstones, dirty grey, 20 m in apparent thickness. Few fossils, represented by *Schloenbachia* aff. *subvarians* Spath which, according to N.I. Shulgina (in Dibner 1970), is the ammonite that characterises the lower Cenomanian *Varians* zone in east Greenland.

Fine-grained, siliceous-quartzose sandstone (about 10 m in apparent thickness) forms Cape Sugrobov at the east end of Hoffmann Island and is probably coeval with the lower part of this sequence. In the sandstone, N.M. Bondarenko (pers. comm. 1958) found sporadic, poorly preserved spores, similar to those of *Selaginella, Lycopodium triquetrum* and *Protopinus*, as well as conifer pollen (*Podocarpus flava* K.-M. and *Podopicea* sp. of the subgenera *Haploxylon* and *Diploxylon*) and pollen of angiosperms such as *Carya* and *Extratripollenites*. Bondarenko tentatively assigned these to the Lower Cretaceous, but E.N. Kara-Murza (pers. comm.) believes that the presence of *Carya* and *Extratripollenites* pollen instead suggests the lower Cenomanian. This agrees well with the presence of faunistically dated lower Cenomanian deposits a few kilometres west of Cape Sugrobov. The Cenomanian deposits of Hoffmann Island are horizontal or dip gently southwards. Their total apparent thickness is about 35 m.

3.6 TERTIARY – V. D. DIBNER

Danian

The foraminfera *Bulimina pseudopuschi* Subbutina, *Globigerina trivials* Subbotina, *Stensioina caucasica* (Subbotina) and other forms typical for the Danian were found in 1958 by Shchedrina (1958) 60–70 m down in a core taken in the northern part of the St. Anna Trough (80° 31' N and 70° 31.5' E) during a cruise with the "Sadko" in 1936. The tests were thought to have come from some nearby islands, as suggested by the presence in the core of Recent, and not only local, relatively abyssal species *(Saccorhiza romosa abyssalica* Stsched. and *Reophax nodulosus* Brady), and also *Elphidium gorbunovi* Stsched., a typical shallow-water form. However, if the bottom current in the St. Anna Trough was, as now, from north to south when the ooze containing the fossils was accumulating, islands, or preferably sites where submarine erosion was taking place, on the eastern periphery of Franz Josef Land are the most probable provenance for Danian deposits.

Eocene

A reworked assemblage of pelagic diatoms, identical to the "Lower Tertiary diatoms in the deposits of the Simbirsk Region", was identified by Grunow (1884) from collections trawled by the Austro-Hungarian Polar Expedition (Payer 1876) south of Wilczek Island, between 79° 00' to 79° 15' N and 59° 15' to 63° 22' E at dephts ranging from 100 to 500 m. The presence of *Chaetoceras* (cf. *clavigerum)* is known to place this assemblage in the Lower Eocene (Kamyshlov after Zhuze 1948). According to Grunow (1884), the Lower Eocene of Denmark (Moler Formation) has as similiar assemblage of diatoms, *Chaetoceras* being the most characteristic genus. Lower Eocene diatoms are probably being washed out south of Wilczek Island, where the water is relatively shallow. The find of a single, reworked foraminfer, *Truncorotalia velaschensis* (Cushman), in the core taken in the St. Anna Trough (Shchedrina 1958) should also be noted. This is an index fossil for the Lower Eocene of the northern Caucasus and Mexico, and was found in the bottom sediments (at 27–33.3 cm) together with the definitely sublittoral form *Elphidiella gorbunovi* Stsched. According to Schchedrina (1958), this suggests their redeposition following erosion of pre-Quaternary deposits on adjacent land or, in the present author's view, on shallow-water banks and their submarine slopes on the northeastern periphery of Franz Josef Land.

Miocene (?)

1.5 km northwest of the end of Cape Sugrobov, the Cenomanian sandstone (see above) gives way to, probably overlying (the contact is concealed by talus and till), cleaved, and locally even folded, light-grey siltstone, silty mudstone and fine-grained sandstone (Dibner 1961b). The sandstone cement contains scattered microscopic remains of charred plant debris which gives rise to a microlamination. In places, the siltstone and mudstone display thin (up to 4 cm) intercalations of polymict conglomerates. The talus, moreover, contains thin slabs of dark-grey bioclastic sandy limestone composed of finely broken coquina (partly replaced by calcite) and tiny pebbles of calcareous siltstone cemented with arbillaceous-carbonate material. The total apparent thickness of the deposits is about 25 m (Fig. 3.6.1). The sequence is overlain by a thin layer of subglacial till.

N.M. Bondarenko (pers. comm. 1959) separated 170 grains of pollen (85.5%) and spores (14.5%) from samples of these rocks. Conifer pollen accounts for 60% of the spectra. It includes *Pinus* of the subgenus *Diploxylon* (49%) and *Picea* sp. (9.5%); pollen of *Podocarpus, Clyptostrobus*(?) and *Psophosphaera* is sporadic. Angiosperms, together accounting for 24%, are represented by *Betula* (12.5%), *Alnus* (5.6%), *Corylus*(?) (2.5%), *Juglandaceae* (1.5%), *Tilia* (1.5%) and sporadic *Fagaceae.* A few grains of *Ericaceae* and *Compositae* were also found. Spores of *Sphagnum* sp. (8%), *Polypodiaceae* (5%) and single examples of *Botrichium*(?) and *Equisetum*(?) were also found. According to E.N. Kara-Murza and N.M. Bondarenko (pers. comm. 1959), the presence in all the samples of *Corylus*(?) and *Juglandaceae,* as well as *Fagaceae* and *Glyptostrobus*(?), probably indicates the Pliocene.

However, data now available on the biostratigraphy of the Neogene of the Arctic continental margin indicate that the deposits on Cape Sugrobov probably belong to the continental Lower to Middle Miocene. This is suggested by the presence of coarse clastics and carbonised plant detritus, as well as the composition of miosphere spectra with dominance of pine and spruce pollen, subdominance of *Fagaceae* and *Betula,* and with *Alnus* and *Corylus* as associated species. The species mentioned are typical for the Lower to Middle Miocene, elsewhere on the Barents-Kara plate.

Fig. 3.6.1 Outcrop of Neogene flaggy silty mudstone at Cape Sugrobov, Hoffmann Island. Photo: V.D. Dibner.

Attempts to find microfauna in the deposits at Cape Sugrobov were fruitless. The broken shells are probably remains of a littoral fauna and, hence, these Miocene deposits may have accumulated in an offshore basin, the calcareous bands indicating a warm temperate climate.

3.7 QUATERNARY – V. D. DIBNER

With few exceptions, flat, low-lying, ice-free parts of Franz Josef Land have a very thin cover (up to 1–2 m, occasionally more) of late-Pleistocene and Holocene deposits, mostly forming marine terraces (strandlines). Some glacial deposits also occur, but they have almost entirely been deposited below sea level. The Quaternary deposits are composed of locally derived material, as shown by their angular to sub-angular shape and the close similarity between their petrology and mineralogy and the underlying, pre-Quaternary rocks.

Three divisions of Quaternary deposits are recognised here: 1) upper Pleistocene glacial and fluvioglacial drift (related to the last stage of the continental glaciation of the archipelago), 2) marine deposits forming Holocene terraces, 3) recent continental deposits.

3.7.1 Upper Pleistocene glacial and fluvioglacial drift

Among the oldest deposits recognised is glacial drift in the form of drumlinoid features up to 15–20 m high. They are common in "Central Land" on Alexandra Land and on the Armitage Peninsula on the adjacent part of George Land. This glacial drift is cut by recent glacier snouts and post-Pleistocene terraces are cut into it, suggesting that it is relatively old, as shown below. On smoother plateaus which show no glacial ploughmarks, such as Cape Nansen and Cape Johansen on George Land, and the capes of Stolbovoi, Schmarda, Heller, Sugrobov and others, glacial drift takes the form of sheets of till. Study of aerial photographs suggests that these are also widely developed on the Armitage Peninsula, southeast of the area with drumlinoid features.

The till mostly consists of broken stones and blocks, generally almost indistinguishable from products of frost weathering, but a few well-rounded boulders up to 1.5 m in diameter also occur. Hummocks a few metres high, very characteristic of ground moraine, occur here and there, such as in the middle of a glacial lake on Alexandra Land and on the Nansen Island plateau (Dibner & Zagorskaya 1954, Dibner 1958). In "Central Land" and at the west end of Alexandra Land (on Cape Mary Harmsworth), where the bedrock is only basalt, boulders and coarse gravel of granitic rocks, gneiss, quartzite, quartzitic sandstone and some dolomitic limestone, are present. This material may have been transported from Upper Triassic-Liassic conglomerates found on the southeastern islands. Such a northwesterly direction for glacial transport agrees well with the essentially northwesterly trend of the drumlinoids on Alexandra Land, although it cannot be ruled out that some of the drumlinoids are concealed doleritic dykes on the same trend, that have been smoothed by glacial erosion. Northerly boulder transport was determined on the eastern margin of Franz Josef Land where the author saw gravelly boulder clay, up to 3.0 m in apparent thickness, con-

Fig. 3.7.1 Varved glaciolacustrine silt, Hayes Island. Photo: V.D. Dibner.

taining boulders of quartzitic sandstone lying on the Neogene deposits of Hoffmann Island. The boulders characteristically contain garnets with a very high refractive index, which are otherwise only known in the Liassic sandstone on the east end of Becker Island, south of Hoffmann Island (Dibner 1962a). Another indication of northerly ice transport is the discovery of a granitic boulder by Payer (1876) on the basalt of Cape Germany (Rudolf Island) where it may have been transported from Upper Triassic-Liassic conglomerates known only from the area south of the cape.

As the distribution of erratics and the position of terminal moraines suggests a relationship between glacial drift and the melting of the ice sheet covering the whole of the archipelago, the author tentatively correlates them with the late-Sartan phase of the Valdayan/Zyryanka Glacial (= Weichselian), which has so far only been identified biostratigraphically on the Kanin Peninsula (Samoilovich et al. 1992).

In Romantikov valley on Hayes Island, M.G. Groswal'd and V.D. Dibner in 1957 observed varved deposits being washed out of the base of a marine terrace (Groswal'd 1963) (see section 3.7.2). They were composed of intercalated blue loam (about 3 cm thick) and light-orange sandy loam (about 8 cm thick), and had a total apparent thickness of about 6 m (Fig. 3.7.1). In some places, these typical glaciolacustrine deposits were observed on roches moutonnées of Upper Triassic sandstone. They are disconformably overlain by a thin (0.2–0.3 m) sheet of gravelly sand with many marine molluscan shells.

3.7.2 Holocene marine deposits

The proposed Holocene age is based on recent opinions that the Holocene epoch began 16,000 years ago (Zubakov 1986).

Upper terraces

In the western part of Franz Josef Land, on the rocky capes of such islands as George Land, Bell and Mabel, above a set of well-defined lower terraces (see below), Koettlitz (1899) recorded narrow platforms cut into the rock at heights of 50 to 250 m above sea level, and sometimes disappearing beneath glacier ice. They were otherwise covered by boulders and pebbles of local rocks, generally showing evidence of weathering. Seal and walrus bones were found on the plat-

Table 3.7.1. Species composition of the fauna in the deposits of the lower complex of raised beaches.

Ecological groups		Boreal	Arctoboreal															Essentially Arctic					Arctic						High Arctic	
Height of coastline (m a.s.l.) and number of localities with finds of fauna (numbers on the right) / Species composition		*Mya arenaria* L.	*Balanus balanus* L	*B. crenatus* Brugniere	*Puncturella noachina* (L.)	*Margarites cinereus* Couth.	*Buccinum fragilex* G. Sarr	*Natica clausa* (Brod. et Sow)	*Polynites pallidus* (Brod. et Sow)	*Sipha islandicus* Chemn.	*Astarte borealis* (Chemn.) f. *typica*	*A. borealis* (Chemn.) v. *placenta* Mørch	*A. compressa* (L.)	*Mya truncata* L.f. *typica*	*Mya truncata* L. v. *uddevalensis* Hancock	*Saxicava arctica* (L.) f. *typica*	*S. arctica* (L.) f. *pholadis*	*Trophonopsis clathratus* (L.)	*Plicifusus kreyeri* (Moll)	*Musculus discrepans* (Gray)	*Astarte montagui* (Dillw.) f. *typica* Jensen	*A. montaqui* (Dillw.) v. *warhami* Leche	*Buccinum groenlandicum* Chemn.	*B. hydrophanum* Hank. v. *elata*	*B. glaciale* L. f. *typica*	*B. tenue* Gray	*Neptunea borealis* (Phill.)	*Cyrtodaria curriana* Dunk.	*Serripes groenlandicus* (Chemn.)	Total number of species
0 – 2 m	1		+	+	+								+	+	+	+	+				+	+			+				+	12
	2		+	+	+								+	+	+	+	+				+	+			+	+	+		+	14
	3		+	+									+																	3
	5		+								+	+		+	+	+	+					+			+					9
	6		+									+		+	+	+	+					+			+					8
	8										+			+			+							+	+	+	+			7
	9										+				+															2
	12		+								+	+		+		+	+		+		+	+			+					10
	13		+								+	+		+		+	+		+		+	+			+					10
	15						+	+																	+					3
	17											+		+	+		+				+						+	+	+	8
	18											+		+	+		+				+				+		+	+	+	9
3 – 5 m	14										+			+													+			3
8 – 10 m	2													+		+														2
	5											+		+		+														3
	13										+			+			+							+	+	+	+			7
15 – 18 m	4	+		+						+						+											+			4
	8											+		+		+	+													4
	11							+	+		+	+		+		+	+	+		+	+		+	+	+			+	+	15
20 – 25 m	1										+				+															2
	7													+																1
	13					+					+				+	+														4
	16		+											+																2
35 – 40 m	3	+		+																										1
	11											+																		1
	19										+			+		+														3

Fig. 3.7.2 Terrace-like surface with patterned ground developed by solifluction on a thin layer of gravelly-loamy deposits at an altitude of 150–160 m on the Cape Sedov plateau. Photo: A.N. Radygin.

forms, and *Saxicava arctica* and *Mya truncata* shells were observed on Cape Sedov at a height of 150–160 m (Fig. 3.7.2). These platforms are assumed to have been formed by marine erosion, in common with plateaus up to 95–100 m above sea level on Hayes Island and Graham Bell Island. They, too, show no evidence of glaciation and, like any surface that is progressively rising from sea level, they are relatively highly dissected by radial fluvial drainage.

A C–14 age of around 7445 BP obtained from a 26 m high terrace in the lower complex (Groswal'd et al. 1973) can be used as a basis for estimating the age of these platforms. When age estimates are being extrapolated for the upper terraces it should be remembered that, like comparable terraces in Svalbard, these were raised from sea level 15–20 times faster than the lower terraces with an age of 8000–7000 years. Isostatic uplift of the archipelago to a height of about 100 m above sea level would require only 10,000–11,000 years (Groswal'd et al. 1973). The highest (250 m) strandlines are believed to be no older than the Holocene (i.e. 16,000 yrs.).

Intermediate terraces
In their surface features and the degree to which unconsolidated material is preserved, terraces eroded into the bedrock 35–40 m above present sea level are transitional between the upper and lower sets of strandlines. Occasional molluscs (Table 3.7.1) found there include *Astarte borealis* (Chemn.) var. *placenta* Morch., *Mya truncata* L., *M. arenaria* L., *Saxicava arctica* L. and *Balanus* sp. Bones of seals and whales, ancient driftwood (unknown at higher levels), and partially disintegrated algal peat were found on these terraces. Their faunal content and height allows them to be assigned to the onset of the Atlantic period (8000–7500 yr.).

Lower terraces
These terraces, situated between 25–20 m and 5–3 m above present sea level, have also been cut into the rock. They have a well-preserved, thin cover of unconsolidated beach deposits, chiefly sand, gravel and poorly rounded stones of mixed lithologies, and occasionally boulders and pebbles of basalt and dolerite. This material contains lithothamnium, coquina, marine vertebrate bones, driftwood, and lenses of algal peat and buried sea ice, as well as ice wedges. Beach ridges sometimes occur on the slopes or edges of the terrace scarps. In many places, lakes are ponded up by these ridges, and these were formerly lagoons. The maximum thicknesses, about 5 m and over, were recorded in ridges at the edges of the scarps.

The most clearly expressed strandline in Franz Josef Land is one at a height of 20–25 m. Its chiefly sandy deposits have yielded valves of *Astarte borealis* Chemn. f. *typica* Morch, *Mya truncata* var. *uddevalensis* Hancock and *Saxicava arctica* (L.) f. *typica*, sporadic gastropods (*Margarites (Pupillaria) cinereus* Couth.) and fragments of the loricae of *Balanus* sp. (Fig. 3.7.3). Partially preserved skeletons of Greenland whales have been found within and on the surface of this strandline (Fig. 3.7.4). On Hooker Island, Groswal'd (1963) found a partly buried trunk of driftwood which gave a C-14 date of 7445 ± 135 BP. This driftwood, located 25 m above sea level on the landward edge of the strandline at Cape Dundy, suggests that this strandline formed over a time span of 1000–1500 years, i.e. 6000–7500 years ago (Groswal'd 1963).

A strandline 15–18 m above sea level has a thin (0.2–0.3 m) cover of sand with numerous shells and pieces of ancient driftwood (Groswal'd 1963). This strandline often takes the form of a beach ridge on the slope of the 20–25 m terrace. The shells consist of a mixed assemblage of invertebrates (18 species) including a preponderance of arctoboreal forms such as *Balanus crenatus* Brugniere, *Natica clausa (Cryptonatica, Tectonatica)* Brod. et Sow., *Polynites (Eispira) pollidus, Sipho islandicus* Chemn., *Astarte borealis* f. *typica, A. borealis* var. *placenta* Morch., *Mya truncata* (L.) f. *typica, Saxicava arctica* (L.) f. *typica* and *S. arctica* (L.) f. *pholadis*, essentially arctic species such as *Trophonopsis clathratus* (L.), *Musculus discrepans* Gray, *Astarte montagui* (Dillw.) f. *typica* Jensen,, *Buccinum groenlandicum* (Chemn.), *B. hydrophanum* Hank. var. *elata, B. glaciale* L., *Neptunea borealis* (Phill.) and *Cyrtodaria curriana* Dunk., and the high-Arctic species *Serripes groenlandicus* (Chemn.). Whale bones are common on this strandline. On Hayes Island, the 15–18 m terrace is cut into roches mouttoneés formed of Triassic sandstone and overlying varved deposits (see section 3.7.1). A C-14 age of 5500 ± 235 BP. was obtained on algal peat on this strandline at Cape Nagursky on Alexandra Land (Groswal'd et al. 1964, 1973). This date suggests that the strandline formed during the climatic optimum (5000–6000 years ago), as corroborated by the faunal assemblage with its varied composition and abundance of arctoboreal invertebrates, which contrasts greatly with the very poor fauna in the overlying intermediate and upper strandlines.

A terrace situated 8–10 m above sea level is known from such islands as Hooker, Hayes, Hall, Graham Bell, Jackson, Luigi, Salisbury and Rudolf, but has been best studied in the northern part of "Central Land" on Alexandra Land. There, boulders and pebbles are mixed with red-brown clay originating as an ancient, lateritic weathering crust of basalt (see section 3.5). In places, the terrace is covered with algal peats, characterised by the development of patterned ground comprised of quadrilaterally-shaped polygons.

The deposits of the 8–10 m strandline contain a sparse invertebrate fauna of mainly arctoboreal and, less commonly, arctic character. On the coast of Dezhnev Bay (Alexandra Land), it consists solely of *Mya truncata* L. and *Saxicava arctica* L. which, together with calcareous crusts of *Lithothamnia* algae, form a 0.2–0.4 m thick layer. *Astarte borealis* (Chemn.) var. *placenta* Morch supplements these on the tombolo linking Rubini Rock to Hooker Island. Farther east on Hayes Island, these species, which are very typical for Franz Josef Land terraces, are supplemented by various arctic species of buccinums, such as *B. hydrophanum* Hank. var. *elata, B. glaciale* L. f. *typica* and *B. tenue* Gray; *Neptunea borealis* (Phill.) also belongs to this assemblage.

C-14 age determinations were made on two samples of driftwood from the surface of this 8–10 m strandline. The first sample, collected by V.D. Dibner in 1956 from the south coast of Alexandra Land (10 m above sea level), gave an age of 4250 ± 90 BP (Dibner 1961e). The second, taken by L.S. Govorukha in 1960 from a 10 m high terrace on the northeast coast of Hayes Island yielded a similar date of 4775 ± 135 BP (Groswa'ld et al. 1961). The close similarity of the dates suggests that it is valid to correlate the 8–10 m high strandlines on islands distant from each other in Franz Josef Land. (This does not include an older terrace belonging to the intermediate complex, whose isochronous surface inclines eastwards from Alexandra Land (35 m) to Graham Bell Island (5–8 m) (Groswal'd et al. 1973).) According to the Blitt-Sernander scheme, the period covered by these radiocarbon dates is the subboreal interval, a relatively cold interval following the climatic optimum, and this is consistent with the arctic fauna recorded above.

A 3–5 m high strandline is occasionally found. Near Capes Schmarda and Heller on Wilczek Land, it is composed of sand, gravel and poorly rounded dolerite pebbles. The deposits also occur on Cape Ostry Nos (Payer Island), Cape Pronosnoi (Bolshoi Komsomolsky Island), Yuzhny Oktyabryenok Island, and the Milovzorov skerries where there are 5 m high beach ridges. At Cape Pronosnoi, V.D. Dibner collected a poor fauna of arctic and arctoboreal species, namely, *Buccinum glaciale* L., *Astarte borealis* (Chemn.) f. *typica*, *Mya truncata* (L.) f. *typica* and *Neptunea borealis* (Phill.).

Driftwood from a 5 m high terrace on the north coast of Dezhnev Bay, Alexandra Land, yielded a C-14 age of 1550 ± 115 BP (Vinogradov et al. 1966), corresponding to the middle of the subatlantic period.

Recent beach ridges and beaches are composed of boulders and pebbles (locally only boulders, Fig. 3.7.5), cobbles and, less commonly, sand and silt, and are developed from the water's edge to 1.5–2.5 m above sea level. This beach is several kilometres wide on Graham Bell Island. The deposits contain an invertebrate assemblage dominated by arctoboreal forms such as *Balanus balanus* L., *B. crenatus* Brugniere, *Puncturella noachina* (L.), *Margarites cinereus* Couth., *Buccinum fragilex* G. Sarr, *Natica clausa* Brod. et Sow., *Polynites pallidus* (Brod. et Sow.), *Sipha islandicus* Chemn., *Astarte borealis* (Chemn.) f. *typica*, *A. borealis* (Chemn.) var. *placenta* Morch., *A. compressa* (L.), *Mya truncata* L. f. *typica*, *Saxicava arctica* (L.) f. *typica* and *S. arctica* (L.) f. *pholadis*. They are accompanied by essentially arctic species, namely, *Trophonopsis clathrutrus* (L.), *Plicifusus kreyeri* (Moll.), *Musculus discrepans* (Gray), *Astarte montaqui* (Dillw.) f. *typica* Jensen and *A. montaqui* (Dillw.) var. *warhami* Leche. A high-Arctic species, *Serripes groenlandicus* (Chemn.), was also found. On the whole, this assemblage shows an even greater diversity than that listed for the 15–18 m strandline. However, the complete lack of boreal species suggests that it is more cold-enduring.

3.7.3 Recent non-marine deposits

Glacial drift is represented by lateral, median and, relatively seldom, terminal moraines, as well as ground moraine.

Lateral and median moraines are formed where land ice forms pronounced ice streams, flowing slowly down either side of a nunatak or cape from which debris derived by weathering falls to form surface moraine. Such lateral moraines are particularly well seen alongside the Yury Glacier on Hooker Island, where they mark recent stages of glacier retreat. The oldest moraine there (Yury-1 stage in the scheme devised by P.A. Shumsky (pers. comm. 1950)) is a 10 m high ridge extending onto the tombolo linking the Rubini Rock to the main part of Hooker Island and traceable along the southern slope of the rock. Other ice streams on Hooker Island also have similar coastal and lateral moraines. Comparable features have also been observed on the islands of Nansen, Brady, Luigi, Salisbury, Hall and others in the central part of Franz Josef Land, as well as on Wilczek Land, i.e. on islands with the most highly dissected bedrock topography. Only a few glaciers and separate ice streams have terminal and ground moraines. Ice streams are rimmed by multiridged morainic ramparts consisting of rock debris, clay and blocks. At Cape Vasiliev and elsewhere, the space between the inner edge of the end moraine complex and the glacier front is filled by random conical hummocks of ground moraine which become more evident as the ice margin is approached. They appear as the ice melts back beyond accumulations of coarse material in the subglacial tunnels (Dibner & Zagorskaya 1954).

Recent fluvioglacial material forms outwash plains produced in summer by numerous streams

Fig. 3.7.3 Shelly debris on the surface of the 20–25 m terrace, northeastern part of Hayes Island. Photo: E.G. Yudovny.

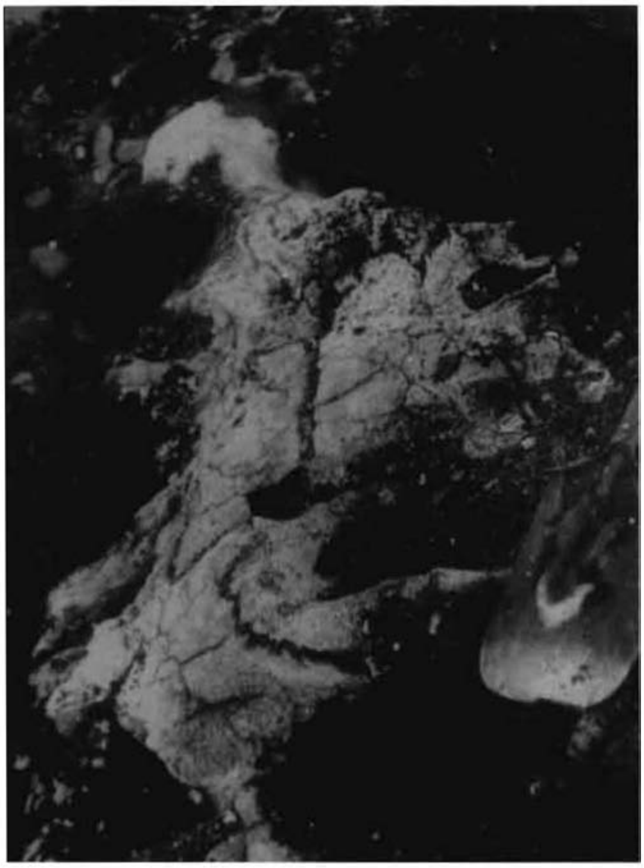


Fig. 3.7.4 Whale skull partly buried in sandy deposits of the beach ridge crowning the 25 m terrace on Alexandra Land. Photo: V.D. Dibner.

which repeatedly change their courses. The streams pour down the ice sheets and glaciers and, on their way to the sea, wash out and carry away material from recent and older moraines. The author has observed well-developed outwash plains on Alexandra Land and the Armitage Peninsula, where they are made up of silt with stones and boulders, as well as on the plateau of Cape Sedov (Hooker Island), the northern part of Nansen Island, along the south-eastern periphery of Hydrographers Glacier (Hayes Island), and elsewhere.

Recent glacial and fluvioglacial deposits are always related to simultaneously forming lacustrine deposits left by running water. These lakes and streams constitute an incipient drainage system fed by melting ice and snow, or merely snow. However, on Alexandra Land, the deposits do not differ from the fluvioglacial drift. In late July or early August, when the spring flood declines, accumulation practically ceases. Streams become a number of separate, small lakes located in topographic depressions such as rills ahead of the glacier snouts, and filled with silt and clay. Most of these ephemeral lakes disappear in early September. Thus, only flood-plain deposits form here, fluvial deposits, characteristic of stable streams, being unknown in such locations.

Alluvial deposits are laid down by streams on Graham Bell Island and Hayes Island and in some other similar locations where material on ground gradually rising from beneath sea level is dissected by a network of numerous, relatively stable streams which deposit most alluvium in their incipient deltas and foredeltas.

Fig. 3.7.5 Boulder beach on the south end of Arthur Island. Photo: V.D. Dibner.

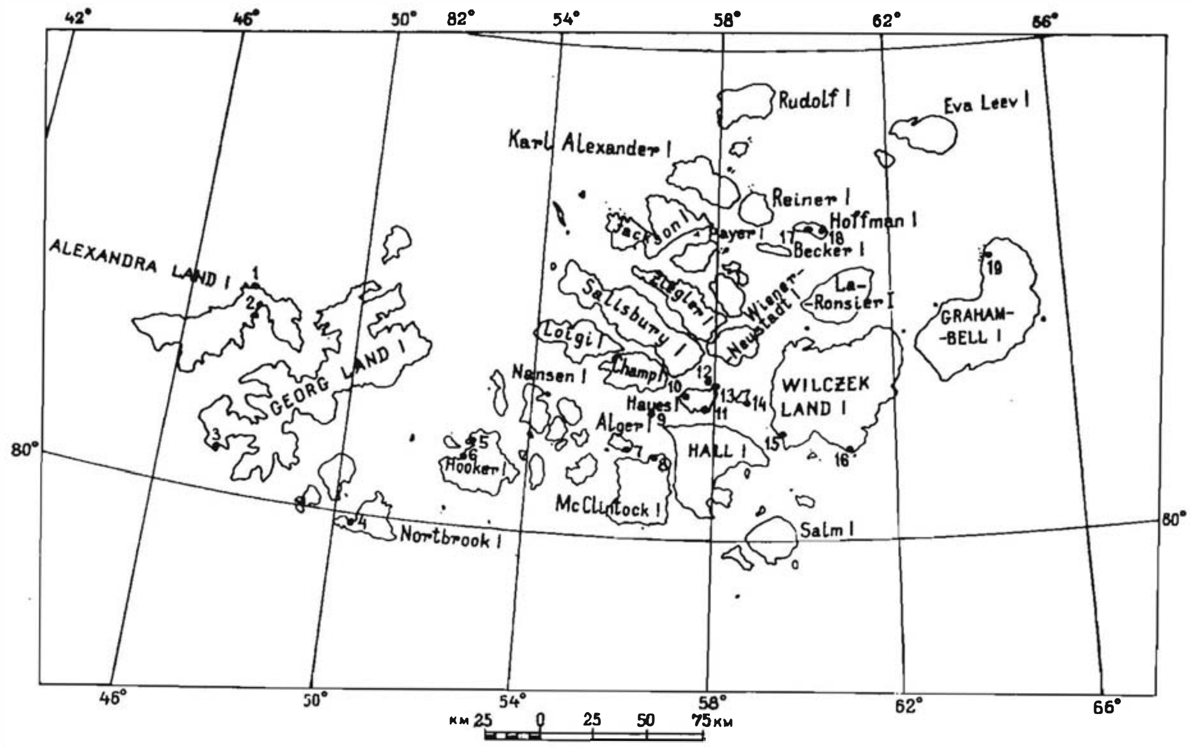


Fig. 3.7.6 Sites where invertebrate fauna were collected on the lower terrace. 1 Alexandra Land, north coast, 2 Alexandra Land, south coast, 3 Cape Crowther, George Land, 4 Wind Valley, Northbrook Island, 5 Tikhaya Bay, Hooker Island, 6 Cape Medvezhy, Hooker Island, 7 Alger Island, 8 Greely Bay, McClintock Island, 9 Newcombe Island, 10 Hayes Island, northwest margin, 11 Cape Ostantsovy, Hayes Island, 12 southeast coast of Salisbury Island, 13 northeast coast of Hayes Island, 14 Cape Pronosnoi, Bolshoi Komsomolsky Island, 15 Storm Bay, Wilczek Land, 16 Dowes Island. 17 Voronin land, Hoffmann Island, 18 Sugrobov land, Hoffmann Island, 19 Kholmisty Peninsula, Graham Bell Island.

Normal lacustrine sediments were found by L.S. Govorukha (Govorukha & Simonov 1965) on the floor of ancient lagoons now separated from the sea and transformed into freshwater lakes on the lower terraces. In particular, thin (under 0.5 m) silty and sandy sediment with sapropelic crusts occurs on the floor of Lake Kosmicheskoe (where the Druzhnaya Observatory and its equipment for studying the upper atmosphere was erected in 1957) on a 20 m high terrace at the northeast end of Hayes Island. Govorukha assigned these freshwater (as suggested by diatoms) sediments to the past 5000 years since they rest on a layer of barren deposits formed by ice-sheet melting during the Atlantic optimum (6200–5300 years ago). Silty sand containing brackish water and marine diatoms occurs at a greater depth. This sand was formed during earlier Atlantic stages, before the lagoon became fresh water 8000–6200 years ago (Govorukha & Simonov 1965).

Mass-movement (debris) deposits consist of stony and blocky material derived from the destruction of basalt and dolerite and by sand and clay deriving from outcrops of Mesozoic sedimentary rocks. On slopes composed of basaltic lavas or sills in the upper part and sedimentary rocks in the lower part, these sediments form a steep, talus-covered scarp. On the surface, the talus is usually composed of basalt and dolerite fragments which frequently entirely conceal not only bedrock, but also debris weathered from the sedimentary rocks. This has to be borne in mind when carrying out geological mapping of the islands. Mass-movement deposits include coarse fan material accumulating in the lower parts of small hollows and gullies dissecting slopes of sedimentary rocks.

Block fields are mainly formed on basaltic and doleritic plateaus devoid of glacial and marine deposits. They are composed of stony and blocky material mixed with gravel.

Eolian deposits are found here and there. On Graham Bell Island, even at minus 40 °C, the feet sink into quicksand which does not freeze entirely because of the permanent winnowing of sand from the Vasiliev Formation. In summer, this process sometimes becomes strongly pronounced. For instance, on a flight over Graham Bell Island in August 1953, a sandstorm with clouds of fine sand and dust falling on the nearest glaciers was seen by A.N. Radygin (pers. comm. 1953).

4. SEDIMENTOLOGY

Brief data on the sedimentology of the Proterozoic and Carboniferous strata of Franz Josef Land were included in sections 3.1 and 3.2. This chapter chiefly concerns the mineral and chemical composition and the sedimentary structures of the Mesozoic strata, which are the most widespread and best studied part of the Franz Josef Land succession.

4.1 SEDIMENTOLOGY OF TRIASSIC DEPOSITS RECORDED IN BOREHOLES – E.N. PREOBRAZHENSKAYA, D.V. SERGEEV & O.V. MOZHAEVA

Section 3.3.1 dealt with the stratigraphy of the approximately 5000 m of Triassic rocks logged in three boreholes. The rocks were shown to be mostly terrigenous and to have originated through cyclic deposition (Fig. 3.3.2), mostly in the Middle to Upper Triassic. The lower parts of cycles are composed of shallow-water marine deposits consistent with the initial phase of a transgression. They consist of poorly sorted, silty to sandy rocks, argillaceous rocks (with an admixture of silty, sandy and locally gravelly material), and sedimentary breccia. Evidence of bioturbation, rolling and slumping are common (Fig. 4.1). Fossils are represented by a marine fauna comprising ammonoids, bivalves and foraminifers; remains of higher plants are uncommon. Authigenic minerals are glauconite, pyrite and siderite.

The middle parts of cycles, represented by deeper marine deposits, correspond with the main transgression phase. They mostly consist of mudstone and argillaceous siltstone, containing pyrite, phosphatic nodules and ironstone concretions, along with local, thin bands of biogenic limestone.

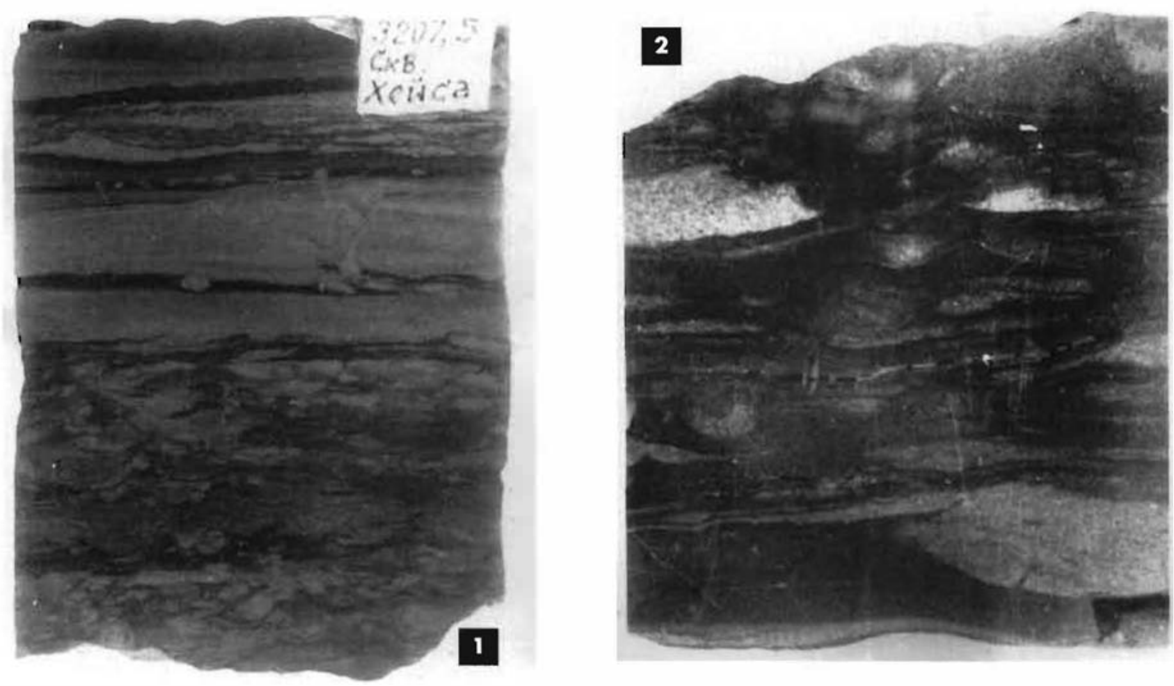
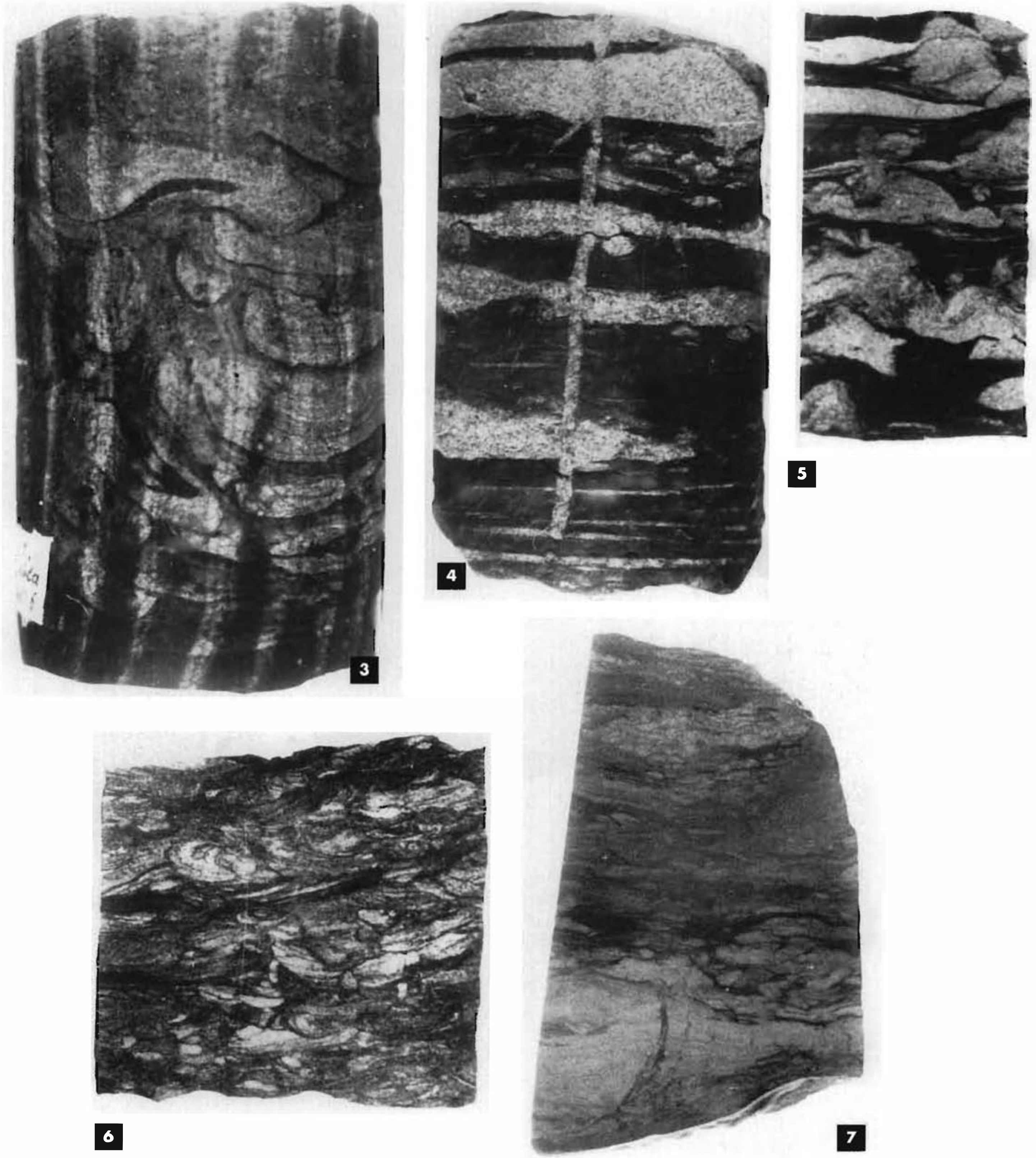


Fig. 4.1 Core fragments (natural size) of rocks belonging to the initial phase of transgression (lower part of the cycle). 1. Poorly sorted clayey siltstone with signs of rolling and bioturbation, passing into a unit of intercalating siltstone and mudstone. Upper Anisian. Hayes borehole, depth 3207.5 m. Polished section. 2. Poorly sorted clayey-sandy-silty rocks showing signs of small-scale slumping and bioturbation. Lower Ladinian. Hayes borehole, depth 2536.6 m. Polished section. 3. Slumping structures; turbulent lamination in siltstone. Lower Ladinian. Hayes borehole, depth 2400.6 m. Core surface. 4. Vertical and horizontal burrows made by mud-feeding animals in an undulating, interlensing, poorly sorted mudstone, siltstone and sandstone unit. Lower Ladinian. Hayes borehole, depth 2383.4 m. Core surface. 5. Slumping structures and lenses of sandy sediment in clayey material. Lower Carnian. Hayes borehole, depth 1413.7 m. Polished section. 6. Rock of mixed clayey-silty-sandy composition with rolling and bioturbation structures. Upper Carnian. Severnaya borehole, depth 1551.4 m. Polished section. 7. Slumping structures in a unit of undulating, interlensing clayey siltstone and sandstone. Upper Carnian. Hayes borehole, depth 967.4 m. Polished section.



The rocks display horizontal or lenticular-sinuous lamination. Fossils include ammonoids, bivalves, echinoderms, foraminifers, ostracods and algae.

The upper parts of cycles are composed of offshore, lagoonal and lagoonal-continental, generally coal-bearing deposits, corresponding to a regressive phase of sedimentation. Fine cyclic interlayering of mudstone, siltstone and sandstone, locally containing sedimentary breccia, is observed. Carbonaceous rocks and coal lenses can be found. The rocks are well sorted. They display cross

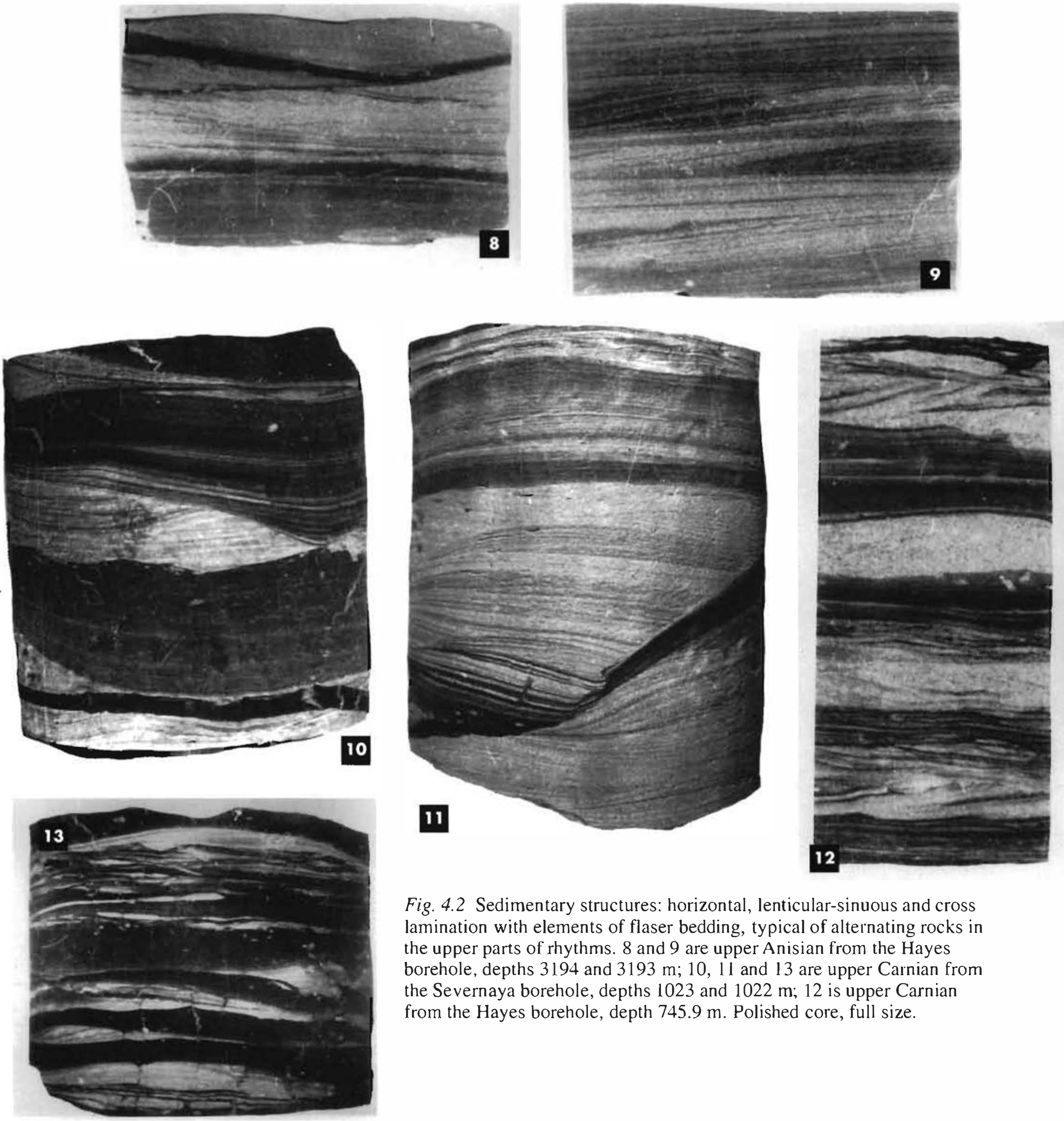


Fig. 4.2 Sedimentary structures: horizontal, lenticular-sinuous and cross lamination with elements of flaser bedding, typical of alternating rocks in the upper parts of rhythms. 8 and 9 are upper Anisian from the Hayes borehole, depths 3194 and 3193 m; 10, 11 and 13 are upper Carnian from the Severnaya borehole, depths 1023 and 1022 m; 12 is upper Carnian from the Hayes borehole, depth 745.9 m. Polished core, full size.

lamination, lenticular-sinuous lamination, flaser lamination and, less commonly, horizontal lamination (Fig. 4.2). Rare fossils include bivalves and a few foraminifers. Carbonaceous phytoplankton, detritus of higher plants, including leaves, are common. Authigenic minerals are dominated by titaniferous minerals (which cannot be identified more precisely), iron hydroxide (limonite) and siderite.

Transgressive facies are mostly developed in Middle Triassic first- and second-order cycles, this being typical of marine successions. Regressive facies are more common in Carnian cycles. The

Table 4.1 Average composition of clastics in the Triassic siltstone and sandstones, given in percentages

Log	*Age*	*No. of samples*	*Clast comp./ type of sst.*	*Qtz*	*Feld-spar*	*Mica*	*Rock clasts*
	Carnian	12	Polymictic (greywacke)	31	20	5	44
Sever-naya borehole	Upper Ladinian	1	Quartzo-feldspathic	62	16	4	18
		7	Polymictic (greywacke)	29	27	14	30
	Lower Ladinian	4	–	32	30	9	29
			–				
	Carnian	13	Polymictic (arkose)	28	34	5	33
	Upper Ladinian	3	Quartzo-feldspathic			2	18
Hayes borehole		10	Polymictic (greywacke)	36		8	
	Lower Ladinian	4	Quartzo-feldspathic	65	16	2	17
		11	Polymictic (greywacke)	30	24	9	37
	Upper Anisian	8	–	29	26	10	
Nagur-skaya borehole	Upper Ladinian	8	Quartzo-feldspathic	69	16	2	13

basal parts of sequences are most distinctively marine, but their thickness is minimal. The upper Carnian consists of microcyclic lagoonal-continental facies, carbonaceous lithologies dominating. The Norian cycle, formed during a weak transgression, differs in character, the most marine deposits occurring in the middle-lower Norian.

About 75% of the Triassic terrigenous sequence in the boreholes is composed of argillaceous rocks. Silty to sandy rocks account for 15–20%, sandy material increasing somewhat in the Severnaya borehole. Carbonate rocks amount to 8–9%, and poorly sorted rocks of mixed composition, chiefly sedimentary breccia and grit, total 1–2%, the grit mainly occurring in the middle part of the sequence.

Rocks of mixed composition occur at the base of large cycles. They are common in the lower part of the Ladinian where the most poorly sorted varieties are encountered. The rocks are grey, composed of clayey, silty and sandy material, and show a characteristic lenticular lamination and evidence of sediment rolling. Terrigenous grains are poorly rounded. The deposits are mostly greywackes and contain considerable amounts of rock fragments, feldspar and quartz. Quartzo-feldspathic varieties are less common. The feldspar is chiefly acid plagioclase, and rock fragments are

Table 4.2 Average mineral composition (< 0.005 mm) in argillaceous rocks, determined by X-ray analysis and given in percentages

Log	*Age*	*No. of samples*	*Hydro-mica*	*Chlor-ite*	*Kaolin-ite*	*Montmoril-lonite*	*Mixed-layer mins.*
	Norian	3	20	20	40	15	5
Sever-naya bore-hole	Carnian	6	40	35	15	5	5
	Ladinian	19	50	35	5	–	10
	Anisian	8	55	35	Trace	–	10
	Carnian	9	50	30	10	10	Trace
Hayes bore-hole	Upper	7	45	35	10	Trace	10
	Ladinian						
	Anisian	9	60	30	5	–	5
Nagur-skaya bore-hole	Upper Ladinian	12	40	20	25	–	15
	Olenek-ian	4	55	15	20	–	10
	Induan	6	55	25	5	–	10

mainly composed of acid effusives and mica schist. The detritus contains up to 10% mica, which is mostly biotite, sometimes muscovite, at the base of the Ladinian. A chaotic arrangement of mica flakes is characteristic. The argillaceous deposits mainly consist of hydromica, chlorite amd small amounts of mixed-layer minerals; kaolinite is present in the upper part of sequences. Carbonate varieties containing up to 40% iron-bearing magnesite of phytogenic origin are present. Characteristic are various co-existing authigenic minerals, such as pyrite, siderite, glauconite, phosphate and titaniferous minerals. Rocks of mixed composition are generally a few centimetres to a few metres thick.

Siltstone and sandstone are unevenly distributed, but mainly occur at the top of cycles of all orders. They are most abundant in the upper part of the section. The grey, bluish-grey or buffish-grey rocks differ in degree of compactness. Both massive and stratified rocks are present. The latter are mostly cross-stratified or have discontinuous-sinuous stratification, but some have horizontal stratification. The stratification results from the uneven distribution of argillaceous and carbonaceous material, carbonised plants, carbonate phytoplankton and mica. Graded bedding is rare. Siltstone and sandstone are always poorly sorted. Siltstone, mixed silty-sandy rocks and fine-grained sandstone are the most common lithologies. Medium- to coarse-grained sandstone only occurs at the top of Ladinian, Carnian and Norian cycles. Detrital material shows practically no rounding. The siltstones and sandstones are mostly greywackes, quartzo-feldspathic varieties only occurring in the Ladinian (Table 4.1). The polymictic character of the silty-sandy rocks increases eastwards. The detritus in these rocks contains quartz grains which are lath-like, acicular, wedge-like or lenticular in shape, i.e. typical erosion products of metamorphic schists. Feldspars are dominated by acid plagioclase. Mica, mostly buff biotite or, less commonly, muscovite, occurs throughout the section, locally forming sinuous-lenticular microlaminae up to 1 cm thick. Rock fragments are dominated by acid effusives and various schists, but occasional fragments of intermediate and basic effusives also occur. The fragments are cemented with argillaceous or sometimes carbonate material. Secondary quartz cement is rarely observed. Argillaceous cement, accounting for 3–30% (commonly 10–15%) of the rock, fills pores and contact rims; in places the

Table 4.3 Comparison of clarkes and mean element contents based on X-ray spectrography and flame photometry of Triassic sedimentary rocks (Hayes borehole)

Rocks		Pb	Sr	U	Th	Rb	K	Na
		Contents of elements (10–3 %)						
Mudstone	(19/13)	1	11	0.3	0.7	11	2200	1072
Siltstone	(21/10)	0.9	12	0.3	0.8	7	1314	1496
Sandstone	(19/13)	0.7	10	0.2	0.6	4	965	1445
Terrig. carb. rocks	(6/7)	0.9	16	0.2	0.9	6	1100	1277
Clarkes after K. Tarkyan	Argill. rocks	2	30	0.37	1.2	14	2660	960
K. Vedepol	Sst.	0.7	2	0.045	0.17	6	1070	330
	Carb. rock	0.9	61	0.22	0.17	0.3	270	40
Clarkes after A.P. Vinogradov	Argill. rocks	2	45	0.32	1.1	20	2280	660

The first number in brackets shows the number of samples analysed by X-ray spectrography and the second those analysed by flame photometry.

cement is of basal type. X-ray analysis shows that it consists chiefly of chlorite, hydromica and kaolinite; montmorillonite was found only in Carnian arenites. Carbonate cement, represented by calcite or, less commonly, siderite, accounts for 1–3%, occasionally up to 50%, of the rock. Beds, bands and laminae of siltstone and sandstone vary from a few millimetres to 10 m in thickness. Some units (mainly silty-sandy) exceed 10 m in thickness.

Argillaceous rocks form an important part of the sequence and consist of dark grey and black mudstone and claystone, generally more or less silty and grading into clayey siltstone. The content of silty material varies from 3–7% up to 30–70%, its uneven distribution being caused by frequent sinuous-lenticular lamination which shows evidence of rolling and bioturbation. Sandy material (up to 5–7%) appears in the uppermost part of the sequence. Well-sorted mudstones with indistinct or horizontal bedding and a conchoidal fracture are less common. They occur in the Olenekian, upper Ladinian and lower Carnian. Chlorite and clay minerals constitute less than 0.005% of the rock and the latter are principally hydromica and a little kaolinite, mixed-layer minerals, including montmorillonite, only being present in Carnian and Norian strata. However, kaolinite is one of the most common clay minerals in the Nagurskaya borehole (Table 4.2). Lower to Middle Triassic argillaceous rocks are generally poor in carbonate. They contain some siliceous material, and pyrite is always present as both scattered and interstitial material in organic remains and concretions. Carnian mudstones also contain siliceous material, but pyrite is much less common. The content of carbonaceous material increases upwards. Scattered glauconite is present throughout. The laminae, beds and units of argillaceous rocks vary in thickness from fractions of a centimetre to tens of metres. Units of intercalating mudstone and clayey siltstone may reach hundreds of metres in thickness.

Terrigenous-carbonate rocks include siltstone and sandstone cemented with carbonate (calcite or siderite), ironstone concretions and bands, and rocks containing calcareous phytoplankton. The latter variety is most common. Scale-like, blue-green algae replaced by dark yellow argillaceous magnesian siderite are present in all rock types, but are most common in siltstone. Hydrochloric acid extraction indicates that the carbonate content related to phytoplankton varies from 7–30%, usually around 15–17%.

The composition of accessory heavy minerals was studied in the silt fraction of siltstones and

Table 4.4 Comparison of clarkes and mean element contents based on semi-quantitative X-ray spectrography of Triassic sedimentary rocks

Rocks	*Name of borehole*	*Content of elements (10–3%)* *Ba*	*Be*	*Ca*	*Cu*	*Cr*	*Co*	*Fe*	*Ga*	*Mg*	*Mo*	*Mn*	*Na*	*Ni*	*Pb*	*Sr*	*Ti*	*V*	*Zn*	*Zr*	*Y*
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
	Nagurskaya (91)*	212	0.7	2467	5	27	2	14780	3	6065	0.7	159	4626	13	2	30	897	39	9	23	4
Mudstone	Hayes (100)	62	0.4	614	3	14	2	8120	1	1700	0.4	138	4750	15	2	27	439	21	14	19	4
	Severnaya (55)	114	0.6	1582	4	13	3	14145	2	3781	0.4	135	4836	13	2	27	724	31	13	22	4
	Nagurskaya (37)	200	0.7	2473	4	30	2	14864	3	6054	0.4	148	4864	12	1	31	935	88	7	27	4
Siltstone	Hayes (55)	70	0.5	1234	3	16	2	7982	1	1664	0.4	124	4836	11	2	30	453	15	11	29	5
	Severnaya (77)	95	0.5	1641	3	12	2	12285	2	2493	0.4	112	4506	9	2	27	722	19	8	26	4
	Nagurskaya	–	–	–	–	—	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
Sandstone	Hayes (35)	51	0.4	1280	1	14	1	6200	1	1114	0.3	91	4400	8	2	26	357	12	8	23	4
	Severnaya (71)	95	0.5	2471	2	13	2	8211	1	1609	0.3	115	4422	6	2	29	625	13	6	24	4
Terrigenous carbonate rocks	Nagurskaya	–	–	–	–	—	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
	Hayes (35)	58	0.4	4689	2	11	1	9029	1	1686	0.5	200	4457	8	1	33	307	19	12	21	5
	Severnaya (18)	126	0.6	7385	2	12	2	10000	1	1769	0.4	192	4846	7	2	33	569	13	6	25	4
Argillaceous rocks	Clarkes after	58	0.3	2210	4.5	9	1.9	4720	1.9	1500	0.26	85	960	6.8	2	30	460	13	9.5	16	2.6
SandstoneK.	Tarkyan &	1–9	0.01–0.09	3910	0.1–0.9	3.5	0.03	980	1.2	700	0.02	0.1–0.9	330	0.2	0.7	2	150	2	1.6	22	4
Carbonate rocks	K. Videpol	1	0.01–0.09	30230	0.4	1.1	0.01	380	0.4	4700	0.04	110	400	2	0.9	6.1	40	2	2	1.9	3
Argillaceous rocks	Clarkes after A. Vinogradov	80	0.3	2530	5.7	10	2	3330	3	1340	0.2	67	660	9.5	2	45	450	13	8	20	3

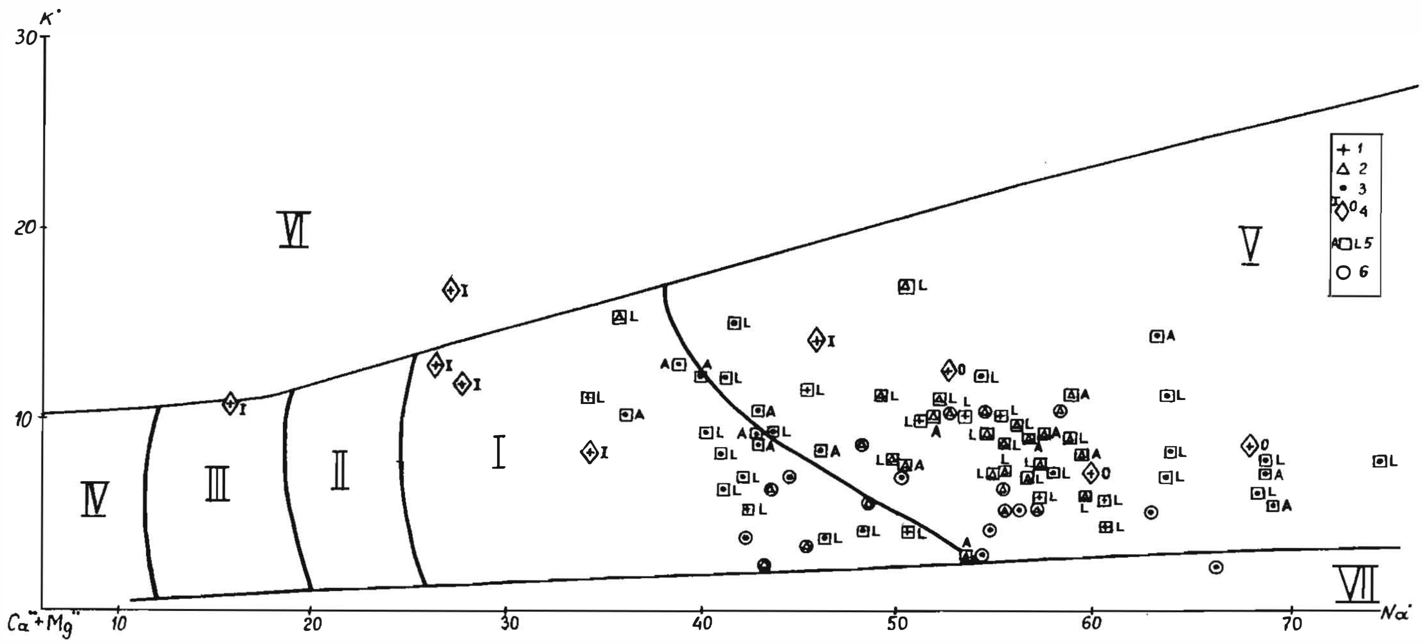


Fig. 4.3 Diagram showing the environments under which Triassic sediments were formed. I normal salinity, II marine basins with incursions of fresh water, III brackish lagoons, IV freshwater basins, V saline marine basins, VI potash-type lagoons, VII soda-type lagoons. 1 Alexandra Land, 2 Graham Bell Island, 3 Hayes Island, 4 Lower Triassic (I – Induan, O – Olenekian), 5 Middle Triassic (A – Anisian, L – Ladinian), 6 Upper Triassic.

sandstones. A single heavy-mineral complex was established for the Triassic deposits in the three boreholes, with two associations being predominant.

Firstly, there is a mica-garnet association consisting of mica, garnet and occasional chloritoid, andalusite and kyanite. Probably related to erosion of various kinds of metamorphic schists, this association is widespread throughout the sequence. However, variations in the abundance of its main components are observed, and the lower part (including the lower Ladinian) is dominated by mica and the upper part by garnet.

Secondly, an apatite-tourmaline-zircon association is found, also containing minor rutile and monazite. Different parts of the sequence are locally dominated by one or more of the main constituents, which may have originated from the erosion of acid igneous rocks, as suggested by abundant acid plagioclases and fragments of acid effusives in the silty-sandy strata. Rare grains of augite, hypersthene, aegirine, epidote and sphene are found throughout the sequence, together with occasional fragments of intermediate and basic effusives in the siltstones and sandstones, indicating that intermediate and acid igneous rocks were also present in the source area.

The authigenic heavy-mineral association includes magnesium-iron carbonates, siderite, pyrite, limonite and titaniferous minerals (mixture of finely crystalline sphene, anatase and brookite with leucoxene). The distribution of authigenic minerals through the sequence is a good indicator of variations in the redox potential during the sedimentation of second-order cycles. The main indicators of variations in the redox potential are pyrite (reducing conditions), siderite (subreducing conditions), and titaniferous minerals and iron hydroxides (oxidising conditions). Within the cycles, authigenic index minerals define a gradual transition from reducing to oxidising conditions. The sequence clearly exhibits a cyclic replacement (in ascending order) of pyrite by titaniferous minerals (upper Anisian cycle), magnesium-iron carbonates by titaniferous minerals (lower Ladinian cycle), and pyrite and magnesium-iron carbonates by titaniferous minerals (upper Ladinian cycle). The Upper Triassic shows evidence of rapidly shifting, rhythmic alternation of subreducing (siderite) and oxidising (titaniferous minerals and iron hydroxides) conditions.

Semi-quantitative X-ray spectrography, wet chemistry for iron and sulphides, and X-ray powder patterns for clay minerals were used to determine the chemistry of the Triassic deposits. X-ray spectrography and flame photometry were used to determine U, Th, Rb, Pb, Sr, K and Na in specimens from the Hayes borehole.

Abnormally high concentrations of individual elements were not found. Two groups of elements were recognised on the basis of ratios between mean concentrations and clarkes (Table 4.3). In one group, comprising Ca, Cr, Fe, Ga, Mg, Ti, Zn, Zr, Y, Pb, Sr, Th, Rb and K, the mean concentrations for all the rock types differ from clarkes by less than an order of magnitude. Mean concentrations of a second group of elements, such as Ba, Be, Cu, Co, Mo, Mn, Ni, V, U, Na for argillaceous rocks, also differ from clarkes by less than an order of magnitude, but exceed clarkes by more than one order in sandy varieties, and exceed the clarkes of Co and Mn by two orders of magnitude.

Comparison of mean concentrations for rock types (Table 4.4) allowed the recognition of a group containing Ba, Be, Cr, Co, Fe, Ga, Mo, Pb, Ti, Zr, Y, Sr, U, Th and Na. The mean values for these elements remain almost constant in different rock types, whereas the quantities of other elements vary with the rock types. Ca and Mn enrich terrigenous carbonates, especially concretions. The amounts of Cu, Mg, Ni, V, Zn, Rb and K substantially increase in fine-grained rocks. Appropriate paired correlation coefficients are as high as 0.7–0.9. Cu, Mg, Ni and Ga show the greatest common genetic character with organic matter. In this case, paired correlation coefficients equal 0.4–0.6. Ca and Fe are noticeably associated with carbonate rocks. Sr and Mn are the most characteristic elements associated with calcite. Mn, V and Na usually accumulate in ferruginous carbonates.

Substantial variations in chemical composition through the sequence or across the area were not noted.

In general, variations in component ratios in reactive iron through the sequence suggest reducing and subreducing conditions in the Triassic strata in the boreholes. The most oxidising conditions were found in the Carnian rocks, where minimum concentrations of pyrite were only found in a few samples.

The composition of complex, absorbed and nearly insoluble salts was studied in argillaceous rocks to determine the palaeohydrochemical depositional conditions of these Triassic strata. The results were plotted on the genetic diagram proposed for Mesozoic deposits by Gramberg (1973). The ratio of the alkalies plotted on the diagram (Fig. 4.3) shows that all the points lie in the field of normal saline water and saline marine basins. The concentrations of calcium and magnesium oxide compounds in nearly insoluble salts also points to the marine character of the strata. The Induan, Anisian (Hayes borehole), some of the upper Ladinian (Nagurskaya and Hayes boreholes), the Carnian and early Norian rocks were formed in the most marine conditions (normal saline water). As a rule, departure of salinity conditions from a normal salt content (salinity increase or, less commonly, decrease) occurs at the tops of cycles of one order or another. Lower Ladinian deposits, which were entirely formed in saline marine basins, are an exception to this rule. Marine depositional conditions clearly prevailed over a greater thickness of strata in the Nagurskaya and Hayes boreholes in contrast to the conditions indicated by the more arenaceous character of the log and rarer finds of ammonoids in the Severnaya borehole.

During the sedimentation, the redox potential for the MnO:MgO ratio (in the composition of nearly insoluble salts) underwent variations similar to those just described concerning the distribution of authigenic minerals and reactive iron. The lower portion of the sequence displays reducing and subreducing conditions, replaced by suboxidising and oxidising conditions in second-order and third-order cycles. The MnO:MgO ratio varies from 0.03 to 0.1, with 0.03–0.05 predominating. The Anisian deposits in the Severnaya borehole, with values chiefly around 0.1–0.2, suggesting purely oxidising conditions, are an exception. A transition towards oxidising conditions, with MnO:MgO values rising to 0.15, occurred by the end of the early Ladinian. The upper part of the sequence is characterised by sharp variations in MnO:MgO values (0.03–0.07 to 0.1–0.45), suggesting frequently recurring reducing and oxidising conditions in late Ladinian and Late Triassic time. Oxidising conditions predominated in the later part of the period in the area where the Hayes borehole is situated.

Similar lithologies, a common cyclic character and the same fossils and thicknesses throughout the region suggest identical depositional environments for the Triassic sediments. Usually, the deposits were formed under the same environmental and tectonic conditions in a marine basin characterised by substantial subsidence and very high rates of sedimentation. Sedimentation at the end

Fig. 4.4 Sandstone with ripple marks, Wilczek Formation, Cape Hansa area. Photo: V.D. Dibner.

of the Anisian and in the second half of the Carnian occurred in offshore shallow water and under lagoonal-continental conditions, respectively. The marine character of the Middle Triassic deposits becomes more evident in the area between the Severnaya borehole and the Hayes and Nagurskaya boreholes, the volume of sediments formed under normal salinity conditions, accompanied by a dominance of reducing and suboxidising conditions, increasing. The irregularity in the distribution of the sediments and the content of typical marine fauna increases in the process. The area of metamorphic and acid igneous rocks undergoing erosion may have been situated east-northeast of Franz Josef Land, as suggested by the considerable coarsening and increasingly polymictic character of the detrital material in the sediments in the Severnaya borehole compared with the Hayes and Nagurskaya boreholes.

Periodic slumping caused by extreme rates of basin floor downwarping occurred from the beginning of the Ladinian.

4.2 SEDIMENTOLOGY OF EXPOSED UPPER TRIASSIC AND JURASSIC-CRETACEOUS DEPOSITS – V.D. DIBNER, V.K. RAZIN & Z.Z. RONKINA

This section is mainly based on material obtained during field work in 1953–1957 and 1976, and on the results of laboratory investigations (Dibner & Sedova 1959, Dibner 1960, 1961a, d, 1970, 1978, Dibner & Shulgina 1960, Dibner et al. 1962). Microscopy of cemented sedimentary rocks was chiefly carried out by V.K. Razin who examined more than 500 thin sections. About 60 mineralogical analyses were made, primarily of Upper Triassic and Lower Jurassic rocks. Samples from collections made in 1953 and 1956 were analysed in the sedimentological laboratory of the Institute of Arctic Geology (NIIGA). Unfortunately, a mixed silty-psammitic fraction (0.05–0.25 mm) was examined there. Consequently, when collections made in 1957 were being studied, two fractions, 0.1–0.25 mm and 0.05–0.1 mm, were analysed to obtain results that could be compared with the previous data. Grains were only calculated in the 0.05–0.1 mm fraction because the finer fraction usually contains only a small amount, and little variety, of terrigenous minerals and has a high content of authigenic minerals. In view of the peculiarities of the psammitic fraction, the authors considered it was possible to use data from the older analyses. With this aim in mind, the authigenic minerals only had to be excluded from the sum of the 100% heavy-mineral fraction. The light-mineral fraction was determined by E.G. Yudovny.

4.2.1 Lower Norian marine deposits at Cape Hansa

These deposits consist of dark-grey, cross-bedded siltstone with thin beds of silty limestone and numerous calcareous concretions. Locally, the siltstones show distinct stratification, even foliation and boudinage. Occasional folding and doming of the Upper Triassic and younger beds has been caused by diapirism (section 3.3). The outcropping sediments are about 22 m thick. The clastic component of the siltstones (70–80%) is angular grains (0.05–0.1 mm), almost all of which are fragments of metamorphic rocks or weathered feldspars, micas and other minerals. Carbonised fragments and argillaceous material also occur, defining a microlamination. Silico-argillaceous cement contains minute flakes of mica and chlorite. Authigenic pyrite is the sole heavy mineral in the siltstones, amounting to as much as 3.5%.

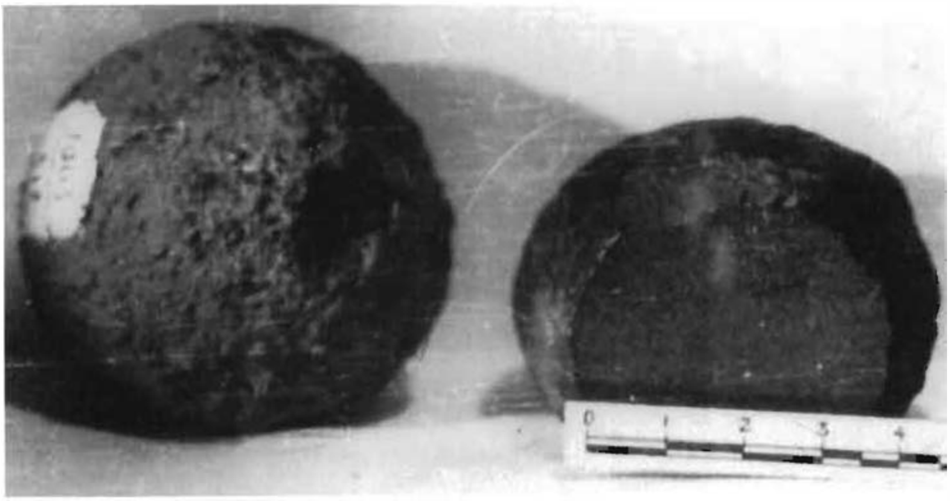


Fig. 4.5 Pyritic nodules from the Vasiliev Formation sands, Graham Bell Island.

4.2.2 Upper Triassic-Lower Jurassic offshore and continental deposits

Wilczek Formation (Upper Norian)
The Wilczek Formation consists predominantly of sandstones and siltstones and becomes generally coarser upwards. The clastic component of the sands and sandstones is almost purely siliceous (80% quartz and 15% flint). Siliceous cement (with some carbonate cement) transforms the sandstones into quartzitic sandstones. Grits form 2–4 cm thick lenticules in the sandstone uppermost in the Wilczek Formation on the east coast of Hayes Island. They are composed of small quartz pebbles, flints and other hard rocks cemented with fine-grained siliceous sandstone with a carbonate matrix.

The sandstones are fine grained to inequigranular, and interlayered sands are cross bedded, mainly siliceous and contain mica and coal dust; ripple marks are occasionally seen (Fig. 4.4). The light-mineral fraction is polymictic. The heavy-mineral fraction in the sandstones on Cape Hansa and Cape Heller amounts to only hundredths of a percent. The terrigenous component mainly consists of leucoxene and titaniferous minerals. The heavy-mineral fraction in the upper part of the formation (on the east coast of Hayes Island) differs in composition, consisting of equal amounts of clinopyroxene and ore minerals, plus garnet.

Vasiliev Formation (upper Norian-Rhaetian)
The Vasiliev Formation consists of a variety of lithologies, this being most evident in the middle portion which is composed of a 50–60 m unit of variegated deposits. The light-mineral fraction of the sands and sandstones is also polymictic. The clastic portion consists of angular and, less commonly, subrounded grains (0.15–0.5 mm) of quartz, flint, acid plagioclase and orthoclase, as well as fragments of acid effusives, chloritised rocks, carbonaceous shale, mica schist, coal dust and so on. At Cape Goristy on Champ Island and Cape Vasiliev on Wiener-Neustadt Island, quartz reaches as much as 63–85%. In addition to psammites, the formation contains occasional bands and lenses of silt, siltstone, mudstone and argillaceous limestone, and also mainly quartzitic grits and conglomerates. Coal seams appear in the upper part of the formation.

The variegated unit of the formation on Cape Goristy, and also some other localities (Hayes Island, Cape Hofer on Wilczek Land, Graham Bell Island, etc.), consists of fine-grained siliceous sand intercalated with poorly cemented grey, dark-grey, yellow, brown and bluish sandstones containing a few seams of brown coal and cryptocrystalline ironstone concretions (up to 5 cm across). On Cape Goristy, Piroznikov (1960) found interbeds (up to several decimetres thick) of poorly cemented, brown sandstone, 50% of which consists of large, glistening mica flakes (bleached biotite), the remainder being quartz, flints, feldspar and a little very loose, argillaceous cement. Macroscopically, the rock is almost indiscernible from slightly weathered mica schist. Only indistinct cross lamination at an acute angle to the foliation (cleavage), observed on fresh fractures, suggests the sedimentary origin of the rock. The content of micas (biotite and muscovite) gradually decreases eastwards to 1–2% on Graham Bell Island.

In samples from the islands of Champ, Wiener-Neustadt, Salisbury and Hayes, the heavy-mine-

Fig. 4.6 Sandstone loaf in the Vasiliev Formation, central part of Hayes Island. Photo: V.D. Dibner.

ral fraction varies from a few tenths of a percent to over 6.0%, the terrigenous constituents being ore minerals (up to 56.5%), epidote-zoisite group minerals (up to 34%), garnet (up to 23.5%), unidentifiable titaniferous minerals and leucoxene (up to 24.7%). A large amount of staurolite and, in a few samples, biotite and chlorite (up to 41.9%) are also notable.

Samples from the islands of Wilczek Land, Graham Bell and Becker, however, differ from the above in having a still lower heavy-mineral content (0.25–1.75%). In two samples from Wilczek Land, the terrigenous minerals are mainly biotite and chlorite (61.2%), ore minerals (3.65%), zircon (up to 23.6%), garnet (up to 15.7%), unidentifiable titaniferous minerals and leucoxene. In the terrigenous suite of twelve samples from Graham Bell Island, ore minerals (15.0–59.6%), garnet (9.5–25.8%), unidentifiable titaniferous minerals, leucoxene (up to 67.2%) and zircon (1.2–11.0%) are the essential minerals. Examination of the heavy-mineral fraction of the concentrate produced by panning the sands of the Vasiliev Formation on Graham Bell Island showed that ore minerals are represented by ilmenite (36.8%), magnetite (1.5%) and occasional fine octahedra of chromite.

The sandstones uppermost in the Vasiliev Formation are cemented with interstitial, argillaceous or pure siliceous (opal?), material locally replaced by carbonate.

Concretions, in the form of numerous pyritic nodules (up to 8 cm across), are common in the variegated unit of the Vasiliev Formation (Fig. 4.5). With a few exceptions, they are ball shaped. They are buff on the surface, but fractures are a steel-grey colour and show metallic lustre. The concretions are composed of siliceous or oligomictic, inequigranular (even gritty) sandstone, like the remainder of the formation, cemented with pyrite, and make up more than 50% of the nodules.

On exposure surfaces, present-day hypogenic processes may be responsible for sulphatisation through the weathering of pyrite, since concretions are sometimes coated with fine acicules of selenite, and pyrite dispersed in the sand has "dovetails" of selenite on its surface.

Large (up to a few metres) sandstone loaves are common in the psammites of the Vasiliev Formation (Fig. 4.6).

Tegetthoff Formation (lower Lias)

The Tegetthoff Formation consists of inequigranular, mainly siliceous sands and sandstones. The sandstones generally have a carbonate cement, but in the occasional quartzitic sandstones it is siliceous. Beds and thicker units of siltstones and sometimes argillaceous limestones are present, and here and there numerous interbeds of gravel, poorly cemented conglomerate and coal.

Conglomerates and grits form lenses and layers varying in thickness from a few centimetres at Cape Sedov to a few metres at Cape Tegetthoff. Eastwards, the clasts increase in size from 1–2 up to 5–8 cm and decrease in roundness. The psephites at Cape Tegetthoff are made up of pebbles of quartzitic sandstones, flints, fine-grained quartzites and limestones, generally in a siliceous sandstone matrix.

Modal analyses show that the clasts of the Tegetthoff Formation differ in composition from place to place. The light-mineral fraction at Cape Sedov chiefly consists of quartz (66–74%), acid plagioclase (12.3–18.5%) and some orthoclase (3.0–6.6%) and rock fragments (7.0–9.0%).

At Cape Tegetthoff, the light-mineral fraction is dominated by quartz, although this amounts to

Fig. 4.7 Boulder of metamorphosed Middle Devonian cuticular leptobiolith from the Vasiliev Formation conglomerates, Kholmisty Peninsula, Graham Bell Island. Full size.

no more than 31.2–47.0%. Orthoclase accounts for 12.9–25.0%, significantly exceeding plagioclase (6.0–6.1%) which, in addition to omnipresent acid plagioclase, also includes intermediate and rare basic varieties. The heavy-mineral fraction amounts to 0.98–3.82%. The terrigenous portion is composed of ore minerals (56.3–61.6%), zircon (9.6–10.2%), garnet (8.4–9.8%), leucoxene (4.8–8.6%) and a few grains of glaucophane. Authigenic minerals (4.1–4.9%) are represented by pyrite and limonite. Quartz accounts for 44.5–51.5% of the light-mineral fraction in samples from Cape Galkovsky. Orthoclase (15.8–19.6%) and acid plagioclase (17.1–20.4%) are almost equal in amount. The terrigenous portion of the heavy-mineral fraction (about 0.6%) is mainly composed of garnet (71.5–83.2%), which differs strongly from that which is common in the Upper Triassic and Jurassic deposits. Authigenic minerals are rare or absent.

Petrography of conglomerate and grit in the Wilczek, Vasiliev and Tegetthoff Formations

Quartz is sheared, crushed and shows undulating extinction, and fissures are filled with calcite. Flint pebbles consist of minute granules of chalcedony showing a variable degree of crystallisation and forming spots that may be both cryptocrystalline and medium grained. In places, the chalcedony, forming spherules up to 0.1 mm across, is accompanied by 1 mm long quartz grains with a parallel-fibrous or fibro-radiated texture. The flint clasts sometimes resemble fine-grained quartzites. Some flints in the Vasiliev Formation are coloured pinkish by finely dispersed haematite. They display irregular accumulations of minute argillaceous material containing foliate chlorite as well as cryptocrystalline carbonate and scarce tourmaline. Some pebbles have abundant, recrystallised radiolarian remains (0.1–0.2 mm) filled with spherules of chalcedony and quartz, and also foraminiferal tests (?) which are well defined in plane light as thin opaque outlines of clay particles. Crossed polars reveal that the test wall is made up of microcrystals of chalcedony and quartz arranged parallel with its surface. There are also elongate fragments, resembling bryozoans or sponge spicules, filled with extremely fine-grained quartz granules. The flints are generally fractured, the fissures (0.1–1.5 mm across) being filled with microcrystalline quartz arranged parallel with their walls. Locally, the branching and criss-crossing quartz streaks give the flints the appearance of grit.

Radiolarite clasts consist of rounded remains of 50% chalcedonised and silicified, unidentifiable radiolarians (up to 0.2 mm) embedded in an almost black silico-argillaceous mass. The rock is biogenic. Its parallel microtexture resembles radiolarian shale. Like the flints, the radiolarites are traversed by a network of narrow fissures healed by microscopic (0.05 mm) grains of quartz. Individual microcrystals and aggregates of pyrite are scattered throughout the rock.

Quartzites are represented by grey, dark-grey, pink and violet varieties showing granoblastic, sutured texture. Quartz grains, 0.1 to 2.0 mm in size, have characteristic, complexly jagged outlines and undulating extinction. In places, abundant argillaceous material, minute hydromicas and cryptocrystalline carbonate occur at the boundaries between large grains. Like the quartz, the quartzites are very crushed and fissured, the fissures being filled with calcite. Rare fragments of flint, sporadic grains of zircon, and an admixture of dispersed iron oxides were found in quartzitic pebbles from the variegated unit on Graham Bell Island.

Quartzitic sandstone clasts on Dawes Island and at Cape Hansa on Wilczek Land have granoblastic texture. Quartz grains (0.1–0.3 mm) are regenerated by recrystallisation of siliceous cement, the outlines of the original grains being marked by a thin line of clay particles, or sometimes minute mica flakes. Rare zircons, as well as epidote, scapolite, biotite, muscovite and chlorite have been observed in quartzite and quartzitic sandstone pebbles on Graham Bell Island.

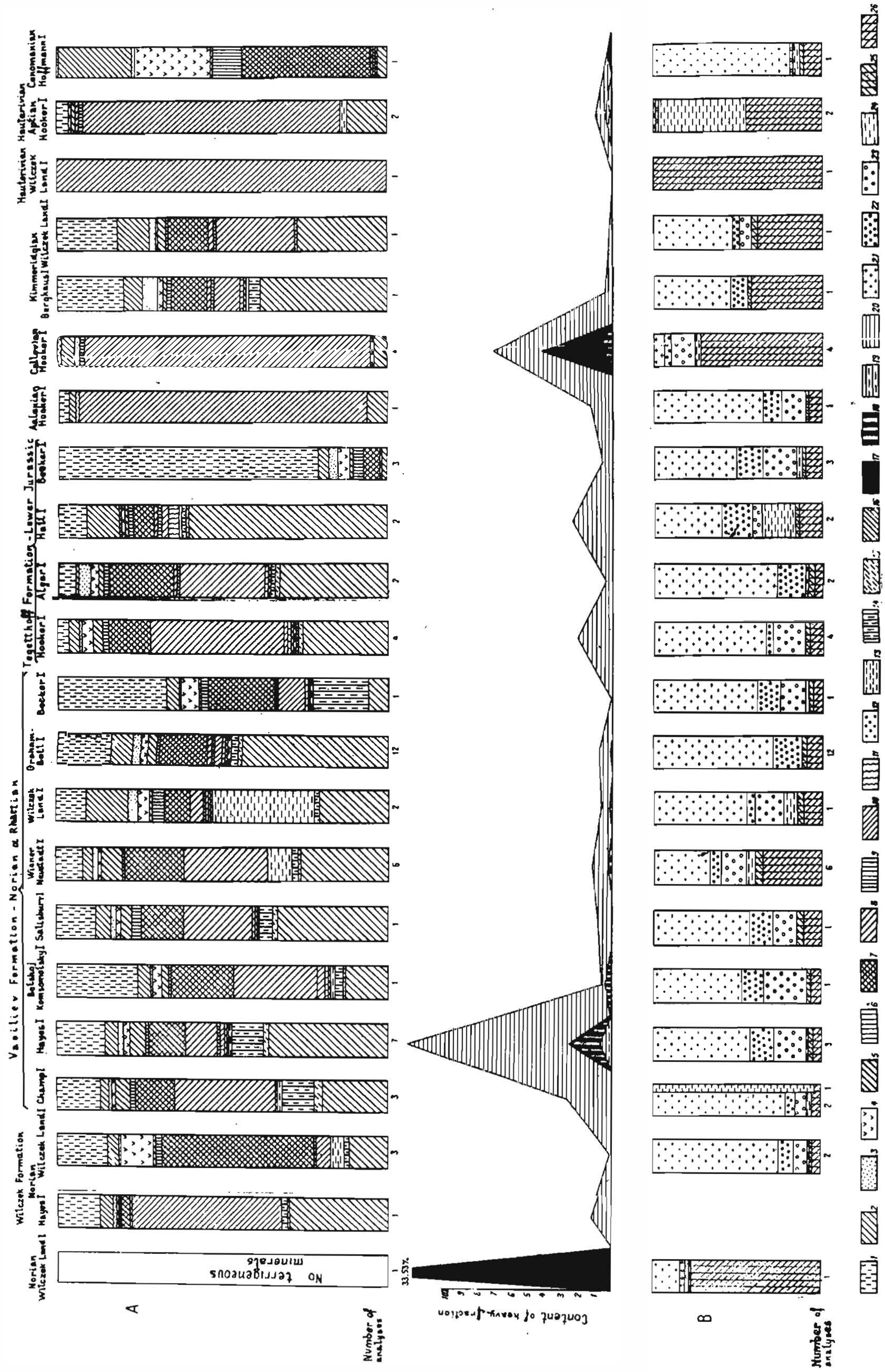


Fig. 4.8 Average mineral composition of heavy (A) and light (B) fractions (size 0.05–0.1 mm) of Mesozoic deposits. Heavy-mineral fraction: 1 garnet, 2 zircon, 3 apatite, 4 tourmaline, 5 sphene, 6 rutile, anatase, brookite, 7 undifferentiated titaniferous minerals, leucoxene, 8 epidote, zoisite, 9 amphiboles, 10 pyroxenes, 11 spinel, 12 chloritoid, 13 biotite, chlorite, 14 staurolite, 15 kyanite, sillimanite, 16 ore minerals; authigenic minerals: 17 pyrite, 18 iron hydroxides, 19 carbonates, 20 terrigenous portion of heavy-mineral fraction. Light-mineral fraction: 21 quartz, 22 orthoclase, 23 plagioclase, 24 biotite, chlorite, muscovite, 25 quartz aggregates, 26 weathered minerals and rock fragments.

Shale clasts are covered by numerous minute hydromica flakes and transected by very narrow veinlets of microcrystalline calcite and sometimes quartz.

Acid effusives are represented by only one thin section of amygdaloidal porphyry from Cape Hofer. This is a porous, pinkish-grey rock. Its groundmass is partly micropoikilitic, partly microfelsitic and is generally indistinctly crystalline. It is composed of quartz and minute orthoclase and albite crystals, as well as amphibole which is opalised or sometimes chloritised. Apatite and zircon are accessories. Numerous rounded and ellipsoidal pores are filled with quartz and chlorite.

Feldspar clasts are represented by scarce fragments of chessboard albite and microcline found in the siliceous grits of the Vasiliev Formation on Hayes Island.

There are two varieties of limestone clasts. The first is microgranular limestone composed of fibrous aggregates of calcite (up to 90–95%) showing fan-shaped extinction, and finely dispersed clayey and silty material. Sporadic microcrystals of pyrite and grains of glauconite are present, as well as minute sericite and chlorite flakes. The second variety is cryptocrystalline limestone. Its groundmass consists of carbonate which is almost opaque in polarised light. Silt-sized grains of quartz and authigenic pyrite locally fill microfissures and form rims on limonite. The groundmass also contains abundant foraminiferal remains, encrusted with fine-grained calcite. They include *Parathurammina* sp., *Tuberitina collosa* Reitl., *Glomospira* sp., *Ammovertella* aff. *vaga* Reitl., *Schubertella* sp., *Tetrataxis* sp., *Globivalvulina* sp. and single forms of large fusulinids from the subfamily *Fusulina* Moell. The latter, as well as *Schubertella* sp., suggest the Middle Carboniferous (M.F. Solovieva, unpubl. manus.).

Coal clasts include a small boulder of coal (Fig. 4.7) found in 1953 in debris consisting mainly of quartz and quartzitic conglomerates eroded from the variegated unit on Graham Bell Island (Dibner 1957a, b). According to Korzhenevskaya (1957), this is a unique example of an ancient pitch coal, namely, metamorphosed, cuticular leptobiolith, resembling a compact pitch-like variety of Middle Devonian coal from the River Barzak area in the Kuznetsk Basin.

On the islands of Nansen and Pritchett, Spizharsky (1947) found thick beds of conglomerate in continental, chiefly arenaceous, deposits (later assigned to the undifferentiated Upper Triassic-Lower Jurassic) overlain by basalts. Along with the usual quartz, quartzite, silicified rock and limestone clasts, there are pebbles of granitoids, basalts and highly deformed metamorphic schists. A few calcareous pebbles yielded brachiopods and microfossils of Carboniferous and Permian age as well as rounded solitary corals (Spizharsky 1936a, b).

4.2.3 Middle to Upper Jurassic marine deposits

Aalenian

The petrography of this unit has mainly been studied in samples of dark-grey silt, siltstone and mudstone from three localities on Hooker Island, the southeastern corner of Tikhaya Bay, the foot of Mount Ciurlionis (upper Aalenian) and the north coast of the bay (undifferentiated Aalenian). These deposits contain numerous marl nodules whose groundmass consists of calcite and scattered aggregates of minute pyrite grains with organic matter and is in part limonitised. The texture is partly spherulitic, partly granoblastic. The clastic material was studied in immersion liquids, which showed that the light-mineral fraction chiefly consists of quartz (64.8%), acid and intermediate plagioclase (10.8% and 3.5%, respectively) and orthoclase (11.5%). The terrigenous portion of the heavy-mineral fraction is almost completely composed of clinopyroxene (87.1%) with some ore minerals (6.2%). Abundant, intact pelecypod shells, as well as large and small fragments of other shells, are seen in the central parts of many concretions.

At Cape Flora on Northbrook Island, Nansen (1900) described numerous sandy-marly nodules, up to 30 cm in diameter, which make up bands reaching 60 cm in thickness in Aalenian clay.

Bathonian

Details concerning the sedimentology are only known for lower Bathonian deposits exposed at Cape Flora on Northbrook Island, and especially for the middle to upper Bathonian at Cape Medvezhy on Hooker Island.

At Cape Flora, Koettlitz (1899) and Nansen (1900) described clay crammed with nodules and fragments of sandy marl. The clay occurs above an 80 m high talus slope developed on Aalenian beds. The nodules have dark-brown or black cores composed of calcium phosphate, carbonate and silica dust, as well as minor iron oxides and organic material. The outer part of the nodules consists of fine-grained, compact, argillaceous, in places calcareous, sandstone containing muscovite flakes. The nodules contain a partially pyritised fauna and some plant remains. The Bathonian deposits at Cape Medvezhy, on the coasts of Tikhaya and Yury bays, are greenish-grey, flaggy, clayey siltstones (very sticky when soaked). Microscopy reveals a homogeneous, isotropic argillo-siliceous mass that is yellow or buff in translucent light and contains numerous, minute hydromica flakes. Tiny, anhedral carbonate grains and minute pyrite nodules (up to 1.5 mm in diameter), which may have formed around brown spots of organic matter, are scattered in the mass. Large (up to 3–4 cm) crystals of gypsum grow where pyrite is most abundant, as the result of its sulphatisation on the exposed surface of the bedrock. Examination of silty material in immersion liquids showed that basic plagioclase (up to 53%) and various weathered minerals and rock fragments (33.0%) form most of the light-mineral fraction. The terrigenous portion of the heavy-mineral fraction (which varies from 0.35 to 7.27%) usually consists 90–100% of clinopyroxene, but one sample contains only 56.3% of clinopyroxene, and ore minerals (15.5%), zircon (12.1%) and epidote-zoisite group minerals (5.5%) are also common.

Large numbers of globular calcareous concretions (up to 30–40 cm across), generally containing animal fossils, are scattered through the Callovian mudstone. In appearance and composition they are scarcely distinguishable from the Aalenian concretions. They are transected by a network of fissures (up to 1 cm wide), usually forming hexagonal chambers 10–15 cm in diameter. The fissures are filled with dark-grey calcite crystals growing from the walls to meet each other. Geode-like cavities, partially or completely filled with light-green, slightly recrystallised calcite, occur in the largest fissures between two lines of crystals. Hexagonal prisms formed by the calcite streaks were described by Vlodavets (1934) from samples collected by Ivanov (1935). The concretions contain dispersed pyrite grains, which sometimes have gypsum crystals growing on their surface. Inside the concretions, gypsum is less common in cavities and fissures.

At Cape Hofer on Wilczek Land, the uppermost Callovian and lower Oxfordian beds are exposed, represented by the so-called "brown clay". According to Yu.A. Mikhailov (these and subsequent data on the mineralogy of Upper Jurassic and Neocomian deposits at Cape Hofer and Cape Lamont on Wilczek Land are taken from Mikhailov et al. (unpubl. manus. 1977)), they are plastic, fine-grained rocks composed of kaolinite (50%), hydromica (30–35%) and mixed-layer minerals (15–20%). They abound in half-moon shaped calcareous concretions with a cryptocrystalline groundmass.

Oxfordian

The Oxfordian is best studied at Cape Hofer (this is also true of the Upper Jurassic rocks). The lower Oxfordian is the upper part of the "brown clay". The upper Oxfordian, Kimmeridgian and lower-middle Volgian (Tithonian) are represented by a sequence often referred to as the "black clay". It is dark-grey to almost black argillaceous silt composed of material that differs sharply in composition from that in the underlying lower Oxfordian and Callovian. The pelitic fraction consists of three clay minerals, kaolinite (65–15%), hydromica (35–15%) and montmorillonite (70–5%). Unlike the Callovian and lower Oxfordian deposits, mixed-layer minerals are only encountered in occasional samples.

Kimmeridgian

The Kimmeridgian at Cape Hansa on Wilczek Land and on Berghaus Island consists of poorly cemented, laminated siltstones which contain calcareous concretions at Cape Hansa and arenaceous limestone on Berghaus Island which fossil evidence suggests is partly coeval, partly younger. Macroscopically, the arenaceous limestones largely resemble sandstones. They are thinly to moderately platy, compact, dark-grey rocks. Microscopy reveals that calcite microcrystals, stained yellowish and locally grey-brown probably by organic matter, account for 80–90% of the groundmass. This carbonate contains shell fragments and microfossil remains, as well as some terrigenous and authigenic minerals, totalling 10–20% of the rock. Some specimens contain up to 50% clastic grains and are transitional to sandstone with carbonate cement. These clastic components and fragments deriving from the siltstone at Cape Hansa were also examined in immersion liquids. Their mineralogy is very similar. The light-mineral fraction is made up of quartz (26.0–47.5%), weathered minerals and rock fragments (3.0–41.7%) and feldspars, dominated by acid plagioclase. The terrigenous portion of the heavy-mineral fraction (0.05–0.4%) is mainly composed of ore minerals

(27.5–38.3%), clinopyroxene (7.9–23.6%), garnet (19.0–20.3%), leucoxene (12.4–13.3%), zircon (5.5–9.2%), apatite (2.04–4.5%) and single grains of glaucophane. Authigenic minerals (13.4-14.9%) are mostly represented by pyrite, with a little siderite and limonite. Occasional grains of glauconite were identified in thin sections (Dibner et al. 1962).

Volgian

At Cape Lamont, the lower Volgian part and the lower 50 m of the middle Volgian consist of a different facies, the so-called "dark sand", which is poorly sorted. This is especially true of its basal part, which comprises a mixture of fractions ranging from clay (0.001 mm) to fine-grained sand (0.2–0.315 mm). The light-mineral subfraction contains abundant fragments of fine-grained micaceous rocks (up to 50%), approximately equal amounts (15–20%) of quartz and feldspar and some flakes of muscovite and biotite (up to 5%). The rock fragments are mainly angular. The heavy-mineral fraction contains garnet (10–20%), staurolite (1.7–5.4%), kyanite (0.2–1.9%) and glaucophane, suggesting erosion of a source area which, like in the Late Triassic, was composed of strongly metamorphosed rocks. This is also suggested by varieties of micaceous sand which contain numerous platy and lenticular quartz grains, probably derived from gneiss or schist. Indeed, the composition of the heavy-mineral fraction is identical with that of the Upper Triassic sand, except for the appearance of clastic barytes (0.2–5.5%).

Further up the middle Volgian is the relatively well-sorted "light sand", which forms beds of indurated, fine-grained, relatively well-sorted quartzo-feldspathic sandstone. The light-mineral fraction is dominated by angular fragments of feldspar, quartz and a zeolite-like mineral (laumontite?). The heavy-mineral fraction differs from that of the underlying beds in having a high content of ore minerals, approaching 45%.

4.2.4 Lower Cretaceous terrigenous strata

Only the Berriasian and Valanginian beds at Cape Lamont have been studied petrographically.

Berriasian

At Cape Lamont, the Berriasian includes the uppermost part of the "light sands", which is rather well sorted and markedly coarser than the lower part. The 0.200–0.160 mm and 0.160–0.100 mm fractions total about 50%. The light-mineral fraction here is dominated by angular grains of quartz, feldspar and laumontite. A higher content of ore minerals, about 50%, was recorded in the heavy-mineral fraction of the Berriasian sandy beds.

Berriasian-Valanginian

The Berriasian-Valanginian is represented by a variegated unit exposed at Cape Lamont, Cape Fiume and Inaccessible Rocks and made up of moderately well-sorted, quartzo-feldspathic sands, which are fine grained in the lower part and medium grained in the upper part. The fine-grained sandstone is strongly dominated by the 0.200–0.160 mm (26%) and 0.160–0.100 mm fractions (34%) along with some medium-grained sand and silty argillaceous material, 10% each. The medium-grained sand contains about 40% of the 0.315–0.200 mm fraction, accompanied by an appreciable amount of argillaceous material (about 20%). The light-mineral fractions of the two types of sand are very similar in composition, being dominated by angular and subangular fragments of quartz, feldspar and laumontite(?). The heavy-mineral fraction has a predominance of ore minerals (56–60%), and contains more staurolite (4.7–6.2%) and kyanite (3.4%), as well as single grains of glaucophane. Two kinds of silty-clayey material are interlaminated with the sandstones. Practically monomineralic clay consisting of 90% kaolinite occurs in the lower portion (beds 2–5, 2–3), whereas the upper portion has clayey material composed of kaolinite (60%) and montmorillonite (40%). A transitional variety consisting of kaolinite (85%) and montmorillonite (15%) occurs in the middle part of the unit. The mineral composition of the Valanginian clay differs from that of the Kimmeridgian-Volgian and Callovian-Oxfordian in the lack of hydromica and mixed-layer minerals, respectively.

4.2.5 Lower Cretaceous sedimentary-volcanic strata

Beds and partings of clay, calcareous and carbonaceous shales, brown coals, siltstones, sands, sandstones, grits, as well as tuffites and tuffs separate Lower Cretaceous basaltic flows and sheets.

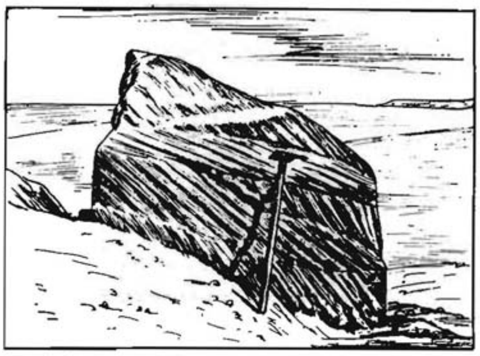


Fig. 4.9 Ephemeral-stream type bedding with beds dipping predominantly eastwards. Vasiliev Formation, central part of Hayes Island. Sketch by K.F. Nevskaya from photo by L.P. Pirozhnikov.

Fig. 4.10 Cross-bedded sandstone units, cemented with readily weathered argillaceous material; beds dip west-southwestwards. These units alternate with flat-lying layers of more resistant sandstone. This erosional remnant is about 3 m high. Vasiliev Formation, central part of the Kholmisty Peninsula, Graham Bell Island. Sketch by K.F. Nevskaya from photo by V.K. Razin.

Fig. 4.11 Erosional remnant of flat-bedded sandstones, central part of Hayes Island. Sketch by K.F. Nevskaya from photo by L.P. Pirozhnikov.

Berriasian-Barremian

Samples of thinly platy sandstone from beds separating basaltic sheets on Mount Ciurlionis and Cape Medvezhy on Hooker Island and overlying and underlying a 2 mm parting of brown coal were examined petrographically. They are fine- to medium-grained rocks with a psammitic texture. Their clastic portion consists of subrounded and angular grains of quartz (90%), flints (5%), very altered feldspars (5%) and sporadic garnets. The silty, fine-grained sandstone also contains minute flakes of biotite and sericite, and a detritus of carbonised flora. The cement (30–40%) is interstitial, and is carbonate containing cloudy, amorphous clots of organic matter, or silico-argillaceous replaced by limonite; it contains a few mica flakes. The sandstone includes very thin partings of coal-clay, shale and brown coal (up to 2 mm). Two samples from the unit associated with the brown coal were studied in immersion liquids. The light-mineral fraction is mostly composed of zeolite (thomsonite) in one sample and of highly altered mica(?) in the other. The heavy-mineral fraction totals 0.23–1.65%. Its terrigenous portion is chiefly clinopyroxene (74.2–82.2%). Authigenic minerals are iron hydroxides and pyrite.

According to Weber (1908), two basaltic sheets separated by polymictic sandstones and grits (as suggested by drift), and also shale and brown coal, are exposed on a southeastern cape on Hochstetter Island. A sample of grit housed in the Chernyshev Central Geological Museum was microscoped by L.A. Chaika (unpubl. report). Small pebbles (up to 1.0 cm) of sericitised mudstone, hornfelsed sandstone, granite-porphyry with a highly sericitised felsic groundmass and dolerite showing ophitic texture were identified.

Aptian-Albian

Carbonaceous siltstone containing coal seams at Cape Kavagli (Salisbury Island), and silty limestone found in weathered debris at the top of the uppermost bed on Alexandra Land, were examined in a microscope. The carbonaceous siltstone consisted of an opaque mass of highly decomposed detritus (70%) containing sand-sized and silt-sized grains of quartz, flints and plagioclase, as well as fragments (up to 3–4 mm) of charred wood. Argillaceous material containing minute flakes of mica was also present. The silty limestone is a very thinly laminated rock with a texture typical for such sedimentary rocks, and consisting of irregular calcite grains (60%) showing radial or undulatory extinction along with angular quartz and some feldspar, as well as tiny flakes of biotite and muscovite.

According to N.M. Krylova (Dibner & Krylova 1963), Barremian-Aptian and Aptian-Albian coals, like Norian-Rhaetian coal in Franz Josef Land, are typical humic rocks, equivalent to the brown coal stage. In composition, they are clarain and ultraclarain. Large fragments of yellowish-brown, platy sapropelite found on beach ridges on Scott-Keltie Island are the sole exception to this rule. These may have derived from the nearest bedrocks of the sedimentary-effusive strata.

4.2.6 Upper Cretaceous

Cenomanian

On Hoffmann Island, the upper Cenomanian marine deposits are represented by upward-fining, thickly flaggy, quartzitic sandstone overlain by semi-consolidated siltstone, totalling 35 m in apparent thickness. The sandstone has a granoblastic texture and mainly consists of quartz (85–95%) and flints which have a jagged outline and are almost adjoined; they have mostly been regenerated at the expense of the siliceous cement. The clastic portion also includes twinned feldspars (1–2%) and large calcites. Tiny calcite and siderite grains fill interstices in the rock. Rare flakes of muscovite and biotite and numerous minute grains of haematite occur in the cement, which consists of aggregates of minute mica flakes and quartz grains mixed with opaque argillaceous matter. Examination of the clastic material in immersion liquids showed that the terrigenous portion of the heavy-mineral fraction (0.23%) chiefly consists of leucoxene and unidentifiable titaniferous minerals, tourmaline, zircon and rutile. Pyrite is almost the only authigenic mineral.

4.2.7 Types of stratification – V.D. Dibner, Yu.A. Mikhailov

Two types of stratification, horizontal and cross bedding have been recognised. Cross bedding is almost confined to the mainly continental deposits. Two varieties occur. The first is characterised by an alternation of sandstones that have a similar granulometric composition and do not differ greatly in thickness. These sandstones, with steep foreset beds, may have been deposited in alluvial fans by ephemeral streams in an arid region (Fig. 4.9). This type of bedding is mostly recorded in the variegated deposits of the Vasiliev Formation. In the second type (Fig. 4.10), the cross beds are less steep and the material is more coarse grained and relatively loosely cemented and the cross beds alternate with thin, flat beds of fine-grained, well-cemented sediment, the cementation being a result of the concentration of solutions above dense, argillaceous impermeable rocks.

The limited data available show that the cross beds in the Vasiliev Formation dip: (i) west-southwestwards (the northern part of Graham Bell Island and at Cape Hofer on the southwest end of Wilczek Land), (ii) eastwards (in central and western parts of Hayes Island and on Cape Vasiliev on Wiener Neustadt Island), and (iii) westwards (the western part of Hayes Island).

The lower and upper parts of the Vasiliev Formation and the Wilczek and Tegetthoff Formations are typically flat bedded. The coarseness of these deposits (Fig. 4.11) suggests that these units may have been deposited in relatively small lakes occupying depressions. Cross-bedded deposits of alluvial fans may have accumulated around the periphery of the depressions. Horizontal bedding probably of the same origin is also characteristic of Lower Cretaceous continental (interbasaltic) deposits. Marine deposits, such as the Kimmeridgian and younger beds on Berghaus Island (Fig. 3.4.10), are generally flat bedded.

Three types of stratification, namely, horizontal lamination, "ribbon" horizontal lamination and lenticular-sinuous bedding are exhibited by the Callovian and Upper Jurassic deposits at Cape Hofer and Cape Lamont. Horizontal lamination with 1–3 mm thick laminae is typical for the argillaceous siltstones of the Callovian-middle Volgian "black clays". The lamination is responsible for the foliate appearance of the deposits. Ribbon horizontal lamination with laminae ranging in thickness from 0.5 to 2.5 cm is formed by rapid interstratification of sands and clayey silts. The boundaries of the laminae are sharply defined, straight and slightly sinuous. Such lamination is displayed by the early to middle Volgian "dark sands" and by sands deposited in the lower parts of sedimentary cycles in the middle Volgian-Berriasian "light sands". Lenticular-sinuous bedding with 0.5 to 1.5 m thick beds occurs in the upper parts of cycles in the Berriasian deposits. The boundaries of the beds are outlined by lenticular accumulations of gravel and pebbles. Similar bedding was observed in the upper part of the "yellow sands", assigned to the Upper Triassic.

5. PLATEAU-BASALT MAGMATISM

The Mesozoic-Cenozoic plateau basalts of Franz Josef Land are part of the trans-Arctic plateau-basalt belt first recognised by V.D. Dibner and A.V. Zimkin (Atlasov & Dibner 1969, Atlasov et al. 1970a, b). The belt embraces a number of Arctic and subarctic regions and stretches through the Polar Basin from the North Atlantic to the Northwest Pacific. It includes numerous terranes of basic effusives and associated hypabyssal intrusions. The basalts are now exposed on the ancient and young platforms of Greenland, the North Atlantic Caledonides and the northern part of the Barents Shelf plate, and in the Pacific segment they occur in the Palaeogene of the Okhotsk-Chukchi volcanic belt, where basic magmas occur in the central massifs of northeastern Asia, as well as in the Miocene-Pliocene volcanic belt in the De Long Islands and northwest of Wrangel Island (Gelman & Bely 1963, Kosko 1984).

The following is an account of the petrography of the effusives and tuffs of the Lower Cretaceous sedimentary-volcanic sequence (sheets and a shield subvolcano), the stratigraphy of which is presented in section 3.5, the geology and petrography of the hypabyssal intrusions, the geochemistry of the plateau-basalt association, the magnetic properties of the basic igneous rocks, and the K-Ar geochronology of the basic magmatism.

5.1 PETROGRAPHY OF BASALTIC SHEETS - B.I. TEST

This section is based on the petrographic study of samples collected by V.D. Dibner, L.P. Pirozhnikov and V.K. Razin in 1953, 1956 and 1957 (sample numbers from the collections made in 1956 and 1957 are asterisked).

The basalts of Franz Josef Land are relatively monotonous in mineralogical composition, comprising olivine basalts with 6–12% olivine, and rocks containing significantly less olivine, for convenience referred to as olivine-free basalts. However, the rocks show a variety of textures, depending on the degree of crystallinity relative to glass and variations in petrofabrics. For instance, the author (Test 1937) has earlier recognised a rare intersertal texture in basaltic sheets, a very large group of basalts showing tholeiitic textures (i.e. where glass is distributed more or less evenly in

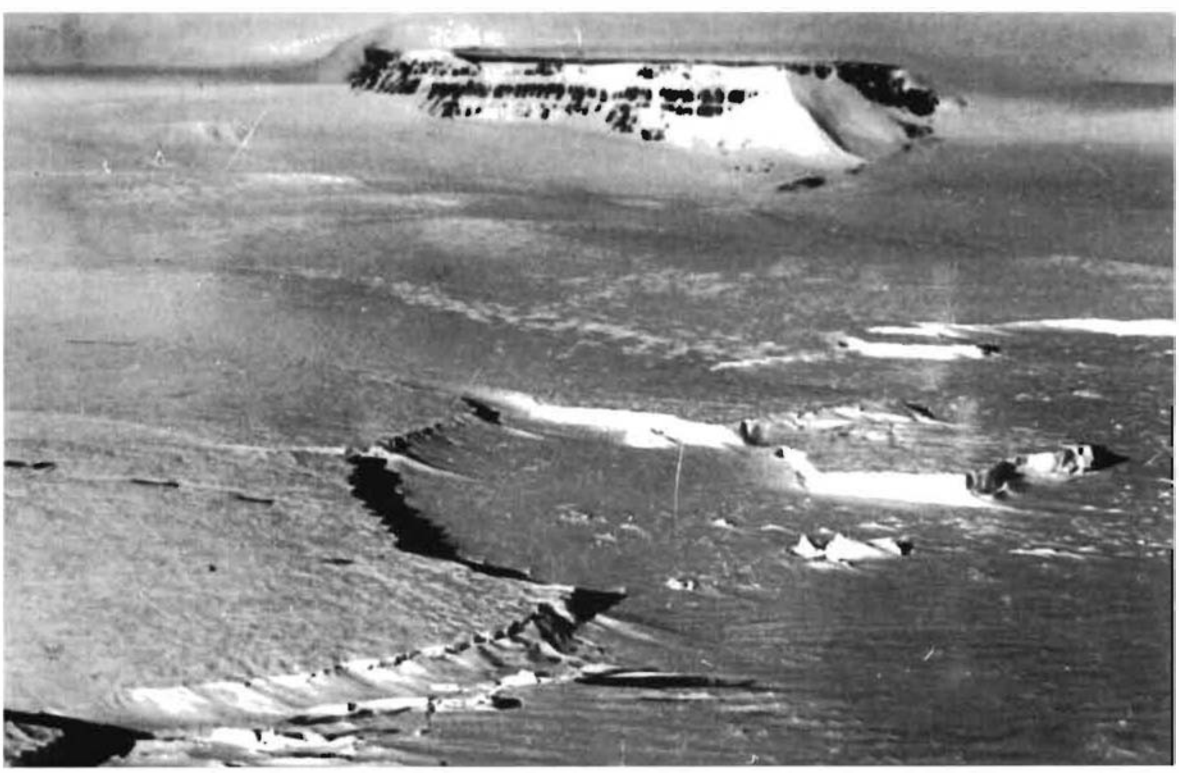


Fig. 5.1 Tass Nunatak on the Hooker Island ice cap, formed of basaltic sheets. View from Tikhaya Bay Polar Station. Photo: D.V. Levin.

the rock) and differing in the presence or absence of microlites and phenocrysts in the glass, and vitreous textures also differing in the presence or absence of microlites in the glass, or in other features of the petrofabric. The position in the sheet where the basalt crystallised determines which variety of basalt forms. For example, the upper parts of sheets and thin (2–3 m) sheets acquire an amygdaloidal texture and were distinguished by the author as amygdaloidal basalt (Test 1937). The lowermost part of sheets contains feldspathic hyalobasalt, rich in glass.

5.1.1 Olivine-free basalt

Macroscopically, this is dark grey or brown, locally almost black, fine grained or sometimes medium grained, in places displaying plagioclase phenocrysts which are locally fawn coloured. Three generations of plagioclase, two, or very rarely three, generations of clinopyroxene, less commonly orthopyroxene, two generations of ore minerals, an insignificant amount of olivine, smoky glass replaced by palagonite, apatite and secondary minerals are recognised.

The *first-generation plagioclase* consists of separate prismatic or tabular phenocrysts, or, more commonly, glomeroporphyritic aggregates of a few or many crystals. It is rather evenly scattered through the rock, usually reaching 10–15%, up to 25–35%. The phenocrysts occur in two sizes: 0.5 x 1.5 mm and 0.5–0.8 x 3.5 mm. In some cases, prismatic crystals are as long as 8.0 mm. Zoned plagioclases are common; fused grains are less common. The plagioclase is mainly fresh, but is occasionally zeolitised. Tiny inclusions of ore minerals and buff, mica-like palagonite are common, and occasional examples of smoky, vitreous material can be observed along cracks. The plagioclase phenocrysts are labradorite-bytownite in composition.

Second-generation plagioclase helps to form the groundmass. It consists of small, euhedral laths forming thin multiple twins, 0.1–0.5 mm up to 0.5–1.0 mm in size, and randomly scattered microlites. It is fresh, except for a few cases where palagonite is observed along cleavage cracks. Plagioclase laths are commonly included in pyroxenes and ore minerals, and less commonly in olivines. This groundmass plagioclase is generally labradorite, rarely labradorite-bytownite.

Third-generation plagioclase consists of very narrow microlites of quite fresh plagioclase enclosed in glass. Their composition is An_{40-45} (symmetrical maximum extinction angles 20–24°). However, microlites of more acid plagioclase are probably present since refractive indices are sometimes less than that of Canada balsam.

First-generation clinopyroxene consists of phenocrysts which are less common than those of plagioclase. They form large, isometric crystals up to 3.0 mm across. Locally, they form simple twins or intergrowths of several grains, rarely together with plagioclase phenocrysts. The pyroxene is fresh, mostly colourless, but occasionally fawn or greenish-yellow. It sometimes contains poikilitic inclusions comprised of plagioclase laths. Inclusions of tiny pseudomorphs after olivine, or minute grains of magnetite, are rarely seen at the edges of pyroxene grains. Magnetite grains sometimes overgrow clinopyroxene. Phenocrystic pyroxene is enstatite-augite.

Second-generation clinopyroxene, along with plagioclase, is a substantial constituent of the groundmass. It forms fresh, anhedral grains, 0.05–0.1 mm up to 0.4 mm in size, filling interstices between plagioclase laths, and generally contains poikilitic inclusions of lath-shaped plagioclase. Second-generation clinopyroxene is usually slightly buff-coloured or, less commonly, slightly pinkish.

Third-generation clinopyroxene is much less common than third-generation plagioclase. It forms very minute, optically unidentifiable, anhedral, sometimes acicular, fresh lilac-tinged grains. The colour suggests that the pyroxene is rich in iron and titanium.

Orthopyroxene is rare. Vlodavets (1934) described hypersthene phenocrysts that were reabsorbed along their margins. He determined the 2V of two crystals as –54° and –55°, and they had an anomalous extinction angle (CNg) of 6°. Hypersthene phenocrysts are mainly rimmed by numerous minute grains of clinopyroxene with a low axial angle and positive sign, suggesting enstatite-augite. The author found a little orthopyroxene in thin sections from sheets at Cape Medvezhy (thin sections 431s, t, f) and on Scott-Keltie Island (thin sections 289a, b) occurring as prismatic, sometimes short prismatic or isometric crystals, up to 0.5–1.2 mm long and 0.1–0.4 mm wide. Poor pleochroism is observed in places. Extinction is straight, rarely up to 2–3°. Rims of tiny clinopyroxenes are sometimes seen on orthopyroxenes (thin sections 289a*, 431c and 1088e, the last one from a sheet exposed north of Inaccessible Rocks on Salisbury Island). Single crystals of plagioclase are locally observed in orthopyroxene phenocrysts.

Measurements of orthopyroxene made by M.A. Krutoyarsky (unpubl. manus.) on a Fedorov universal stage indicate enstatite (CNg = 0–2°, 2V = +62 to +66°) and bronzite (CNg = 0–2°, 2V = –80°).

In most of the samples examined, olivine occurs as rare relict grains almost completely replaced by green or buff palagonite which is always anisotropic; calcite and dolomite occur together along cracks in the palagonite pseudomorphs, sometimes in the centre of grains. Separate, fresh colourless grains of olivine are less common. Optic axial angles of olivine obtained on a Fedorov stage vary as follows: 2V = +76 to +90°, Ng – Np = 1.715 – 1.720.

Two generations of ore minerals occur, probably magnetite and titanomagnetite. The first-generation grains are anhedral, or sometimes irregular-rectangular crystals and growths in the groundmass. Pyroxene and plagioclase contain ore minerals as rare isolated grains and ore minerals very rarely form phenocrysts. Second-generation ore minerals are skeletal crystals, narrow needles and dust in the hyaline groundmass.

Glass filling interstices between mineral grains in the groundmass and making up the groundmass itself is either smoky, or almost colourless, and shows incipient crystallisation. It is often packed with ore dust and microlites of other minerals, locally becoming almost black, and has a refractive index that is less than that of Canada balsam, or is buff, almost opaque, and has a refractive index in excess of Canada balsam. The glass is frequently replaced by palagonite, which occurs as separate spots or veinlets. Palagonite also forms pseudomorphs after olivine, sometimes replaces augite and plagioclase, and makes up most amygdules.

Apatite occurs as long needles in the groundmass and rarely as hexagonal, isotropic grains. It is found where the rock is most completely crystallised. Zeolite (analcite) forms rare aggregates in the vitreous groundmass. Minute (0.01 mm), rounded grains of xenolithic quartz, included in the magma during its passage through quartz-bearing sediments, occur extremely rarely (thin section 431c from Cape Medvezhy).

5.1.2 Olivine basalt

Unlike the basalt described in section 5.1.1, olivine basalt (Figs. 5.2 & 5.3) contains an essential amount of olivine. Test (1937) and Lupanova (1953) recognised basalts whose olivine content locally reached as much as 6–12% (the islands of Scott-Keltie, Nansen and Hooker). Similar percentages were found in samples subsequently collected by V.D. Dibner and coworkers on the islands of Scott-Keltie, Hooker (Mount Ciurlionis) and Rudolf (Cape Säulen). Most of these samples (thin sections 295a*, 312A*, 312B*, 279* and 303*) contain insignificant amounts of glass, with olivine almost completely replaced by palagonite, or even with complete pseudomorphs of palagonite after olivine. Olivine basalt containing a great quantity of glass and showing polyintersertal and vitreous textures in the groundmass was also found (thin section 277* from Mount Ciurlionis). Olivine is almost completely replaced. As mentioned above, the olivine and olivine-free basalts show the same textures (Test 1937) and therefore crystallised in similar environments (Fig. 5.2:3).

Petrographic studies have shown that the basaltic sheets of Franz Josef Land display a relatively constant composition and, in some measure, a symmetrical structure across a sheet, as noted earlier (Test 1937). Thus, the central parts of a sheet are composed of the most crystallised olivine-free basalts and, less commonly, olivine basalts which have intersertal and tholeiitic textures whose interrelationships are uncertain. Towards the upper and lower contacts, these basalts are replaced by increasingly vitreous varieties. Hence, the upper parts of a sheet, composed of very porous basaltic amygdaloidal rocks, show hyalopilitic and vitreous textures in the groundmass. The scoriaceous margins of basaltic sheets contain, along with the usual amygdules, large aggregates of calcite and geodes (up to 20–30 cm) filled with siliceous minerals and calcite which formed during the final stages of the cooling of the sheet (Figs. 5.3 & 5.4); large aggregates of chalcedony with plant remains are the latest of these.

Siliceous sinter found on the surface of the upper sheet on Alexandra Land (thin sections 28d, 37 and 38) and in basaltic debris at the foot of Mount Ciurlionis on Hooker Island (thin sections 272b, 247b) is comagmatic and, probably, coeval. The sinter is a porous, orange-coloured rock composed of almost isotropic opal slightly stained with iron hydroxides and containing a few clay particles. Hyalobasalts, with hyalopilitic, or sometimes hyalo-ophitic and hyaline, groundmass textures, are observed at the lower boundary which is in contact with sediments and basaltic tuff.

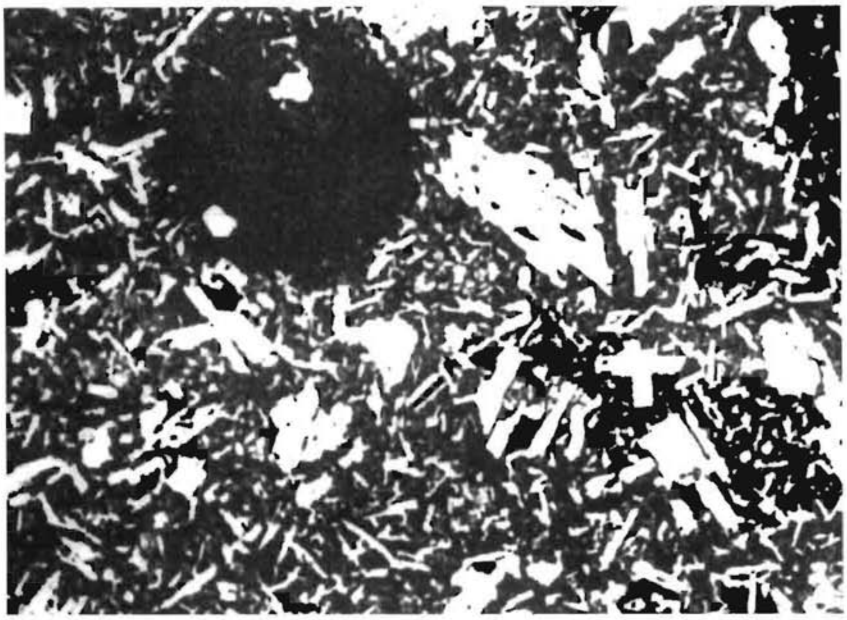


Fig. 5.2 Photomicrographs of basalts. 1 well-crystallised basalt with a rounded fragment of volcanic glass (typical of tholeiites) from the upper sheet on the Ciurlionis plateau, Hooker Island; thin section 278 (1957), x 16, plane light; 2 porphyritic-like hyalobasalt from the base of a thick sheet in the Cape Kavagli area, Salisbury Island, thin section 1089a (1957), x 28, plain light; 3 fine-grained olivine-bearing dolerite from a sill intruded between basaltic sheets which form Scott-Keltie Island, thin section 295a (1957), x 28, plain light.

Most basaltic sheets have porphyritic, or locally glomeroporphyritic, textures with basic plagioclase (labradorite-bytownite) and clinopyroxene (ensta-tite-augite, augite), typical of basalt, large amounts of ore minerals (magnetite and titanomagnetite) are found, and also locally olivine and, in many samples, orthopyroxene (enstatite, bronzite). Palagonite often replaces glass in patches, spots and veinlets. It also generally replaces olivine and sometimes augite and plagioclase, makes up most of the amygdules and fills interstices between any minerals.

The Nagurskaya borehole on Alexandra Land (drilled through the graben that crosses the island as an extension of the Dezhenev Bay channel) passed through a 400 m thickness of the sedimentary-volcanic sequence, the upper volcanic sheets of which consist of zeolitised, subalkaline trachyandesite basalt (Piskareva & Kovaleva 1975).

Contact metamorphic effects

According to Spizharsky (1947), Lupanova (1953) and Dibner (1970), the thermal effect of the basalt sheets on the underlying rocks can be seen to a depth of 0.2–0.4 m. The strongest alteration is observed in clays, which not only become very compact and acquire a dark red or violet colour, but locally turn into thinly schistose shale which contains fine balls of buff glass and is transected

Fig. 5.3 Hydrothermal minerals from the top of a basaltic sheet: sinter forms of opal on the left, chalcedony on the right. Central land on Alexandra Land (1956).

Fig. 5.4 Geode with opal, rock crystal and calcite from the amygdaloidal margin of a basaltic sheet. Cape Khromtsov, George Land (1953).

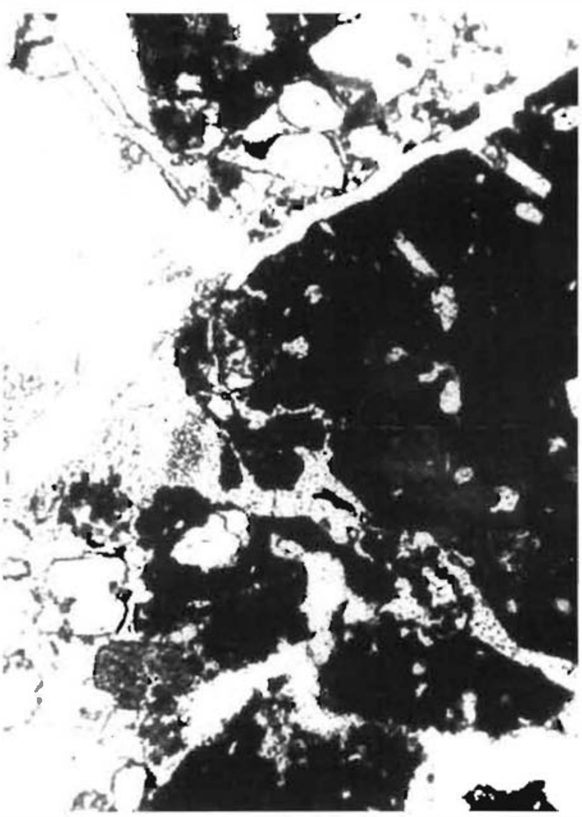
by the finest veinlets of calcite. Psammites and psephites are also substantially contact metamorphosed (to 0.2–0.4 m), and coal is graphitised or turned to ash.

5.2 SHIELD SUBVOLCANOES

5.2.1 Inaccessible Rocks – A.N. Tarakhovsky

A subvolcano is located on the southwest slope of Inaccessible Rocks on Salisbury Island where it was discovered and studied by the author in 1980 (A.N. Tarakhovsky, unpubl. manus.). It is a shield-type edifice exposed in a cliff for 8 km. Its height varies from 25 m in the southeast to 190 m 3.5 km away, in the centre (locality 164).

The volcanic edifice overlies an eroded surface of sandstones and shales, rounded lava tongues apparently having flowed into depressions in an old, rugged topography. Pockets of calcite contaminated with buff iron oxides, locally with semi-transparent calcite (up to 0.5–0.6 m across), occur in the basal part of the volcanic rocks.



Most of the edifice consists of chilled, vitreous, lava breccia. It contains clasts of basalt, particularly in the lower part, which vary in texture and degree of crystallisation and amount to 30–40% of the volume. They vary in size from a few centimetres up to at least 3 m, and are mostly rounded and fused. The number of xenoliths decreases upwards. The basalt forming the clasts is mostly amygdaloidal and is olivine-pyroxene plagiophyric, pyroxene plagiophyric or plagiophyric in composition. The texture is similar to that of the groundmass of the basaltic sheets described in section 5.1.

The lava cementing the clasts consists of dark-buff glass containing intact crystals and fragments of crystals of plagioclase and clino-

Fig. 5.5 Vitreous lava cementing lava breccia; rounded fragments of quartz and plagioclase in calcite-healed fissures. Thin section 162 (1980), plain light, x 36.

Fig. 5.6 Crest-like flow of amygdaloidal basaltic lava breccia, scoria on Inacessible Rocks.

pyroxene, rounded and irregular fragments of basic rocks, and lumps of glass distinguished from cementing glass by a lighter or darker colouring. The whole rock is transected by fissures healed with calcite. Rounded fragments of quartz, plagioclase and orthoclase are common in the fissures (Figs. 5.5 & 5.6).

Further up, ridge-like flows up to 50–70 m long, 3–5 m wide and 2.5–4.0 m high can be recognised. They consist of basalt, similar to that forming the clasts at the base. These flows commonly show fragmentary prismatic or sharp-edged jointing. Small lumps of lava are seen at their base, which otherwise consists of volcanic glass. The flows may have poured out along wide rents in the xenolithic lava which had still not chilled. Basaltic bombs and lapilli occur in the lava. Pancake-shaped to ball-shaped bombs vary in size from a few centimetres to 1.0 m across. They exhibit a distinct amygdaloidal texture. Where the lava contains no bombs or xenoliths, it is broken into flat slabs with subparallel sides. Fragments of silicified trunks of *Xenoxylon* sp. and other remains are scattered throughout the lava suggesting, according to I.A. Shilkina (unpubl. manus.), that the subvolcano formed no later than the Lower Cretaceous.

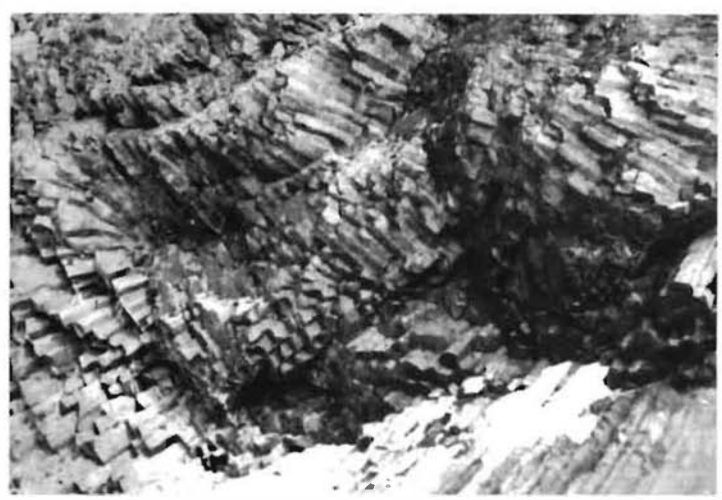
5.2.2 Cape Flora – V.D. Dibner

Nansen (1900) mentioned a gigantic block of basalt (which he called Castle Rock) standing on the low raised beach at the foot of a steep slope on Cape Flora, Northbrook Island. Hoel & Holtedahl (1911) discussed this and believed that it might represent either a block fallen from the mountain top, or a volcanic pipe filled with lava, similar to Halvdan Neck, a Quaternary volcano on the north coast of Wood Bay in Svalbard. H. Johansen, Nansen's companion, reported seeing a similar basaltic block (round in cross section) at another locality on Cape Flora, in the middle of a steep slope (Nansen 1900). This was unlikely to have fallen from the mountain top since it could not have stopped in the middle of the slope, and it cannot be ruled out that this, and perhaps other blocks, represent embryonic volcanoes.

5.3 HYPABYSSAL INTRUSIONS – V.D. DIBNER

Medium-grained, holocrystalline basic rocks were found in Franz Josef Land much earlier than typical basalts. For instance, as early as 1873, in the first observations made concerning geological features in Franz Josef Land, J. Payer discovered that Wilczek Land was composed of "columnar" dolerite. During a sledging journey in 1874 he found similar rocks on some islands in eastern Franz Josef Land from Hall Island (Cape Tegetthoff) in the south to Koburg Island and Rudolf Island (Cape Fligely) in the north. Payer (1876) more than once noted distinct columnar jointing in dolerites. At some localities, the jointing excels in its regular arrangement and the splendour of its tower structure, and at other sites it occupies different angles. In the same (eastern) part of Franz Josef Land, Nansen (1897a) observed outcrops of coarse-grained basalt, showing well-defined

Figs. 5.7 and *5.8* Radial columnar jointing in the dyke swell on Rubini Rock (upper photo) and in a thick intrusion forming Shenaw Island. Photos: V.D. Dibner and O.V. Mironov, respectively.



columnar jointing. This basalt forms Cape Bam, a picturesque, high (up to 100 m) ridge which is as sharp as a knife blade (it is probably a dyke). Nansen also compared Cape Helland with Milan Cathedral. Although neither Nansen nor Payer put forward suggestions concerning the geological relationship between igneous and sedimentary rocks, it is apparent from their observations that the igneous rocks they observed differed greatly from typical basalts subsequently studied in the western part of Franz Josef Land.

Koettlitz (1897, 1898) remarked on this difference. His geological explorations allowed him to suggest that, along with the basaltic sheets that were widely developed in the west, there were also sills and dykes, but he did not hazard a guess at their precise spatial distribution. Among other things, interesting drawings can be seen in Koettlitz's works which depict rocks showing prominent jointing, among basaltic sheets with poor jointing. Prominently jointed columns are strongly curved in different directions, forming the "curved structure of columnar basalt" (Koettlitz 1897, 1898) (Figs. 5.7 & 5.8).

In this respect, the rocks of sills and dykes differ greatly from basaltic sheets, only the centre of which show indistinct jointing which disappears completely in the upper, amygdaloidal, part.

Geological mapping in 1953–1957 and subsequent stratigraphical drilling show conclusively that not only dykes but sills are widely developed in Franz Josef Land. They are very similar to effusives in mineral composition, but differ in texture.

5.3.1 Dykes and their apical swells

The islands of Franz Josef Land and, as suggested by aeromagnetic, geological and hydrological data, the intervening straits and sounds have many dykes which form a system covering the entire archipelago (Figs. 5.9 & 5.10). They vary in thickness from a few metres to 20–25 m, and oc-

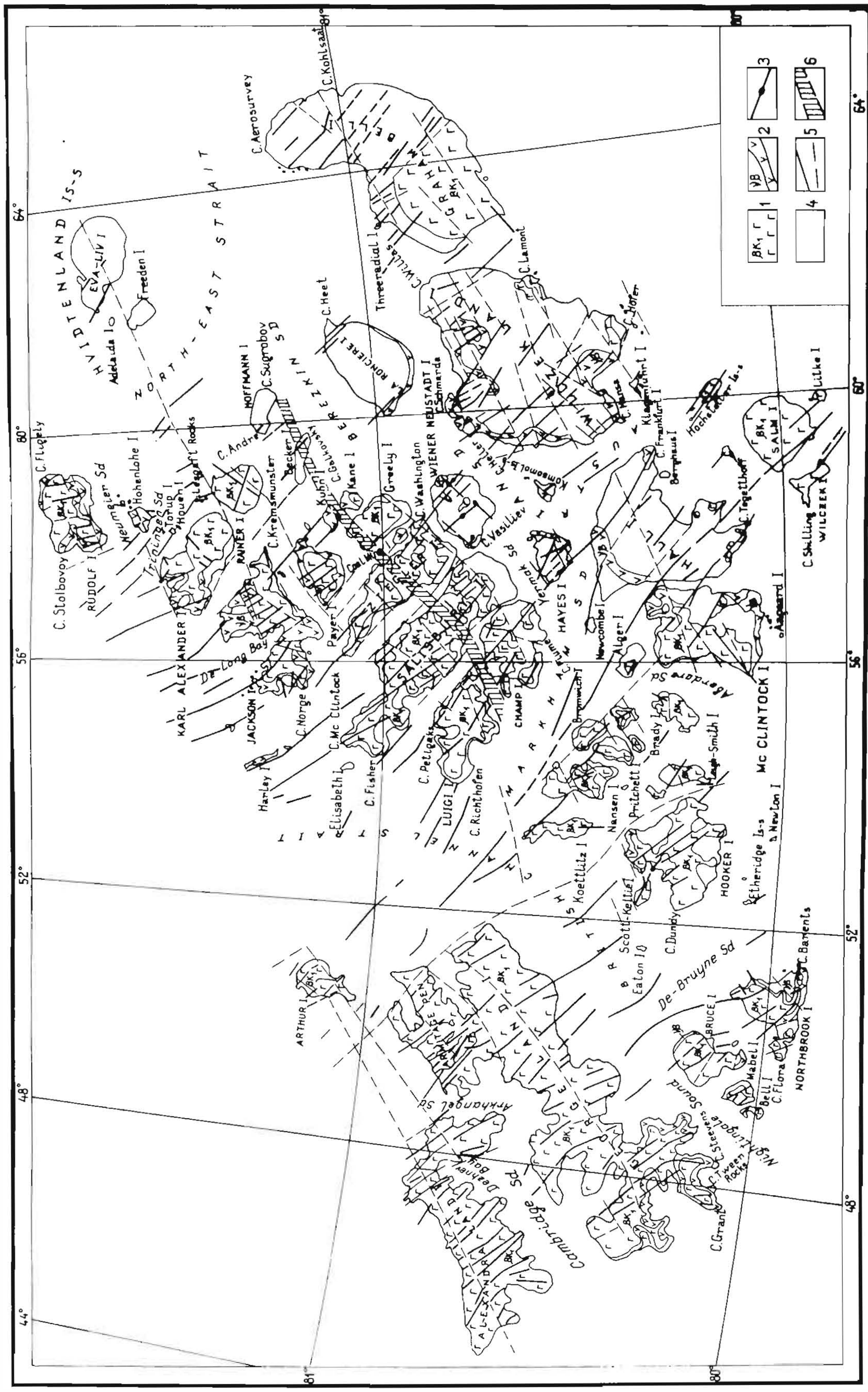


Fig. 5.9 Sketch map showing the igneous and tectonic structures related to the plateau-basalt association. Key: 1 Lower Cretaceous sheets, 2 sills, 3 dykes and their swells, 4 Carboniferous-Cenozoic sedimentary rocks, 5 faults: proved (a) and inferred (b), 6 deep-seated fault zone.

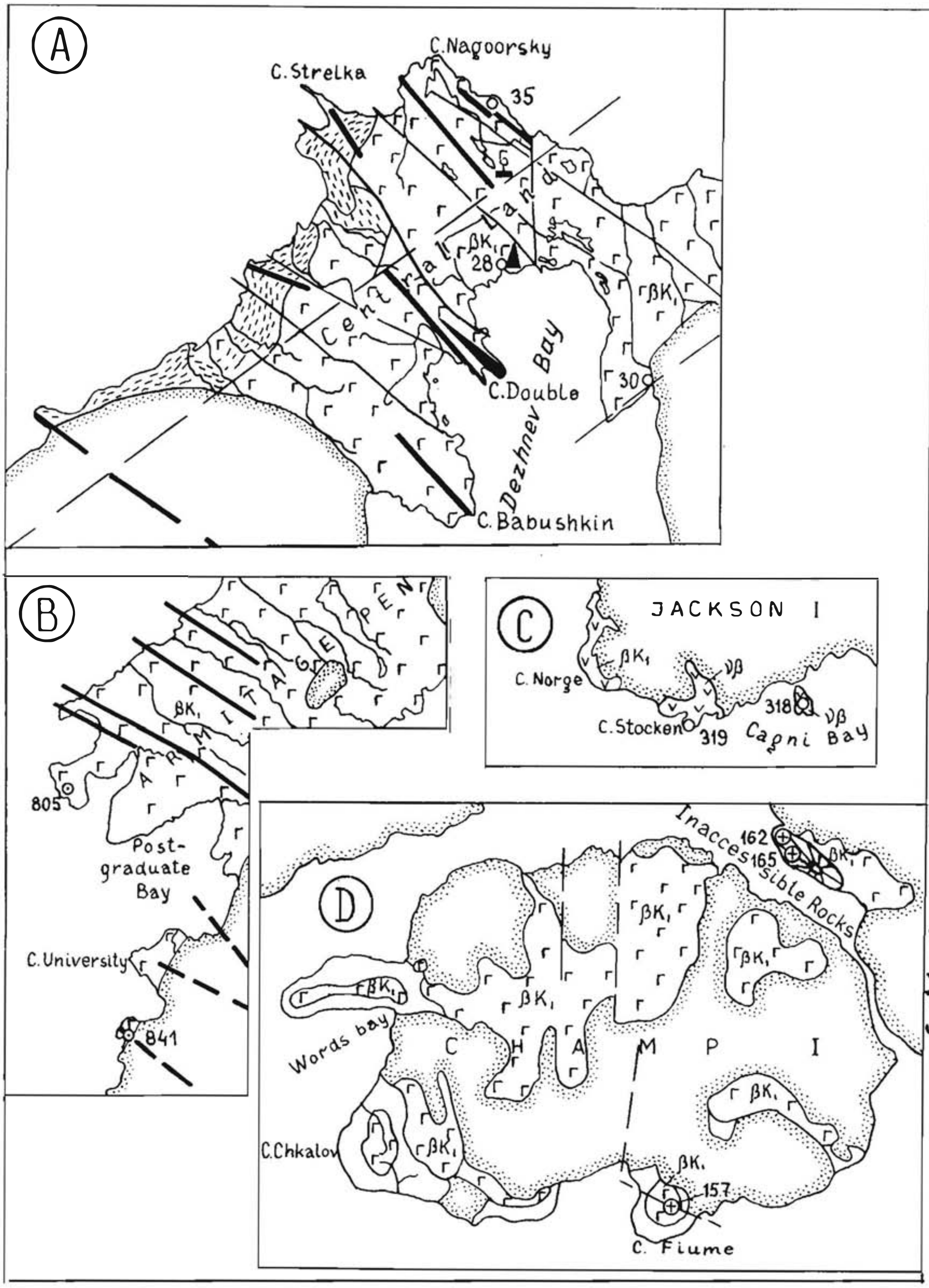
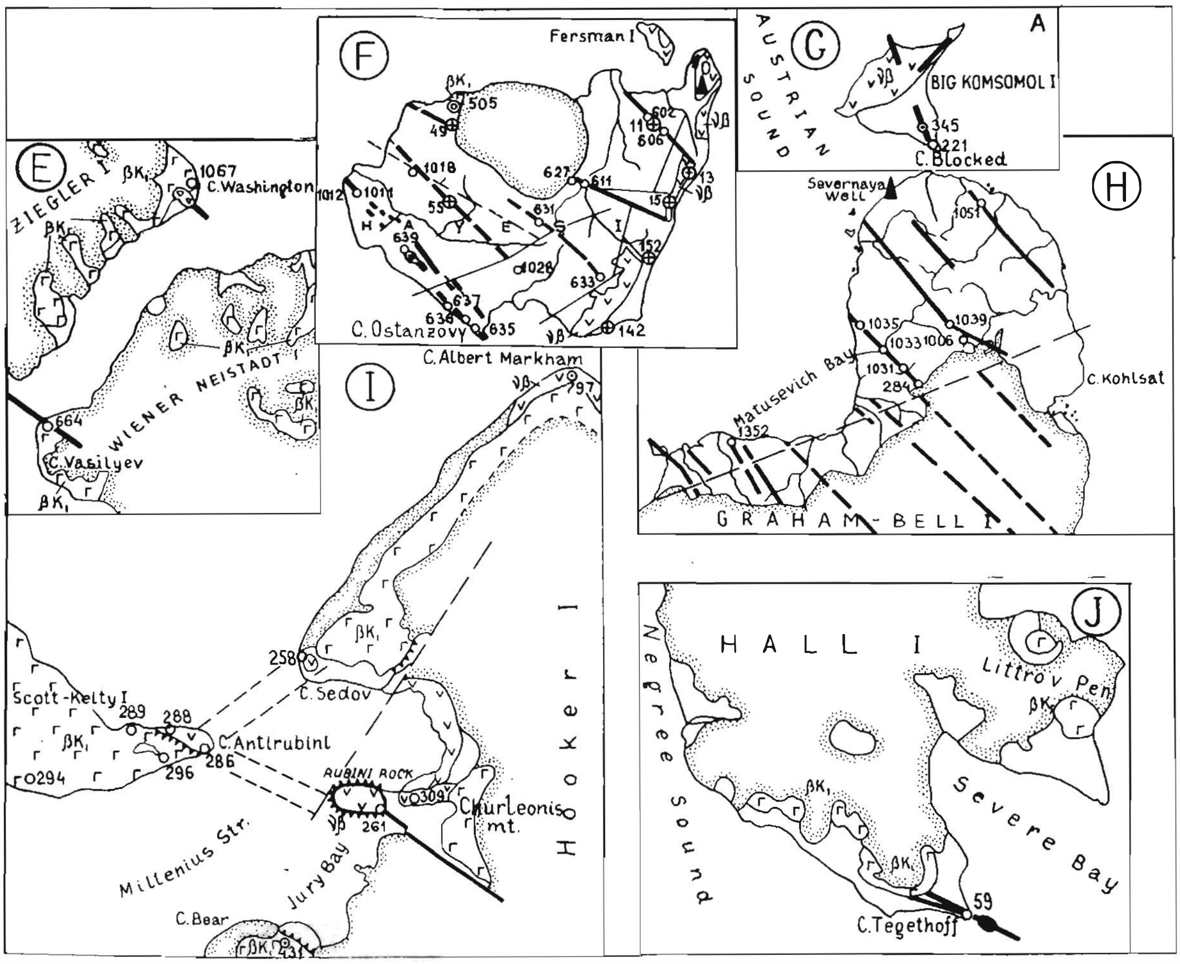


Fig. 5.10 A–L Detailed sketch maps showing igneous and tectonic structures related to the plateau-basalt association. A Alexandra Land, B George Land, C Jackson Island, D Champ Island, E Ziegler and Wiener-Neustadt islands, F Hayes Island, G Bolshoi Komsomolsky Island, H Graham Bell Island, I Hooker Island, J Hall Island, K capes on Wilczek Land, L Location map for the detailed sketch maps. Key: 1 sheets: a) exposed, b) buried under a thin cover of Quaternary deposits. Mesozoic-Cenozoic hypabyssal intrusions and subextrusive piles: 2 sills, 3 dykes and swells, 4 swells filled with agglomeratic tuff, 5 Inaccessible Rocks subvolcano, 6 sedimentary rocks, 7 glaciers, 8 faults. Outcrops: 9 and 10 studied by geological parties in 1953 and 1956–57, respectively; 11 studied by V.D. Dibner in 1976, 12 studied by A.N. Tarakhovsky in 1979–80; 13 boreholes, 14 polar stations and observatories.

Fig. 5.10 continued



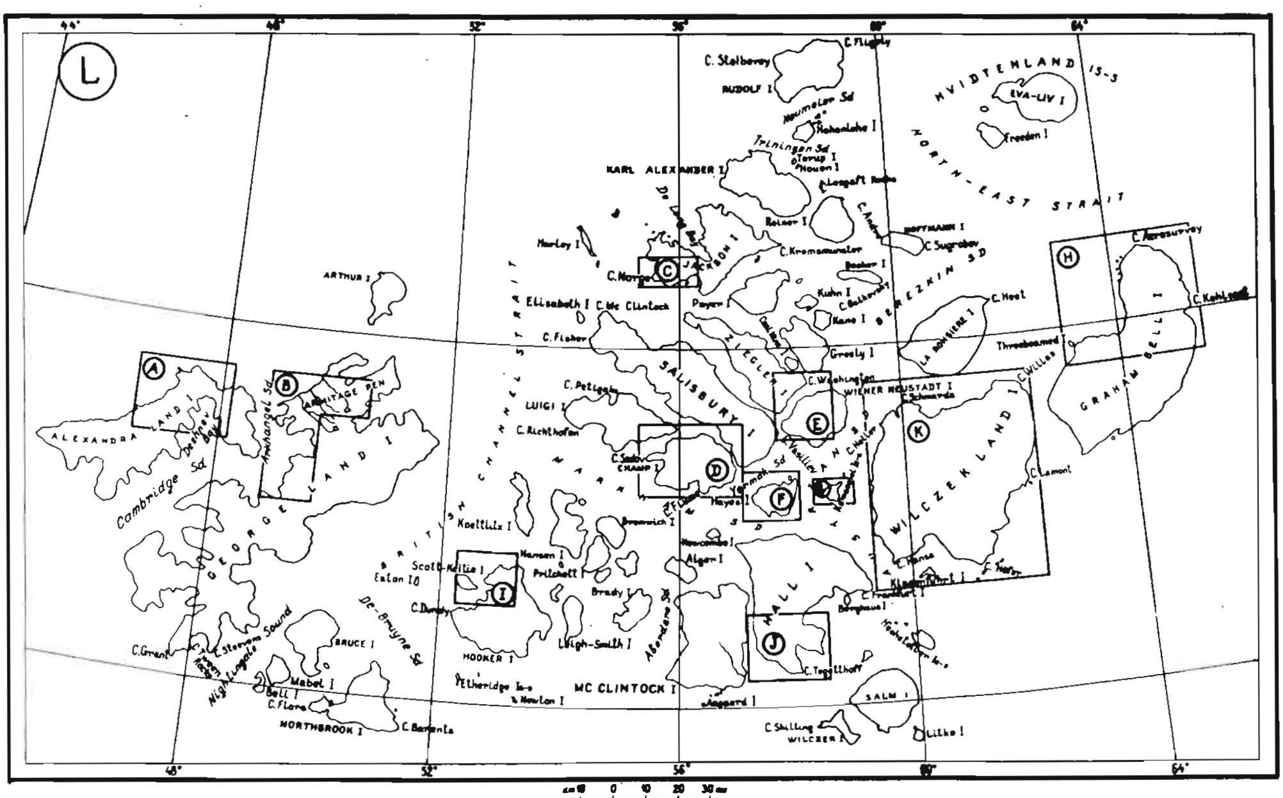
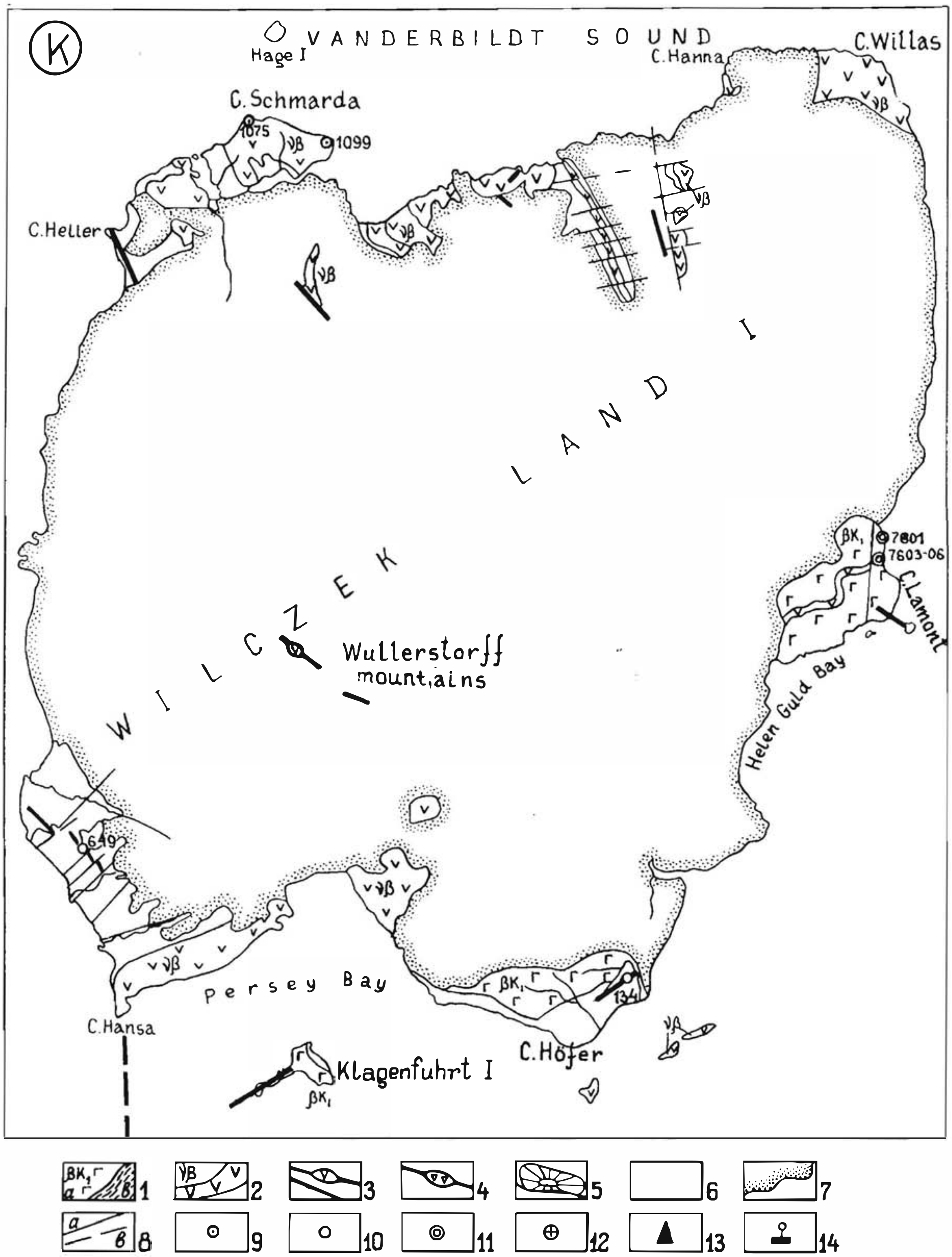


Fig. 5.10 continued



casionally form swells as thick as a few hundred metres (the swells are considered below). The narrowest dykes, made up of harder (glassy) rock, form the highest, ridge-like outliers (Fig. 5.11). Dyke contacts are almost vertical.

There is no doubt that these dykes constitute the most spectacular linear topographical features in Franz Josef Land. They usually form abutments of capes, and also occur as separate nunataks, for instance, the Wullersdorf Mountains on Wilczek Land. In places, dykes, as it were, show through relatively thin glacier ice, being reflected in the glacial topography (Figs. 5.10 & 5.12). Dyke ridges also predetermine stationary polynias in the sea ice of straits and sounds. Because

Fig. 5.11 Crestal monadnocks along a narrow dyke of vitreous dolerite. Southeast corner of Hayes Island. Photo: V.D. Dibner.

they disturb the thermodynamic regime in the water body, the sea-floor dyke ridges can be traced along narrow crevices in the sea ice, often in continuation with dykes on islands. An example is the dykes in Triningen Strait which are the submarine extension of the Lesgaft skerries. The development of polynias above dykes is the result of a drastic, local decrease in the depth of the sea and a corresponding increase in the strength of the current and, according to a hydrologist, D.D. Latkin (unpubl. manus.), a rise of Atlantic water above ridges in the sea-floor topography (Fig. 5.13). One dyke that was traced in this way is oriented NW-SE and crosses the islands, straits and sounds of Franz Josef Land from Hochstetter Island across the islands of Hall, Hayes, Champ and Luigi to Cape Petigax, a distance of 140 km.

In 1961, Franz Josef Land was covered by an aeromagnetic survey on a scale of 1:1,000,000 carried out by an expedition organised by the Russian Institute of Arctic Geology (D.V. Levin, A.M. Karasik and coworkers, unpubl. manus.). As a result, the magnetic framework formed by the igneous bodies and pyroclasts of the plateau-basalt association, was mapped. The geographical ranges of complex, reversed T fields coincide with the terranes of the most completely preserved basaltic sheets whose maximum aggregate thicknesses are observed on the central islands. Zones of quieter magnetic anomalies, persistent in intensity, are induced by sills of basic rocks.

The most impressive are multiple, linear T anomalies, mainly oriented NW-SE, which cross "complex" and "quiet" anomaly fields and which can sometimes be traced across the whole archipelago. They appear to be caused by NW-SE trending dykes, some of which are known to exist from direct field observations. However, when the aeromagnetic data were being interpreted, a discrepancy between the usual, modest thicknesses of the dykes (a few metres) and the width of the zones of linear anomalies (a few hundred metres) was evident. According to Volk (1964), this can to

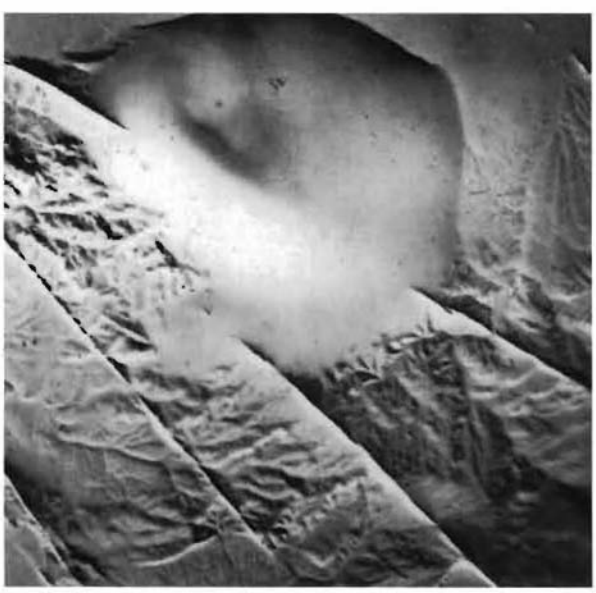


Fig. 5.12 Doleritic dykes cutting Upper Triassic sand and sandstone; the dykes are traceable below and above glacier ice. Aerial photograph of the north-central part of Hayes Island.

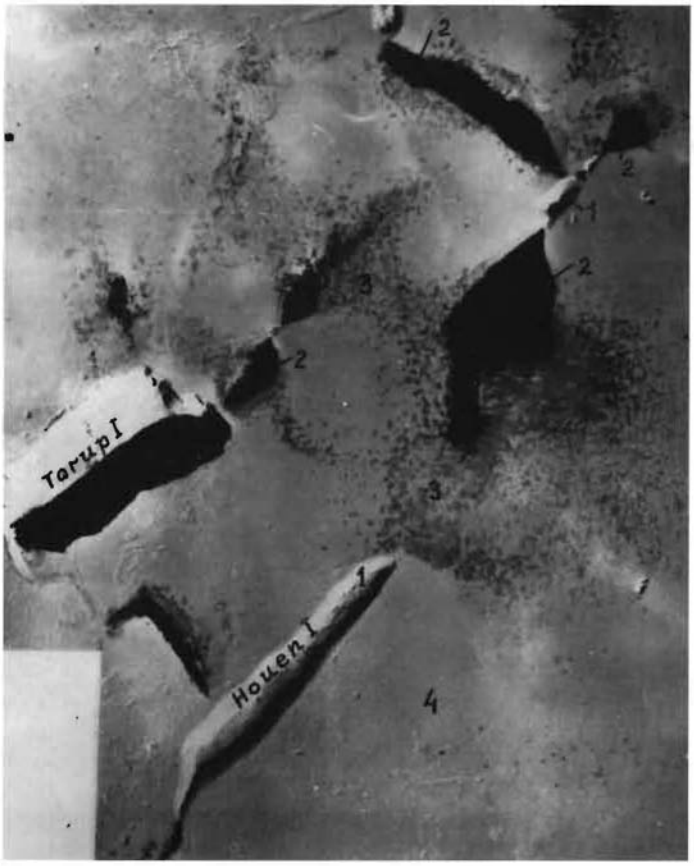


Fig. 5.13 Dykes and steeply dipping sills on the islands and bottom of Triningen Sound. Aerial photograph. 1 transgressive intrusions and sills, forming islands, 2 the same on the bottom of the sound (marked by polynias), 3 weak (current-eroded) ice, 4 ice field.

some extent be caused by a time lag in the readings and by "blurring" of the anomaly with height, but is mainly a result of geological features.

As remarked above, not only dyke swells and explosion pipes, but also the sheets and sills which were fed by them, and possibly older sheets crossed by the dykes and sills, are noted for their extremely high residual magnetisation brought about by accumulations of magnetite and titanomagnetite (in schlieren). In view of this, the large anomalous (magnetic) effect over the dykes is not surprising. Moreover, probably an insignificant proportion of the swells present in Franz Josef Land have been exposed by erosion, especially considering that only 15% of the land area is ice free. Many swells may have formed within dykes in places where they cross relatively soft sedimentary beds.

The composite effect of magnetite mineralisation, localised in multistage dyke swells and through them in proper sheets and sometimes sills, may therefore be sufficient to explain the intense linear magnetic anomalies, both the NW-SE trending ones and others. It is therefore no wonder that the linear permanent magnetic anomaly map (Levin et al., unpubl. manus. 1963) shows good agreement with the positions (in plan view) of dykes mapped directly or indirectly (through geomorphological and hydrological) data. This magnetic map resulted in a great increase of informa-tion on the distribution of dykes on the islands and sea floor of Franz Josef Land. The information is synthesised in Figures 5.9 and 10 which show an extensive dyke swarm. Analysis of the general map (Fig. 5.9) shows that the dykes can be divided into three groups on the basis of their trends (see also Fig. 5.10).

The first group, which has more than twice the number of dykes in the other two groups, comprises NW-SE trending dykes, including those trending more NNW-SSE (especially on the northwestern periphery of the archipelago) and sometimes WNW-ESE. In the south-central and southwestern parts of the archipelago, the dykes curve gently round to other trends, resulting in their concentric arrangement in the southwestern parts of Alexandra Land and George Land and the Bruce Island area. This arrangement may be caused by predyke, arched uplifts of substrate (on George Land this view is supported by unexpected Carboniferous outcrops at Cook Rocks). About 55 separate NW-SE dykes (ranging in length from 7–10 up to 35–40 km) can be traced across the archipelago. Their overall length is no less than 3000 km. They may be divided into five well-defined dyke systems, as follows (from north to south): a) from Cape Hofer through the islands of Wilczek Land, Wiener-Neustadt and Ziegler, 125 km in length; 2) through Hochstetter Island, Hall Island, the northwestern end of Hayes Island, Champ Island and Luigi Island, 145 km; 3) through Salm Island, Hall Island, Markham Strait and Leigh Smith Strait, 220 km; 4) through Smithson Sound, Hooker Island, British Channel and George Land, 115 km; 5) through the southwest part of Northbrook Island, George Land and Alexandra Land, 120 km. These NW-SE trending dykes were usually active longest, as some were feeders to sills and sheets of different age and others cut the oldest and slightly differently oriented dykes of the same group. For example, a thick (up to 100–120 m in separate swells), bifurcating dyke forming Cape Tegetthoff (Hall Island) can be

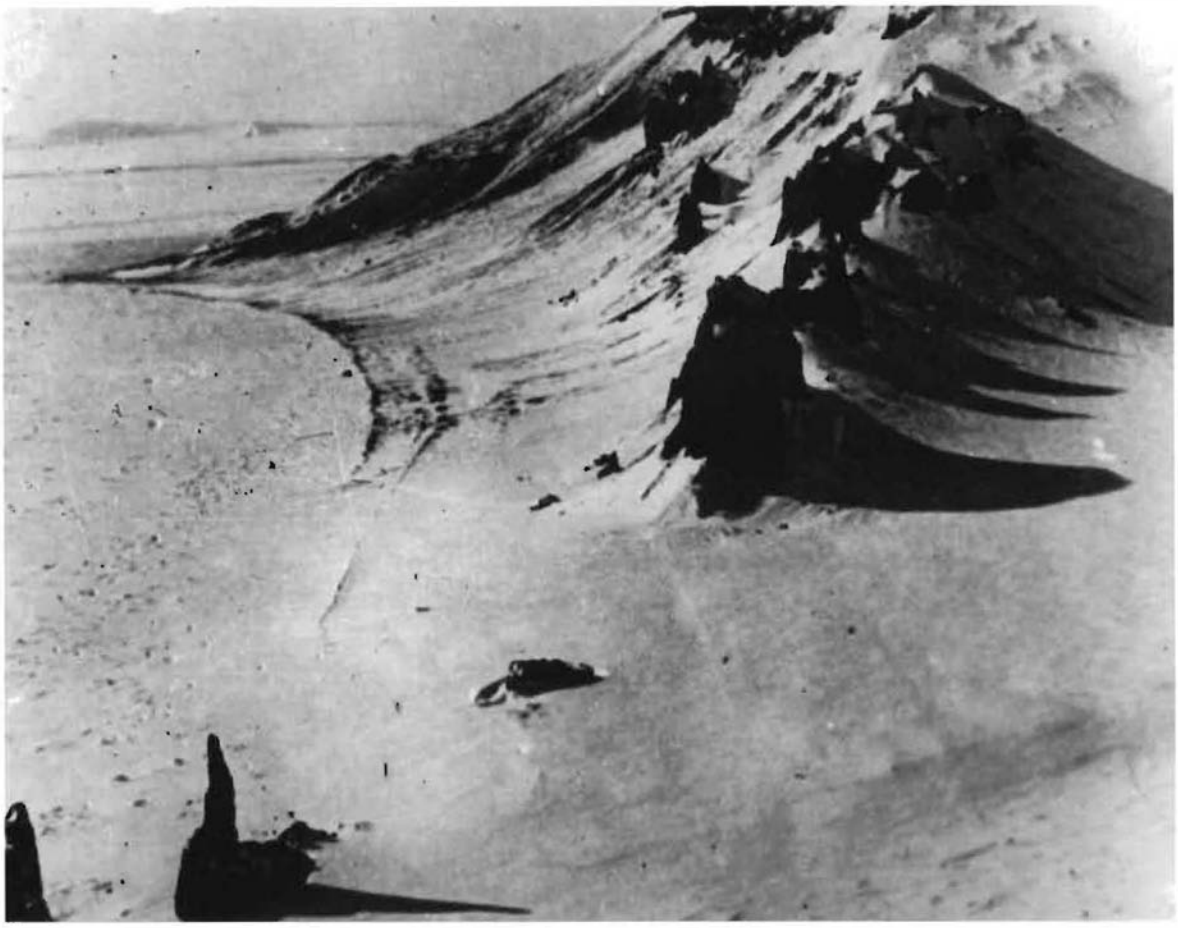


Fig. 5.14 Thick, bifurcating dyke (with swells) on Cape Tegetthoff. Photo: A.N. Radygin.

traced along both its branches as far as the basaltic sheets (base of the lower sheet at a height of about 250 m) which it fed. On the west part of Hayes Island, a narrow (1.0–1.5 m) WNW-ESE trending (300°) dyke is cut by a wider dyke on a NW-SE trend (320°).

NE-SW trending dykes vary in length from a few kilometres to 15–20 km. They are known to occur as discrete igneous bodies on the islands of Rudolf (Cape Fligely), Rainer, Hohenlohe, Karl Alexander (two dykes), Owen and Torup. Those forming the last two islets cut NW-SE trending dykes, recognised by linear polynias in sea ice. NE-SW trending dykes are also known from the islands of Jackson (Cape Kremsmewnster), Graham Bell (Cape Leiter), Wiener-Neustadt (two dykes transecting the whole island), Coldeway, Northbrook (northwestern capes), McClintock and Klagenfuhrt where it is crossed by a NW-SE trending dyke. The overall length of these dykes is about 120 km.

Dykes deviating from a N-S direction by 5–10° (towards NW) form the Lesgaft skerries and cut the onshore and offshore areas of De Long Strait and Jackson Island, and are also found on the islands of Alexandra Land, George Land (southern part), Northbrook (Cape Gjertrud area), Koettlitz and Leigh Smith (Cape Wittenburg). Their total length is about 80 km.

The data currently available indicate that the overall length of all the dykes in Franz Josef Land is about 3200 km.

Some NW-SE trending dykes have thick magmatic swells, obviously caused by the magma being enriched in juvenile gases. In particular, this is suggested by the "whirlwind" arrangement of columnar jointing in some swells (Figs. 5.7 & 5.14). The swells mostly stand out in the topography as impressive monadnocks, generally forming large capes. They are especially typical of the NW-SE trending dykes. For example, the extremity of Cape Tegetthoff (Hall Island) is made up of a bifurcating dyke which is 100–120 m thick in separate swells. Both branches of the dyke can be traced to the basaltic sheets exposed 250 m above sea level. The branches reach the sheets as typical feeders, resulting in the triangular shape of the cape (Fig. 5.14). Rubini Rock is well ex-

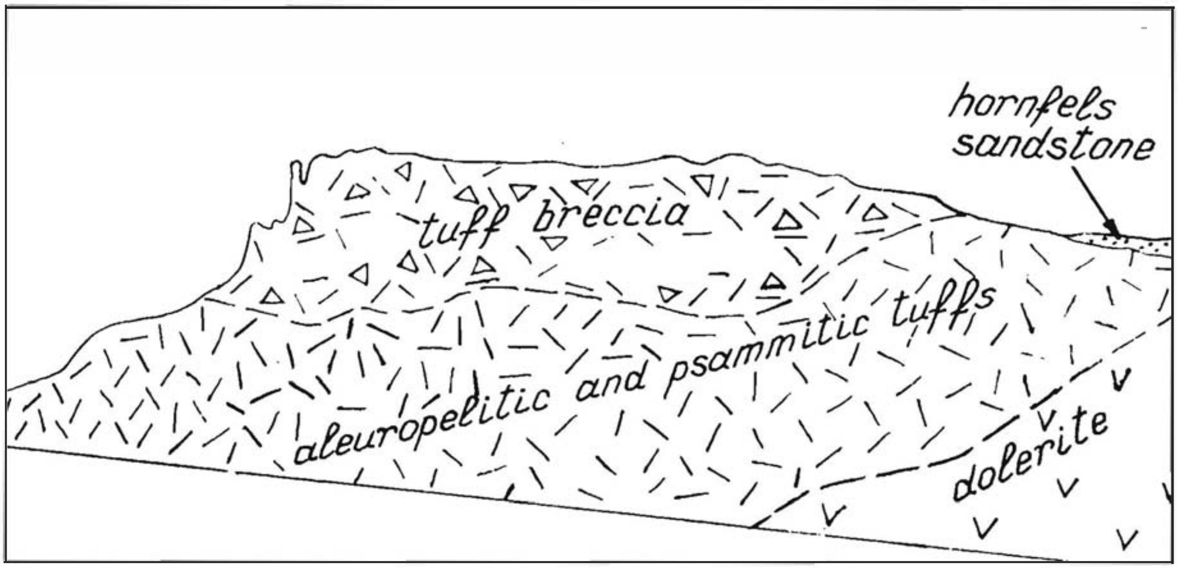


Fig. 5.15 Razbitaya I dyke swell formed of silty and psammitic tuffs and agglomeratic tuff, Hayes Island.

posed on three sides. It is well known in geological and popular scientific literature because of clear-cut (hexahedral, or sometimes pentahedral or tetrahedral) jointing that diverges at different angles to the horizontal and locally radiates (Fig. 5.7). Large-scale columnar jointing is also prominent on Cape Antirubini, one of the eastern points of Scott-Keltie Island. Both swells, up to 600 m thick, formed on a very narrow (a few metres wide) dyke near the surface, which had already been armoured by some basaltic sheets. The Antirubini swell is in direct contact with the sheets. The main (lower) part of both swells is associated with a valley-shaped depression in the surface of Liassic psammites, which was filled with Middle Jurassic clay that was easily absorbed by magma.

The magma penetrated and chilled in the swells in individual pulses, each of which forced its way along selvages in the intrusion formed by the preceding injection (Abdullaev 1957). Such a mechanism for the formation of the Rubini and Antirubini swells can explain not only the arrangement of columnar jointing, but also a surprising uniformity in the petrography of the fine-grained dolerites that make up the entire complex of relatively narrow intrusions that, together, constitute the swell.

Another magmatic swell is Cape Barents Rock on Northbrook Island which, in plan view, is oval-shaped and elongated in a WNW-ESE direction. According to Bisset (1927), the Rock consists of olivine dolerite. Its special columnar structure causes it to resemble the chewing surface of a huge mammoth's tooth when viewed from above. On reconnaissance flights over Franz Josef Land, V.D. Dibner has also seen similar surfaces in dolerite outcrops on Wilczek Island and elsewhere.

A special variety of agglomeratic swells is found on Hayes Island. Usually, where erosion is relatively deep (Graham Bell and other islands), such dykes are noted for their strict linearity and narrowness, generally not exceeding 3–7 m. However, on Hayes Island, they are curved (in plan view) to varying degrees and are impersistent in width, which is known to be characteristic of a vent formed in a magmatic fissure near the surface. In the southwest part of the island, there are two or three small intermittent chains of dyke ridges, varying greatly in width. The separate links, varying from 100–300 m up to 2000–3000 m in length, are associated with "torn" fissures exposed at the present surface at a depth of only tens of metres from the ancient surface. This is suggested by the unusual composition (vitroclastic agglomeratic tuff) of a portion of the Razbitaya I dyke (on the southwest coast of Hayes Island) found by L.P. Piroznikov and studied in detail by V.D. Dibner in 1957. The walls of the dyke, exhumed by erosion, exhibit uneven, but obvious, transitions (upwards) from light-grey, fine-grained dolerite with quartz amygdules to black silty tuff and then to agglomeratic tuff crowded with welded fragments of Upper Triassic sandstone and siltstone derived from the ancient land surface (Fig. 5.15). The agglomeratic tuff forms a stock-like body

Fig. 5.16 Agglomeratic tuff swell in a dyke forming the abutment of Cape Washington, Ziegler Island. Photo: V.K. Razin.

(volcanic pipe) dissected by numerous quartz veins and containing large geodes filled with quartz. Relicts of the Upper Triassic sandstone and siltstone of the roof, which are hornfelsed in the immediate vicinity of the agglomeratic tuff or dolerite, are preserved in the roof of the swell.

A few kilometres north of the agglomerate-filled explosion pipes, a 30 cm layer of dark-grey, ferruginous agglomeratic tuff composed of a fine-grained, silty, tuffaceous groundmass abounding in volcanic bombs was also found in 1957. This sheet directly overlies the Upper Triassic sandstone and is overlain by a basaltic sheet that is a few metres thick. Thus, the pipes can be interpreted as feeders for the basal agglomerate of the volcano-sedimentary sequence preserved in this part of Hayes Island. The next stage in the eruptions was the formation of the subvolcano at Inaccessible Rocks described in section 5.2.

Basaltic agglomeratic tuff has also been found at Cape Washington on Ziegler Island, where it forms a ridge protruding as an abutment (Fig. 5.16), and in talus from ordinary basalt on Harley Island. Finally, strongly zeolitised agglomeratic tuff forms another explosion pipe, topographically expressed as an abutment at Mount Ciurlionis on Hooker Island. This may be genetically related to the Rubini Rock swell described above and, together, they may be associated with a NW-SE trending dyke. The same agglomeratic tuff probably formed a feeder to the fine-grained, silty tuff (also containing zeolites) at the base of basaltic sheets on the summit of Mount Ciurlionis.

To summarise, the following sequence of magmatic and explosive activity took place as the magma became more gaseous: 1) ordinary dyke, 2) dyke with a magmatic swell, 3) dyke with an agglomeratic swell, 4) agglomeratic subvolcano, 5) agglomeratic tuff sheet.

Petrography of the dykes

Narrow dykes consist of porphyritic, fine-grained dolerite which, according to its degree of crystallisation, shows a vitreous, hyalopilitic, intersertal or, occasionally, ophitic groundmass texture.

Fig. 5.17 Contact of doleritic dyke cutting sedimentary rocks at an angle of 65°. A vitreous, fine-grained dolerite outside the contact zone, B contact zone, C Lower Triassic siltstone and clayey siltstone. Polished section of core material from the Nagurskaya borehole; the core is from the contact zone of a discordant intrusion (V) occurring in the interval 1355–1375 m (from data supplied by I.V. Shkola).

Groundmass with a hyaline texture is typical of selvages and is observed at localities far removed from the contacts. Hyalopilitic and intersertal textures are typical of the groundmass of quite narrow dykes and marginal parts of dykes that are 5–7 m or more wide. Their central parts have an ophitic, or similar texture, and occasionally consist of medium-grained, glomeroporphyritic dolerite, or a rock transitional to it. In the central part of an approximately 50 m broad dyke making up Cape Heller, a sample of coarse-grained dolerite collected by V.K. Razin (unpubl. manus.) represents the most crystalline example known of these hypabyssal intrusions. The dolerites have ophitic and, in part, tholeiitic textures. The northern and eastern cliffs of Rubini Rock consist of unusually fine-grained porphyritic dolerite containing phenocrysts of plagioclase and augite (locally bronzite), accounting for 15–20%, up to 25–30%, of the rock and forming glomeroporphyritic aggregates of crystals. The groundmass of dolerite dykes contains titanomagnetite and especially magnetite which may reach 25–30% (see section 6.4).

In Franz Josef Land, the character of the interaction of dyke magma with enclosing deposits that are poorly cemented or entirely non-cemented, is very evident (Fig. 5.17). Samples taken from dyke selvages on Graham Bell Island and studied with the aid of crystal optics by L.A. Chaika, are amygdaloidal fine-grained dolerite composed of fresh, almost opaque, greenish-buff glass with rare (3–5%) microlites of basic plagioclase (0.3–0.4 mm). The glass contains scattered, subrounded grains of quartz and irregular microxenoliths (up to 2.0–3.0 mm) of siliceous quartzose sandstone with carbonate cement, which were incorporated into the magma when it was intruding the psammites. The contact between the microxenoliths and the glass is sharp. No chemical reaction between the xenoliths and hyalobasalt proper has been noted. Sandstone fragments and grains were also observed in specimens taken from 1.0 m into the dyke. They differ in showing partial crystallisation of the glass, therefore exhibiting a felsitic texture in places. Only 2.0 m from the contact, the dolerite acquires the usual intersertal groundmass texture and lacks xenolithic material. A fragment of basaltic scoria, probably representing the outermost part of the selvage, was found in talus near one of the dykes. Microscopically, the scoria is entirely limonitised and has cavities where plagioclase and augite crystals have been leached out.

5.3.2 Sills

Geological mapping in 1953 revealed numerous sills intruding Upper Triassic and Jurassic deposits. They cannot be linked to effusives because of a complete lack of tuffaceous material in the enclosing strata. Moreover, the sills proved to consist of holocrystalline rocks showing ophitic textures, which are known to be absent from even the central parts of thick sheets and flows. Also

Fig. 5.18 Sill (A) at the base of the Tikhaya Bay Formation and an overlying basaltic sheet (B). Cape Albert Markham, Hooker Island. Photo: L.N. Fokin, 1953.

noteworthy is an almost complete lack (even at the actual contact with the overlying rock) of amygdaloidal textures characteristic of the near-top zone of basaltic sheets.

The sills have large columnar joints, expressed topographically as prismatic columns that are vertical or occasionally diverge like gigantic beams. In this respect, they are quite similar to thick dyke swells whose intrusive nature is unquestionable, and they differ from sheets which have much less evident columnar jointing, if any, in the central parts only. The intrusive nature of the sills is ultimately proved by the presence of a hot upper contact.

The sills vary in thickness from 20 or 30 m to 100 m. They occur very widely and are limited to certain stratigraphical horizons. Consequently, like the dykes, they can frequently be traced for considerable distances from one island to another and probably continue over a vast area. They occur, in ascending order: a) at the boundary between the Upper Triassic Wilczek and Vasiliev formations (on the islands of Wilczek Land, Bolshoi Komsomolsky, Hayes, Fersman and Hall), b) at the boundary between the Aalenian and the overlying deposits (Hooker and Rainer Islands), c) at the base of the Lower Cretaceous sedimentary-effusive sequence (on the islands of George Land, Northbrook, Hooker, Alger, Wilczek Land, Ziegler and many others), d) between the Tikhaya Bay and Salisbury formations (on the islands of George Land, Hooker, Salisbury, Luigi and others). These sills, in common with a thick (1300 m) sill(?) encountered at the Vendian/Carboniferous boundary in the Nagurskaya borehole, can therefore be classified as interformational. Two sills (150 and 400 m) were also found in that borehole in the Lower Carboniferous. The Hayes and Severnaya boreholes revealed some sills intruded in the Middle and Upper Triassic, but none were found in more than one borehole.

Figure 5.18 shows an example of a sill which is about 30 m thick. Six samples taken at 5 m intervals show that the sill is composed of similar rock to the porphyritic dolerite and coarse-grained dolerite found in central parts of the thickest dykes. A sample from the centre of the sill is coarse-grained dolerite, with a coarsely ophitic groundmass. Towards each margin of the sill, the groundmass texture is successively replaced by ophitic, locally tholeiitic, and intersertal textures. Above the intrusion, the upper part of the enclosing sheet of porphyritic basalt is exposed, separated from the dolerite by a steep scarp and differing from it by the absence of columnar jointing and by having a contrasting groundmass texture. The sill has a zone near its contact that is less crystallised than the corresponding position in a sheet and its groundmass there displays intersertal texture with 17–18% glass, whereas a basalt sheet only exhibits this degree of crystallisation in its central part. Neither ophitic nor gabbro-ophitic textures have been recorded in basaltic sheets, even the thickest ones.

Sills ranging in thickness from 5 to 30 m were also observed by V.D. Dibner in basaltic sheets on the Armitage Peninsula, as well as on Cape Steven, Cape Astronomic and Cape Forbes (on the southern part of George Land), Cape Mary Harmsworth and Cape Thomas (Alexandra Land) and Scott-Keltie Island. All these consist of porphyritic, locally glomeroporphyritic, dolerites with ophitic and tholeiitic, or intersertal, textures. These dolerites resemble the rock making up the sill on Cape Albert Markham.

Very thick sills were intruded into the Upper Norian Wilczek Formation on the north coast of Wilczek Land. Here, V.K. Razin (unpubl. manus.) described a thick (60–70 m) dolerite sill forming Cape Willas and creating scarps with columnar jointing 240–300 m above sea level (Fig. 5.19A). The same sill protrudes from beneath the ice in parts of the walls of the Stremitelny (Rapid) Glacier valley and crops out extensively on capes Schmarda and Heller. A similar, thick sill forms Cape Kavagli on Salisbury Island (Fig. 5.19B). These sills consist of medium- to coarse-grained dolerite, whose groundmass shows ophitic textures. They are very similar to the rocks forming the northern dyke on Juzhny Komsomolsky Island, being largely crystalline and containing quartz, biotite and brown hornblende, and locally having a fine-grained pegmatitic texture. Some samples, containing up to 8–10% olivine, should be classified as olivine dolerites and coarse-grained olivine dolerites. The rocks usually show evidence of autometamorphism, expressed by replacement of augite by hornblende, and of plagioclase by calcite, accompanied by exsolution of silica as anhedral quartz grains. Similar rock also forms the upper sheet on Hochstetter Island recorded by Weber (1908). One of his samples, housed at the Chernyshev Central Geological Museum, was studied by L.A. Chaika (unpubl. manus.) who found it to be olivine dolerite of definite intrusive origin.

On the whole, the mineral composition of the hypabyssal intrusions is similar to that of the sheets. Petrographic data obtained by Yu.I. Tomanovskaya and M.A. Krutoyarsky from samples collected by V.D. Dibner and V.K. Razin in 1953 show the following main differences. The anorthite content of the plagioclase is no less than 55 mol.% in the intrusions. Clinopyroxene as phenocrysts (up to 0.8 mm across) forms, together with plagioclase and locally orthopyroxene, glomeroporphyritic aggregates up to 3.0 cm across. They are especially typical of coarse- and medium-grained dolerites. Poikilitic inclusions of plagioclase and their mutual intergrowths are locally observed in the phenocrysts. The groundmass clinopyroxene consists of prismatic and euhedral crystals (0.1–0.7 mm), forming simple twins and, in places, micrographic intergrowths with plagioclase. In some

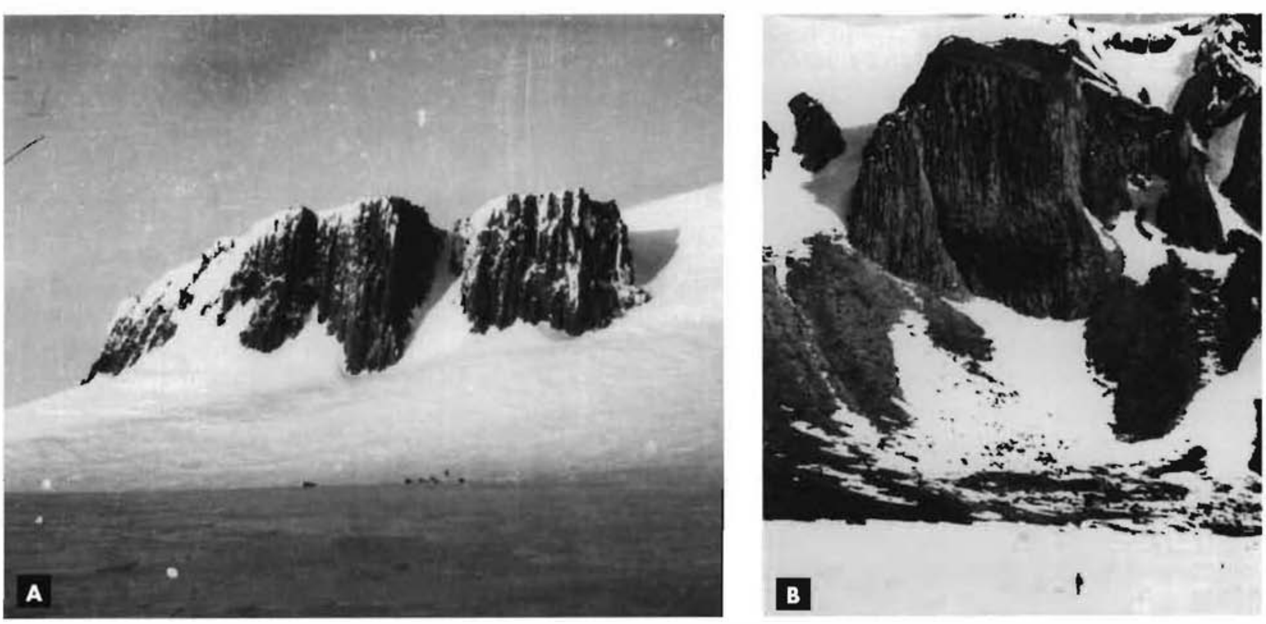


Fig. 5.19 Thick sills forming capes Willas, Wilczek Land (A) and Kavagli, Salisbury Island (B). Photos: V.K. Razin and L.Yu. Budantsev, respectively.

samples, the clinopyroxene is altered to very fine-grained clay minerals, and titanomagnetite and iddingsite have crystallised in fissures. Autometamorphism in coarse-grained dolerites from Cape Heller has slightly amphibolitised the clinopyroxene, or this is sometimes almost completely replaced by biotite. These rocks are also typically protoclastic.

The composition of groundmass orthopyroxene, and of phenocrystic orthopyroxene in medium- and coarse-grained dolerites, is intermediate between clinoenstatite and hedenbergite. The orthopyroxene occurs as long prismatic crystals, which are commonly rimmed by minute grains of clinopyroxene and magnetite. It is occasionally replaced by iddingsite. In the fine-grained dolerites on Rubini Rock, orthopyroxene is represented by irregular prismatic grains of bronzite.

Olivine, identified in some thin sections, is usually present in insignificant amounts (1–2%), forming, sometimes with clinopyroxene, poikilitic inclusions in the plagioclase. In the fine-grained dolerite of one of the narrow dykes on Graham Bell Island, olivine reaches as much as 15%. Olivine dolerite and coarse-grained dolerite are particularly characteristic of some dyke swells and thick sills. The groundmass of hypabyssal rocks also contains ore minerals, up to 10% in dolerite. Distinct skeletal forms point to titanomagnetite and magnetite, which form uniform growths of minute (0.1–0.4 mm) anhedral grains and rectangular crystals. In one dolerite sample taken in the central part of a dyke on Graham Bell Island, magnetite amounts to 30%. Iron oxides, formed by alteration of magnetite, are seen in a few thin sections.

The glass is light brown to fawn in colour. In dykes and margins of sills, as in sheets, it is heavily vitrified (up to 50%) and is transformed into iddingsite-bowlingite and palagonite. It usually contains minute microlites of plagioclase or, less commonly, pyroxene, fine needles of apatite and ore dust, and is consequently almost black in places. In a few samples from fine-grained dolerite dykes, up to 10% of the rock is made up of fine (0.2 to 0.7 mm) amygdules filled with calcite, zeolite and fluorite, and locally rimmed by iddingsite and palagonite.

5.4 PETROCHEMISTRY OF THE PLATEAU BASALTS – A.N. YEVDOKIMOV

General petrological and petrochemical characteristics of the igneous rocks of Franz Josef Land have been given by Newton & Teall (1899), Vlodavets (1934), Spizharsky (1937a, 1947), Test (1937), Lupanova (1953), Dibner (1970) and Tarakhovsky et al. (1983). The following is an account of petrochemical studies carried out in 1991–1993 on samples of volcanics collected by V.D. Dibner, V.K. Razin and L.P. Pirozhnikov in 1953, 1956–1957 and 1976, and by A.V. Ditmar, A.N. Tarakhovsky and Yu.A. Mikhailov in 1978 and 1980. The samples comprise medium- and coarse-grained dolerites, basalt, tuff, and tuffaceous and volcanic breccia; they show different degrees of secondary alteration. Samples were collected on the islands of Alexandra Land, George Land, Hooker, Mabel, Scott-Keltie, Jackson, Champ, Salisbury, Ziegler, Wiener-Neustadt, Hayes, Bolshoi Komsomolsky, Hall, Wilczek Land and Graham Bell, and additional ones came from core material from the Nagurskaya, Hayes and Severnaya boreholes. 45 samples came from dykes, 22 from sills and 48 from basaltic sheets and flows, and the subvolcano at Inaccessible Rocks. 100 thin sections from V.D. Dibner's original thin-section collection were studied, along with 40 new ones made at the University of Oslo from the same collection. Spectral analysis of trace elements, X-ray spectrography, mass spectrometry and oxide analysis were used to determine the geochemical composition of the rocks and the isotopic composition of separate elements.

Two sequences of basaltic sheets on the islands of Mabel and Hooker (Fig. 5.20), described by Yu.A. Mikhailov and A.V. Ditmar (unpubl. manuscripts in 1979–1980), were studied most comprehensively. At Cape Conrad on Mabel Island, nine sheets are partly interlayered with terrigenous rocks, the full sequence being about 100 m in thickness. The sheets are Lower Cretaceous in age, and the sequence lies disconformably on Upper Triassic psammites and siltstones. On Hooker Island, the section studied consists of a series of stepwise outcrops of volcano-sedimentary rocks exposed on the northern coast of Tikhaya Bay near Cape Sedov. Samples were taken from four basaltic sheets, 45 m in total thickness, separated by intercalations of carbonaceous mudstone and resting disconformably on Upper Jurassic deposits. The Y, Zr, Nb, and also V and Ti, contents increase, although unevenly, and Ni and Cr, as well as Al_2O_3 and MgO, decrease upwards in the basalts on Mabel Island, which is taken as the type section (Fig. 5.21A & B and Fig. 5.22). Eighteen analyses for oxides showed, on the whole, a low content of CaO and Al_2O_3, and a high content of total iron relative to their clarkes, thus suggesting a platform type of magmatism, whereas a low sum of alkalis and a low K/Na ratio indicate an oceanic type of magmatism.

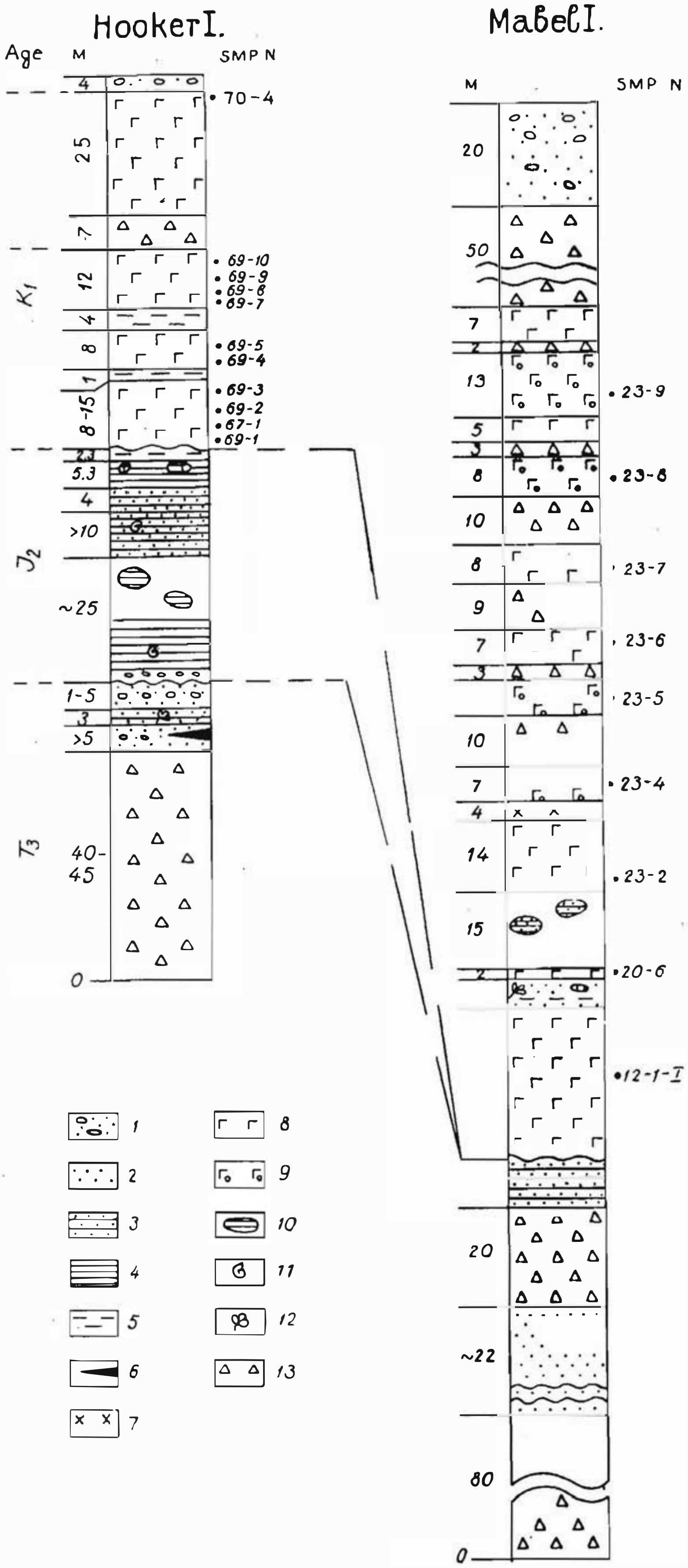


Fig. 5.20 Sequences of basaltic flows and sediments 1 km from Cape Sedov, Hooker Island, and 2 km NNW of Cape Conrad, Mabel Island. 1 grit, 2 sand, 3 sandstone, 4 clay and argillite, 5 siltstone, 6 coal, 7 gravel and pebbles, 8 basalt, 9 amygdaloidal basalt, 10 exposed parts of section, 11 fauna, 12 flora, 13 talus.

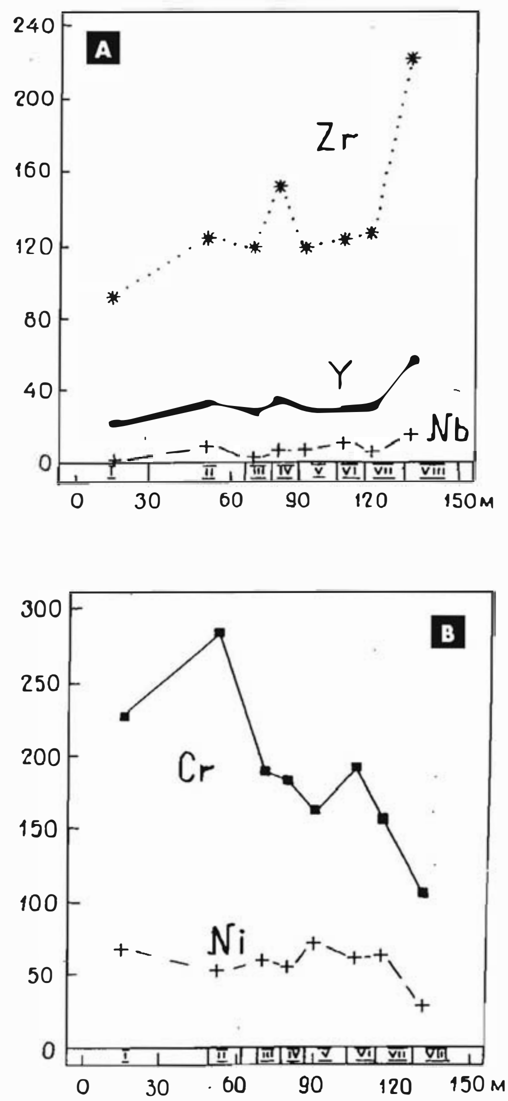


Fig. 5.21 Some trace element contents in basaltic sheets near Cape Sedov on Hooker Island and on Cape Conrad on Mabel Island (identified by Roman numerals), in wt. %. A. Niobium, yttrium and zirconium; B. Nickel and chromium.

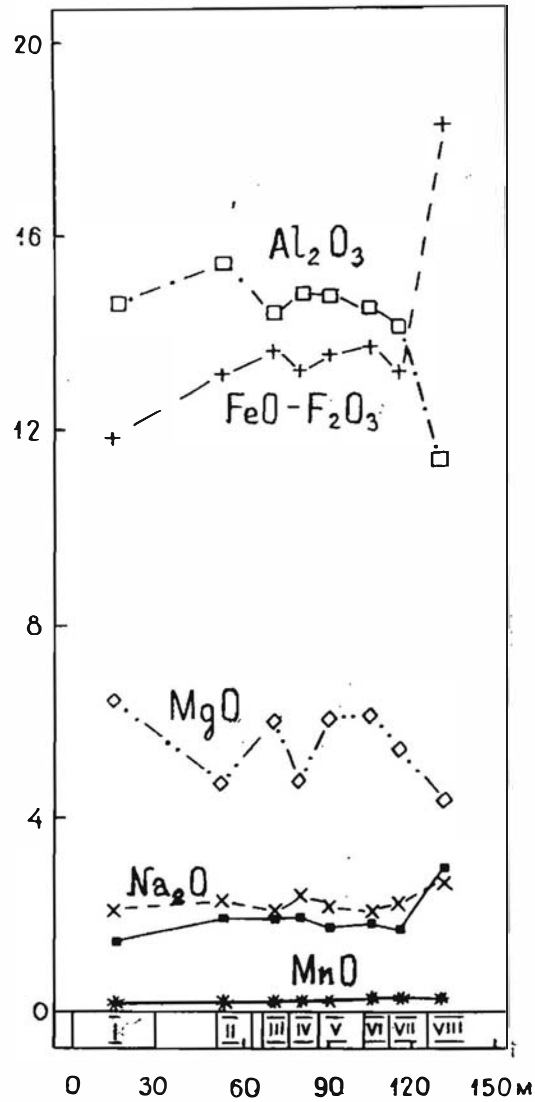


Fig. 5.22 Content of some oxides in basaltic sheets on Mabel Island (identified by Roman numerals), in wt. % x 10^{-4}.

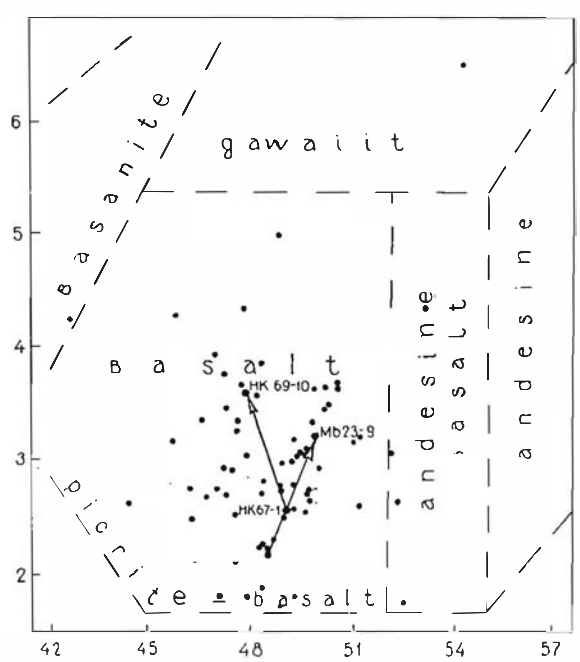


Fig. 5.23 Rocks of the plateau-basalt association plotted on a Cox et al. (1979) diagram, SiO_2 vs. K_2O+Na_2O. HK Hooker Island, MB Mabel Island.

The data confirm the validity of grouping the basalts and dolerites of Franz Josef Land within a normal series of tholeiitic magmas. When plotted on a Cox et al. (1979) diagram, they occupy the fields for basalt and picritic basalt (Fig. 5.23). One analysis, showing high alkalis, falls in the field for hawaiite. This sample derives from a dyke of taxitic coarse-grained dolerite encountered at a depth of 2683.4 m in the Nagurskaya borehole. Some samples with high silica are represented by points in the andesite-basalt field. In addition, linear clusters of points delineate two trends of magma fractionation (Fig. 5.23). They probably mark two stages of magmatic activity, as suggested by K/Ar datings of the intrusions encountered in the Nagurskaya borehole (Tarakhovsky et al. 1980).

A point worth noting is that one sample per basalt sheet has been investigated in the Mabel Island section, and three or four samples per sheet on Hooker Island. This allows the scatter in composition within one sheet and between several sheets to be compared. For example, in four samples from Sheet III on Hooker Island, TiO_2 varies from 1.58 to 2.13% surpassing that of all the other sheets on the island, but some basalts on Mabel Island contain more TiO_2 (1.44–2.98%). The same distribution pattern is displayed by most major and minor elements. Thus, Figure 5.23 shows an increase in the alkalinity of the melt from the lower to the upper basalts, arrows joining points indicating the compositions of the lowermost and uppermost sheets from the Mabel Island sequence. The trend in the compositional variations permits the known relationship between the content of olivine, chromite and/or titanomagnetite and the content of Ni and Cr to be supported by analyses of samples from Franz Josef Land. Maximum variations of Ni and Cr contents are recorded in dyke rocks and basaltic

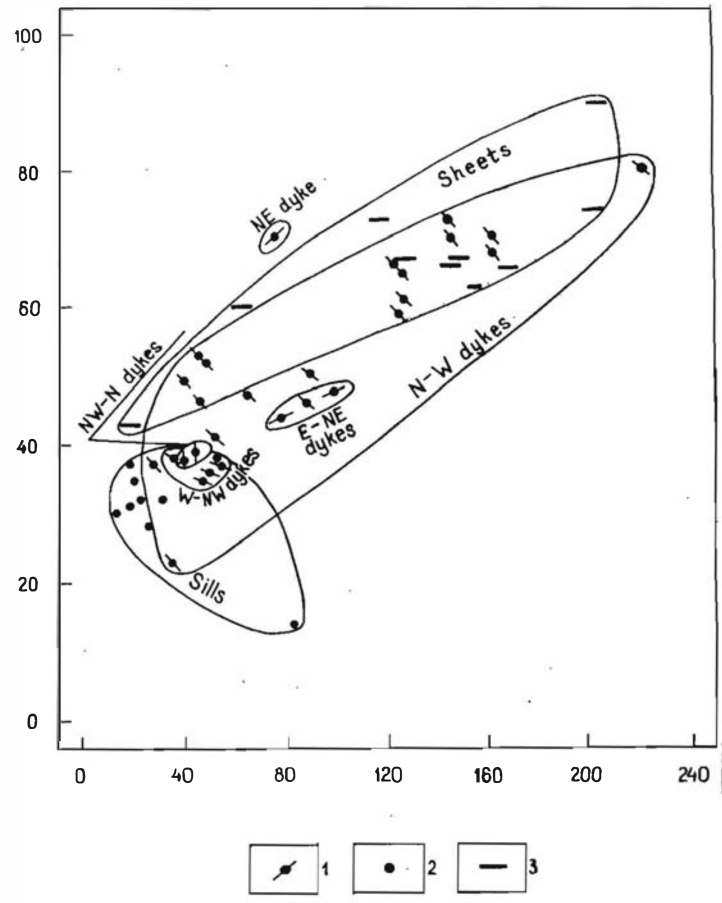


Fig. 5.24 Contents of Ni and Cr in differently oriented dykes, and in sills and sheets, wt. % x 10^{-4}. 1 dykes (orientation shown graphically), 2 sills, 3 sheets.

sheets. On the other hand, an Ni–Cr diagram shows that coarse-grained doleritic sills group together, since neither element exceeds 0.04 wt.% (Fig. 5.24). Bearing in mind the above-mentioned similarity in chemical and mineralogical composition and, sometimes, textures, the relatively low Ni and Cr contents in samples from sills distinguish them from dykes when samples of core material are analysed. If, in Figure 5.24, the fields for the NW-SE trending dykes are omitted, the fields for sills, basaltic sheets and flows, and NE-SW trending dykes can be recognised without overlapping.

In all the basaltic sheets sampled, the contents of Ni and Cr exceed 0.04 wt.%, and consistently decrease from older to younger basalts. This tendency is readily explained by the fact that the earlier melt was more basic and contained more olivine and chromite than later magma.

The studies imply that the chemical evolution of the rocks of the plateau-basalt association took place at the level of both major and minor elements. A distinct increase in alkalinity, the content of ferric iron and a decrease in Ni and Cr are noted in younger melt. With respect to the major elements, this tendency is also seen on a regional scale, in Svalbard, where basic magmatism continued into the Palaeogene and a high alkali content is typical of the Quaternary volcanoes.

Sills differ from dykes in having consistently low Ni and Cr contents. In doleritic dykes and especially basaltic sheets, their content unevenly decreases as the rocks become younger.

5.5 TIMING OF PLATEAU-BASALT MAGMATISM – V.D. DIBNER, V.L. ANDREICHEV, A.N. TARAKHOVSKY AND I.V. SHKOLA

The ages of the basaltic sheets have mainly been determined indirectly by fossils which date the interlayered, underlying and overlying terrigenous rocks. The extrusions chiefly date from the Barremian to the Albian, inclusive. Hypabyssal intrusions were emplaced over a longer period, as shown by the observations at some localities that basaltic sheets rest with a profound unconformity on Triassic and Lower Jurassic beds which are locally gently folded along with the emplaced sills. This suggests that intrusive activity occurred during the Middle-Upper Jurassic. A dyke cutting Cenomanian deposits on Hoffmann Island determines the upper limit of hypabyssal magmatism (Dibner 1961b, 1970, 1978).

A number of K-Ar dates from the early-1980's are available (Table 5.1, Figs. 5.25–5.27), some having been published by Tarakhovsky et al. (1983).

The determinations were made on separate whole-rock samples at the Laboratory of Nuclear Geochronology and Isotopic Analysis in the Komi Republic of the Russian Federation. Radiogenic argon was measured on an IGEM argon plant and an MI-1305 mass spectrograph by the isotopic

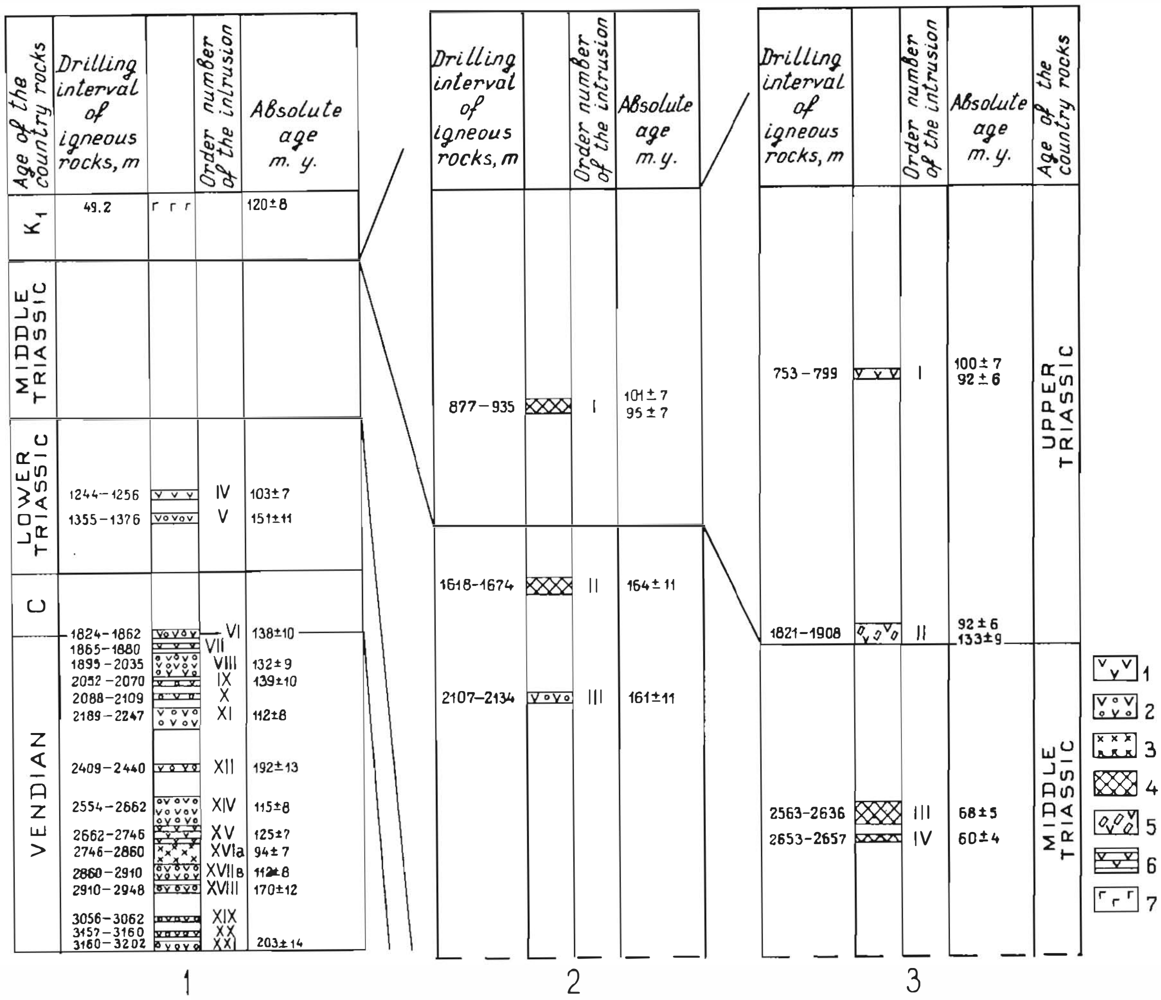


Fig. 5.25 Location and ages of K-Ar dated hypabyssal intrusions in the boreholes: A Nagurskaya, B Hayes, C Severnaya. Symbols of igneous rocks: 1 dolerite, 2 quartz dolerite and coarse-grained dolerite, 3 leucocratic coarse-grained dolerite, 4 olivine-bearing coarse-grained dolerite, 5 micropegmatitic gabbro, 6 taxitic coarse-grained dolerite, 7 basalt.

dilution technique using Ar^{38} as the standard. Potassium was determined by flame spectrophotometry. The following constants, adopted by the Subcommission on Geochronology at the Russian Academy of Sciences on August 24, 1976, were used to calculate the ages: $L_{38} = 0.58.10^{-1} yr^{-1}$; $l_b = 4.962.10^{-10} yr^{-1}$; $K^{40} = 0.0001167$ K (wt.%).

Of the 36 dates in Table 5.1 and Figures 5.25–5.27, 20 were determined on drill core material from the Nagurskaya, Hayes and Severnaya boreholes (Fig. 5.25), 1 on a sample from a trial pit for coal (near the Nagurskaya borehole) and 15 from samples from exposures. Most of the dates (28) refer to hypabyssal intrusions, 17 of them to dykes (including 1 dyke swell) and 11 to sills, 5 are volcanics from the subvolcano at Inaccessible Rocks, and one is from the sheet described in section 3.5 in the northern part of Alexandra Land.

The Nagurskaya borehole provided dates for 10 intrusions, 7 emplaced in the metamorphic basement and 3 in the Carboniferous and Lower Triassic cover. Unfortunately, the paucity of igneous rock core and the complex geology encountered in the boreholes made it impossible to determine the nature of all the intrusions encountered. Intrusions IV and V, occurring in flat-bedded, undeformed Lower Triassic deposits, might be expected to be sills. However, a core from intrusion V showed it to be a dyke cutting the Triassic siltstone at an angle of 65° (Fig. 5.17). The four successive intrusions, VI, VII, VIII and IX, may be thought of as forming a multilayer interformational sill intruded at the unconformity separating the Vendian and Carboniferous strata. The nearly identical dates of intrusions VI, VIII and IX, within 132–139 ± 9–10 m.y., support this assumption.

Table 5.1 K-Ar dates of plateau-basaltic rocks in Franz Josef Land

No.	Location	Feature	Rock type	Sample no. or depth in bore-hole in m	Absolute age (m.y.)	Age of enclos-ing rocks
1	North coast of Severnaya Bay, Alex-andra Land	Sill(?)	Dolerite	2/1974, Livshitz coll.	34 ± 2 (Olig.)	Lower Cret. basaltic sheets
2	Severnaya borehole, Bell Is.	Sill	Porph. coarse-grained dolerite	2654.9	60 ± 4 (Palaeo-cene)	Middle Triassic
3	–	–	–	2618.9	68 ± 5 (Maestri-chtian)	–
4	–	–	Micropeg-matitic gabbro	1857.2	92 ± 6 (Upper Cenoman.)	Upper Triassic
5	Nagurskaya borehole, Alexandra Land	Dyke	Leucocratic coarse-grained dolerite	2805.8	94 ± 7 (Cenomanian)	Vendian
6	Hayes borehole	Sill	Coarse-grained, olivine-bearing dolerite	926.8	95 ± 7 (Cenomanian)	Upper Triassic
7	Severnaya borehole, Graham Bell Is.	–	Vitreous dolerite	755.6	100 ± 7 (Albian)	–
8	Hayes borehole	–	Coarse-grained, olivine-bearing dolerite	882.7	101 ± 7 (Albian)	–
9	North-central part of Bolshoi Kom-somolets Is.	–	Dolerite	224/448 Dibner coll.	102 ± 7 (Albian)	–
10	Nagurskaya borehole, Alexandra Land	Dyke	Vitreous dolerite	1249.3	103 ± 7 (Albian)	Lower Triassic
11	Cape Bliz-netsy (Twins), NW corner of Hayes Island	Swell of Razbitaya I dyke	Dolerite	1011/2, 448 Dibner coll.	111 ± 8 (upper Albian)	–

12	Nagurskaya borehole, Alexandra Land	Dyke	Coarse-grained quartz dolerite	2198.6	112 ± 8 (top of Albian)	Vendian
13	–	–	Quartz dolerite	2864.8	–	–
14	–	–	Coarse-grained quartz dolerite	2607.7	115 ± 8 (Aptian)	–
15	Trial pit for coal, Alexandra Land	Sheet	Palagonitic basalt	49.2	120 ± 8 (Barremian)	–
16	Nagurskaya borehole, Alexandra Land	Dyke	Taxitic coarse-grained dolerite	2683.4	125 ± 7 (Hauterivian/ Barremian)	–
17	–	–	Coarse-grained quartz dolerite	1985.7	132 ± 9 (Valanginian)	–
18	Severnaya borehole, Graham Bell Is.	Sill	Micropeg-matitic gabbro	1902.6	133 ± 9 (Valanginian)	Upper Triassic
19	Nagurskaya borehole, Alexandra Land	–	Coarse-grained quartz dolerite	1840.0	138 ± 10 (Berriasian/ Valanginian)	Carboniferous
20	Middle part of Razbitaya I dyke, Hayes Is.	Dyke	Dolerite	84d Tarakhov-sky coll.	138 ± 10 (Berriasian/ Valanginian)	Upper Triassic
21	Nagurskaya borehole, Alexandra Land	–	Quartz dolerite	2060.3	139 ± 10 (Berriasian)	Vendian
21	Inaccessible Rocks, Salisbury Is.	Subvolcano	Plagiophyric basalt (xenolith)	164i Tarakhov-sky coll.	144 ± 11 (Volgian/ Berriasian)	Tikhaya Bay Formation (K1br–2)
23	–	–	–	168d Tarakhov-sky coll.	145 ± 10 (Upper Volgian)	–
24	Middle part of Razbitaya II dyke, Hayes Island	Dyke	Fine-grained dolerite	81A Tarakhov-sky coll.	153 ± 11 (Kimmeridgian)	Upper Triassic

25	Middle part of Skvoznaya dyke	–	Olivine dolerite	21 Tarakhov-sky coll.	157 ± 11 (upper Oxfordian)	–
26	Northwest outcrop of Skvoznaya dyke, Hayes Island	–	Fine-grained quartz dolerite	70 Tarakhov-sky coll.	158 ± 11 (Oxfordian)	–
27	Hayes borehole	Sill	Coarse-grained qtz-bearing dolerite	2126.3	161 ± 11 (Oxfordian)	Middle Triassic
28	–	–	Coarse-grained, olivine-bearing dolerite	1620.8	164 ± 11 (upper Callovian)	–
29	Middle segment of Ametisto-vaya dyke, Hayes Island	Dyke	Olivine dolerite	10B Tarakhov-sky coll.	170 ± 12 (upper Bathonian)	Upper Triassic
30	East coast of Hayes Is.	Sill	Coarse-grained quartz dolerite	5 Tarakhov-sky coll.	175 ± 12 (Bajocian/ Bathonian)	–
31	Nagurskaya borehole, Alexandra Land	Dyke	–	2416.3	192 ± 13 (Toarcian)	Vendian
32	Southeast outcrop of Skvoznaya dyke, Hayes Is.	–	Dolerite	18 Tarakhov-sky coll.	200 ± 14 (Sinemurian/ Pleinsbachian)	Upper Triassic
33	Nagurskaya borehole, Alexandra Land	–	Coarse grained quartz dolerite	3200.4	203 ± 13 (Sinemurian)	Vendian
34	Inaccessible Rocks, Salisbury Is.	Subvolcano	Glomero-porphyritic basalt (xenolith)	168 Tarakhov-sky coll.	240 ± 124 (Anisian)	Tikhaya Bay Formation (K1Br–a)
35	–	–	–	165g Tarakhov-sky coll.	252 ± 18 (Tatarian)	–
36	–	–	–	162v Tarakhov-sky coll.	288 ± 20 (Gzelian)	–

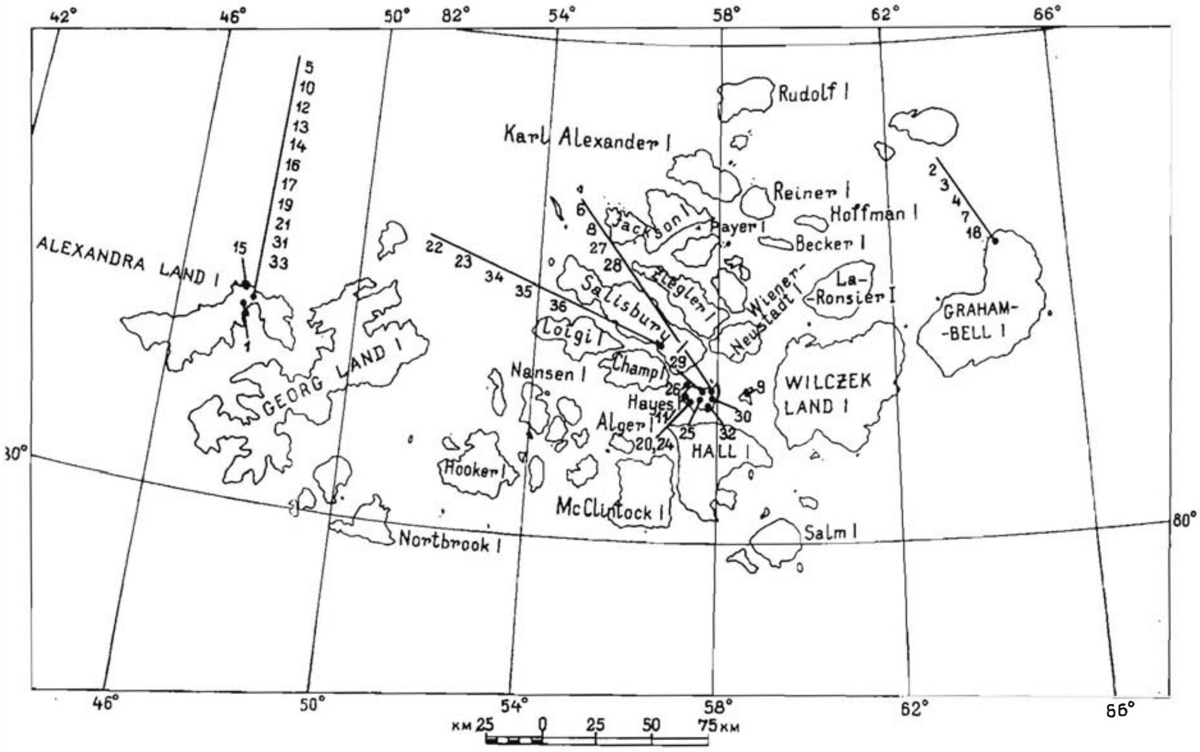


Fig. 5.26 Location of sites where samples dated by K-Ar were taken. The numbers on the map correspond to those in Table 5.1.

Intrusions XI, XIV and XVIIB (112–115 ± 7–8 m.y.) are probably also sills related to a common feeder. The nature of other intrusions in the basement and Triassic sediments encountered in boreholes is quite uncertain. In the Nagurskaya borehole, the relatively wide time interval indicated by the span of dates from 60 ± 4 to 203 ± 14 m.y. (Palaeocene-Sinemurian) is striking. This is accompanied by marked shifts in composition (dolerite, quartz dolerite, coarse-grained quartz dolerite, leucocratic coarse-grained dolerite, taxitic coarse-grained dolerite). Taking into account that on Alexandra Land the basaltic sheets underwent boudinage and multiple faulting into narrow (20–60 m) NW-SE trending blocks (Piskarev & Kovaleva 1975), it should be assumed that all the intrusions suffered these tectonic movements since the upper time limit for the deformation of basaltic sheets is uncertain. This pattern of ages and compositional variations, especially at a depth of 2554–2948 m in the borehole, can be explained by envisaging that all the intrusions are separated into blocks. The Nagurskaya borehole seems to have passed through blocks of different age and composition.

Probably it is no mere chance that a sample of dolerite from a sill emplaced in the Lower Cretaceous basaltic sheets is the youngest rock, 34 ± 2 m.y. old. These sheets occur on the north coast of Severnaya Bay which, like its north-northwesterly graben extension, is likely to have a rift origin (see Chapter 7). Judging by their geomorphological patterns, the rifts of Franz Josef Land seem to be inherited. Being numerous, they could be responsible for long-lasting plateau-basalt volcanism, including that in the Cenozoic. K-Ar age determinations on the earliest plateau basalts (203 m.y.) coincide with existing geological data (Lias), whereas the youngest dates are much younger than other indications suggested (from Cenomanian to Oligocene).

Age determinations were also obtained on nine samples of dolerite, olivine dolerite, fine-grained dolerite and coarse-grained dolerite (two from sills on Hayes Island and Bolshoi Komsomolsky Island and seven from dykes on Hayes Island), five samples from lava breccia from the subvolcano at Inaccessible Rocks, two of them being plagiophyric basalt (144 and 145 m.y. old) and three porphyritic basalt (240, 252 and 288 m.y. old). These five samples are clearly xenoliths since their ages exceed those of the oldest volcanics of the Lower Cretaceous sedimentary-volcanic sequence

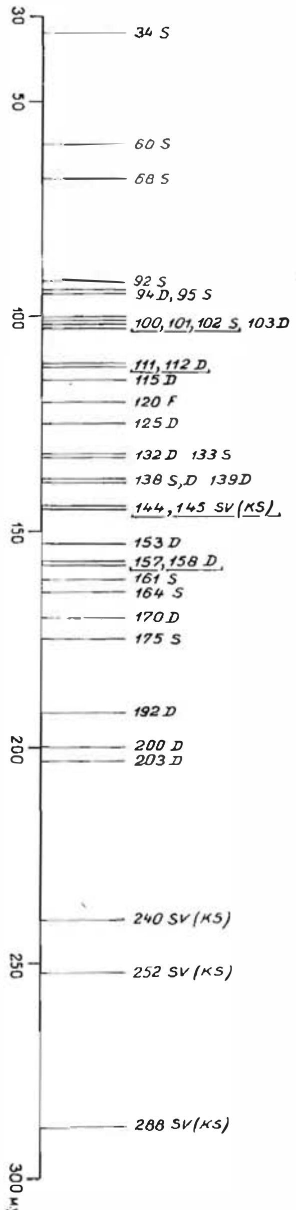


Fig. 5.27 Absolute (K-Ar) age of hypabyssal rocks and volcanics of the plateau-basalt association. D dykes, S sills, X xenoliths in the Inaccessible Rocks subvolcano, F sheets.

with which the subvolcano is associated (indeed, inside the subvolcano, only lava itself can be *in situ*). The most intense plateau-basalt eruptive activity took place from 175 ± 12 to 92 ± 6 m.y. ago (Bajocian?/Bathonian-upper Cenomanian). During this period, there were 23 hypabyssal intrusions, and the sedimentary-volcanic sequence and associated subvolcano (125–97 m.y., as suggested by palaeontological data) were formed. The hypabyssal intrusions not only extend over a wider area (Dibner 1978), but were spread over a longer period. This is characteristic of plateau basalts elsewhere (Belousov & Dzotsenidze 1966).

Discussion

The Mesozoic-Cenozoic plateau-basalt association is widely developed on the Barents Shelf, embracing the majority of its north-central part. On islands, it can be traced from Spitsbergen to the easternmost islands of Franz Josef Land, and on the shelf itself, aeromagnetic data, the composition of rock samples dredged from the sea floor and characteristic geomorphological features show that it can be traced from the Brusilov continental slope into the Eurasian sub-basin in the north to 74° N in the Medvezhy Trough in the southwest (Dibner 1978). Approximately at the same latitude in the southeast, two coarse-grained doleritic sills intruded into Upper Triassic deposits were encountered at a depth of 3365–3500 m in the Ludlowskaya 1 borehole. K-Ar age determinations on these intrusions yielded Valanginian (131–139 m.y.) and middle Oxfordian (159 m.y.) ages (Komarnitsky & Shipilov 1991). Sills and occasional feeder dykes are probably spread over this entire area. However, basaltic sheets are known only in Franz Josef Land and the islands of Kong Karls Land (Smith et al. 1979). In Franz Josef Land, there are also numerous dykes, most of which are feeders to basaltic sheets. Dykes only occur abundantly in Franz Josef Land, and an almost complete absence of these and of basaltic sheets further west on the eastern islands of Svalbard makes the existence of sheets there in the past improbable. Also taking into account that in some regions, for instance South Africa (Du Toit 1954), dyke swarms occur in the central zone of hypabyssal volcanicity, it is evident that a wide distribution of dykes and, consequently, of related basaltic sheets east of the archipelago, too, cannot be expected. This is in agreement with the marked reduction in the width of dykes along the eastern periphery of Franz Josef Land. This suggests that the eastern limit of the subzone of dykes and effusives or, in other words, the eastern boundary of the central part of the North Barents plateau basalts roughly coincides with the eastern boundary of Franz Josef Land (the western flank of the St. Anna Trough). The western limit of the central part of the plateau-basalt terrane approximately coincides with the western edge of Kong Karls Land.

Eastern Svalbard is a terrane of basic hypabyssal intrusions close to Franz Josef Land. In the central-eastern part of Svalbard, on Barentsøya, Edgeøya and Nordaustlandet, the sedimentary cover is intruded by numerous sills and some dykes of quartz dolerite, olivine dolerite and leucocratic coarse-grained dolerite. They intrude Permian, Triassic and Jurassic to Cretaceous rocks. The results of 22 K-Ar age determinations indicate an age range of 198–93 m.y. (Pliensbachian to Cenomanian) for these hypabyssal intrusions (Burov et al. 1976). This is within the period of the most intense hypabyssal magmatism in Franz Josef Land, but spans a much shorter period, not least ending much earlier.

6. PHYSICAL PROPERTIES OF THE ROCKS – E.G. BRO († 1997)

The physical properties of the sedimentary, metamorphic and igneous rocks of Franz Josef Land were studied in samples from outcrops and cores, as well as in logs. Density, wave velocity, heat conduction, susceptibility, natural remanent magnetisation and some other physical parameters were measured in samples; velocity shooting, thermometry and other kinds of logging were done in boreholes. Analysis was performed by conventional methods in the field and at the laboratories of PGO Sevmorgeologia, PGO Volgokamgeologia, VSEGEI and VNIGRI. In different years, the physical properties of the rocks were studied by, among others, V.D. Dibner, A.M. Karasik, B.V. Gusev, Yu.Ya. Livshits, Ya.V. Neizvestnov, A.L. Piskarev, A.N. Tarakhovsky, V.V. Verba, E.G. Bro and V.A. Tyuremnov. Some results have already been published (for references see below). The preparation of this monograph devoted to the geology of Franz Josef Land provides an excellent opportunity to collate and summarise the various data obtained.

6.1 DENSITY

Samples taken on the islands of Alexandra Land, Hayes and Graham Bell were used to determine density (Table 6.1). 8022 density values were obtained on Proterozoic, Carboniferous, Triassic, Jurassic and Cretaceous deposits and intrusions within them. Most of the data concern terrigenous rocks. A few measurements were made on carbonates from Carboniferous deposits in the Nagurskaya borehole and lenticular terrigenous carbonate partings and concretions in the Mesozoic sequence. Data obtained from the Nagurskaya borehole also give an impression of the density of metamorphic rocks. All the measurements made by A.L. Piskarev and G.A. Kovaleva, and a few on samples from other collections, concern the density of igneous rocks. The lowest values were recorded for porous sandstone and amygdaloidal basalt, and the highest for carbonate and dolerite (Table 6.2). The smallest variations were found for metamorphic rocks and the largest for terrigenous deposits and basalts.

Table 6.1 Summary of density measurements in rock samples

Source of information	*Sampling site*	*Age of rocks*	*Number of measurements*
Livshits & Markelova (unpubl. data, 1974)	Outcrops on Alexandra Land	Lower Cretaceous	78
Livshits & Markelova (unpubl. data, 1974)	Outcrops on Graham Bell Is.	Upper Triassic-Jurassic	211
Neizvestnov (unpubl. data, 1974)	Outcrops on Alexandra Land	Lower Cretaceous	19
Piskarev & Kovaleva 1974	Outcrops on Alexandra Land	Lower Cretaceous	2436
Tarakhovsky et al. (unpubl. data, 1976)	Outcrops on Graham Bell Is.	Upper Triassic	12
Verba et al. 1980	Nagurskaya borehole Vendian,	Carbon. Triassic	1000
Bro (unpubl. data, 1980)	Severnaya borehole	Middle & Upper Triassic	2113
Bro (unpubl. data, 1982)	Hayes borehole	Middle & Upper Triassic	2172

The author carried out petrophysical studies to explain the consistent regional patterns of density variations in the terrigenous deposits and the wide range of their values. Density measured in drill core was correlated with the granulometric composition of the rocks, the mineral composition of fragmental grains, the carbonate and organic carbon contents, the clay mineral ratios, bitumenoids, chemical elements and other parameters. It was found that, in common with other parts of the region (Gramberg 1988), the density value is a function of many of the above parameters, but three of them are determining factors for the formation of terrigenous rocks, namely 1) the granulometric composition initiated during sedimentation and determining solution during diagenesis, 2) the primary carbonate content, which was subsequently enhanced and redistributed, 3) the level of carbonification of organic matter, indicating the phases of diagenetic transformation. Some of the other parameters either exert a much smaller influence on density, or correlate with these three determining factors.

Table 6.2 Range of density variation in different rock types

Rocks	*Range, g/cm3*
I Sedimentary	1.65–3.18
1. Terrigenous	1.65–2.7
2. Carbonate	2.66–3.18
II Metamorphic	2.67–2.77
III Igneous	1.70–3.10
1. Dolerite	2.61–3.10
2. Basalt	1.70–3.00

An equation derived by Bro (1980), based on the most informative values obtained through measurements of 104 core samples from the Nagurskaya, Hayes and Severnaya boreholes, serves as a quantitative expression of derivation:

$$d = 1.808 + 0.125N + 0.001SC + 0.008Cr$$

where d is the density in g/cm^3, N is the degree of diagenesis, SC is the content of silt and clay as a percentage of the thin section and Cr is the wt. % of carbonate (dissolved in 10% hydrochloric acid). The multiple correlation coefficient is 0.860 and the standard error is 0.083. The degree of diagenesis is subdivided into 6 values. Values 1 and 2 correspond to protodiagenesis, or the immature phases of diagenesis; value 1 is denoted PC1–PC2, and value 2 PC3. Values 3 through 6 correspond to mesodiagenesis, where 3 is the early mature phase (MC1), 4 is the moderately (average) mature phase (MC2), 5 is the advanced mature phase (MC3), and 6 is the overmature phase (MC4). In additional equations based on material from the Hayes and Severnaya boreholes, the index N was replaced by H, the depth to the present occurrence. In this case, the multiple correlation coefficients are 0.881 and 0.869, respectively.

Sufficiently high coefficients were mainly formed due to a relationship between the density value and N or H, and give information on the phases of diagenetic transformation. However, in the Franz Josef Land area, post-depositional processes have not been confined to diagenesis caused by deep burial of the deposits. An additional increase in density was created by the mechanical and thermal actions of intrusions, and, possibly, by deformations and thermal anomalies near a folded area which may have flanked the north and northeast of Franz Josef Land during the Triassic and served as a source area. A density increase in the intrusion-enclosing rocks can be traced for no more than a few metres from the contact and is insignificant on a regional scale. No evidence of pressure deriving from the presumed folded area has been identified yet, but a slight thermal effect seems to be recognisable.

The distribution of petrophysical data from the boreholes (Fig. 6.1) indicates that in the Severnaya borehole column carbonification of organic matter increases with depth ahead of a build up in density. As this pattern is usually observed close to the folded zones it cannot be ruled out that, not

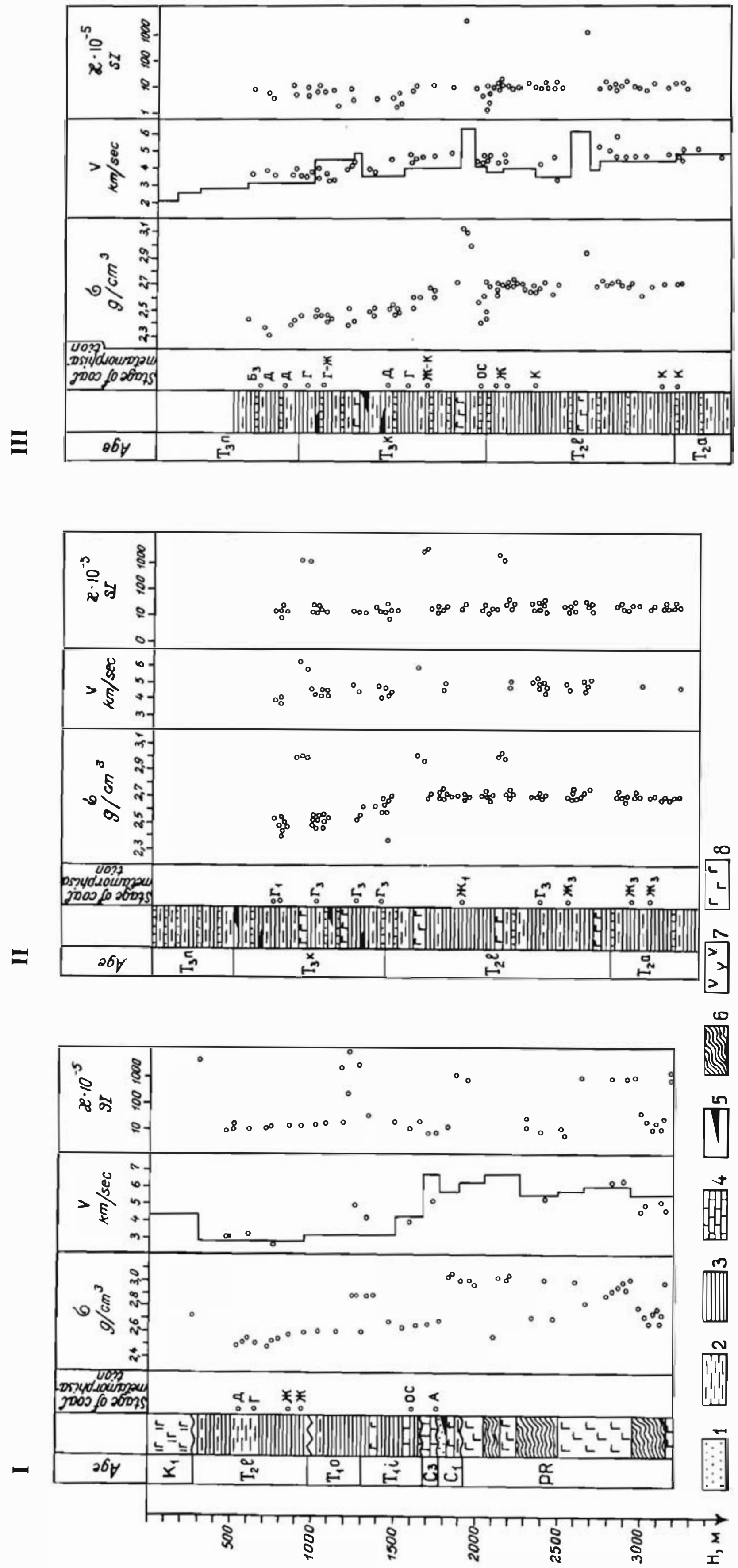


Fig. 6.1 Variations in density (σ), wave velocity (V) and magnetic susceptibility (æ) down the Nagurskaya (I), Hayes (II) and Severnaya (III) boreholes. 1 sandstone, 2 siltstone, 3 mudstone, 4 limestone, 5 coal, 6 fine-grained quartzite and schist, 7 dolerite, 8 basalt.

only late-Caledonian (see Chapters 2, 7, 9) but also Triassic or post-Triassic, orogenesis manifested itself near the eastern boundary of Franz Josef Land. If these assumptions are corroborated, an additional independent variable allowing for the effect of the folded area, for example, the distance from it, should be introduced into the above equation which is, in essence, the simplified empirical density model.

Measurements of the density of sedimentary rocks in samples from outcrops characterise consolidated rocks only, thus putting unconsolidated silty-sandy and moist clayey varieties, widely developed on the surface, beyond the scope of these investigations. Measurements on samples of drill core are more representative, since all the rocks are consolidated below a few hundred metres. Figure 6.1 shows how the density of terrigenous deposits, which dominate in the sedimentary cover, increases downwards as a result of post-depositional transformations. On petrophysical sections, analytical data arrange as a band of points. Measurements made on igneous rocks plot at some distance to the right of the band.

The distribution of points in the band mainly reflects cyclic variations of granulometric composition and changes in the carbonate content. Minima correspond to sandstone with argillaceous cement and maxima characterise carbonate-bearing terrigenous rocks and carbonates. The lack of sandstone in the Triassic deposits in the Nagurskaya borehole is responsible for the narrowness of the band, which shows values from the shallowest depths. The values start to decrease at depths of about 1430 m in the Hayes borehole and 1990 m in the Severnaya borehole. These changes are caused by sandstone with a high content of coarse to medium-grained fractions and little carbonate. They probably complete the regressive part of the Ladinian sequence.

The volume of pore space decreases, density differentiation with respect to rock varieties weakens, and the band of values narrows with a steady downward increase in the intensity of the post-depositional transformation of the rocks. In the zones of the MC3–MC4 phases of diagenesis, a sharp decrease in the gradient of the density increase is observed, the maxima approaching the upper limit that is characteristic for terrigenous rocks. For example, from the top to a depth of 2000 m in the Severnaya borehole, the density variation per 100 m is about 0.03 g/cm^3, but at a greater depth it is 0.003 g/cm^3. Metamorphic rocks complete the tendency, i.e. the gradient becomes practically zero. Hence, the width of the band in Figure 6.1 is, in practice, determined by differences in lithology.

The density of igneous rocks mainly depends on the composition of the initial magma, chilling conditions, and the intensity of subsequent transformations. The composition of the magma predetermines a suite of minerals and their ratios, whereas the chilling rate dictates porosity and the degree of crystallisation. Density decreases as the proportion of vitreous material and the amount and size of interstices increase. Basalt therefore has a lower density than dolerite (Table 6.2). The density of dolerites in drill core is usually 2.8–3.1 g/cm^3. The lowest values were recorded in rocks showing signs of deuteric alteration. The density of basalt in outcrops on Alexandra Land was studied by Piskarev & Kovaleva (1975). They found that porous zeolitised vitrobasalt has the lowest density, 1.70–2.0 g/cm^3. Values of about 2.80 g/cm^3 were recorded in pyroxene-plagioporphyritic rocks with a crystallised groundmass. The mean density of basalt is 2.70 g/cm^3. According to Ya.V. Neizvestnov (unpubl. manus.), the density of basalt on the same island varies from 2.30 to 2.90 g/cm^3.

Density datum horizons in the borehole columns occur at contacts of sequences that contrast in structure and lithology, and at the boundaries of zones of diagenesis where the consistent pattern of density variation breaks down. Igneous and sedimentary rocks differ considerably in density. At the boundary between Triassic terrigenous deposits and Cretaceous effusives there is a sudden drop in density of 0.20 g/cm^3. Because of relatively small thicknesses and, especially, the impersistent trend of intrusions, these differences cannot be used as regional datum horizons. At the top of the basement in the Nagurskaya borehole, the density datum horizon formed as a result of the numerous intrusions in the Proterozoic strata rather than due to a difference in the density of metamorphic rocks and highly post-depositionally transformed sedimentary rocks. According to Verba et al. (1980, 1983), the strong increase in density at the basement/cover boundary is about 0.25 g/cm^3. A decrease in the gradient of the density increase in response to the effect of diagenesis, which was noted in the Hayes and Severnaya boreholes near the Middle/Upper Triassic boundary, can also be traced regionally.

6.2 LONGITUDINAL SEISMIC VELOCITY

V.V. Verba and E.G. Bro (unpubl. manuscripts) reported the results of 346, 251 and 203 measurements of seismic velocity in core samples from the Nagurskaya, Hayes and Severnaya boreholes, respectively. When measuring seismic velocity (**V**) in the laboratory, effective pressures close to those in situ were simulated. Shooting was performed in the Nagurskaya and Severnaya boreholes. Laboratory results and the velocities of formations are presented in Figure 6.1. The seismic velocity is 2.0–5.0 km/s in terrigenous deposits, about 5.0 km/s in metamorphic rocks and 5.0–6.5 km/s in carbonate and igneous rocks. The relationship between the longitudinal seismic velocity and the structure, lithology and other geological characteristics was studied in samples and in situ. Studies on samples of terrigenous rocks showed that the seismic velocity, like the density, is mainly a function of the intensity of diagenetic transformation and the amount of carbonate accumulated during lithogenesis. Coefficients of the paired correlation of wave velocity with both characteristics are +0.622 and +0.329. The effect of other rock characteristics is much weaker; even the role of granulometric composition is not always recognised.

Studies carried out everywhere indicate that velocity, like density, builds up in a sandstone-siltstone-mudstone sequence (of course, all other things being equal). However, this is only the case in zones of early diagenesis. As the collection of drill core samples studied here is dominated by rocks that are severely altered by diagenesis, no consistent pattern has been revealed. The relationship between the wave velocity and the geological age and present depth of the deposits is probably secondary and arises due to correlation of the characteristics with zones of diagenesis. As in the case of density, the effect of intrusions on the wave velocity in country rocks is probably limited. No effect from the presumed folded area has been found. However, north and northeast of the boreholes, measurements approach close to the minima and maxima in the range of wave velocity given above for terrigenous deposits, which are much more liable to density increase than other rocks.

In petrophysical studies of strata as thick as a few hundred metres, velocities measured by shooting in boreholes were correlated with the lithological characteristics at the corresponding intervals. The results obtained show that the distribution of carbonate during sedimentation and diagenesis played a determining role in velocity formation, thus supporting the measurements made on samples. The presence of intrusions drastically increases the velocities in formations. Consistent patterns recognised in a few sequences in Franz Josef Land are in harmony with those revealed in numerous samples from the Pechora Sedimentary Basin and the West Siberian plate.

In general terms, the change in velocity through a borehole column is identical to the change in density. Under the action of diagenesis, the velocity figures obtained from samples and strata increase with depth from 2–3 km/s down to the roof of the metamorphic rocks. High in a column, a few relatively high values in samples are associated with terrigenous carbonates, carbonates or igneous rocks; low in a column, the values measured in igneous rocks contrast with the increasingly high velocities in terrigenous deposits.

The particular laboratory method used meant that velocity could only be measured in consolidated rocks which were not destroyed when drilled and sawn, or while simulating the *in situ* pressure. Completely unconsolidated material, and even many poorly cemented rocks whose density was nevertheless measured, could not be used. This entailed a substantial loss of sample representativeness at the shallowest depths, where the band of values in Figure 6.1 is consequently relatively narrow. Possibly because of this, high in columns where the proportion of unconsolidated and poorly cemented deposits is appreciable, the velocity in samples is generally higher than that in formations, which represent all the rock varieties in the strata. Moreover, partly because of this, the relationship between the velocity value and the granulometric composition of terrigenous rocks becomes indiscernible.

The gradient of the increase in velocity decreases sharply in the Hayes and Severnaya borehole columns near the Upper/Middle Triassic boundary. The reason for this is probably the same as that causing the decrease in the density gradient. For instance, velocity increases at a rate of 0.08 km/s per 100 m in the Hayes column in the depth interval of 750–1450 m. Lower in the column, the velocity reaches an upper limit that is typical for terrigenous rocks, and becomes almost stable. A systematic increase in the velocity of formations as a response to diagenesis is locally reversed. The largest reversals are associated with the lower boundaries of igneous rocks and carbonates.

Since the longitudinal seismic velocity is closely related to density, consistent patterns of variation in both parameters are similar and the density datum horizons recognised may serve as seismic index horizons. Seismic shooting can identify a stratigraphical disconformity at the Middle/Upper Triassic boundary and also the unconformity at the boundary between the basement and the sedimentary cover.

6.3 THERMOPHYSICAL PROPERTIES

From 1979 to 1987, I.V. Shkola, E.G. Bro, U.I. Moiseenko and T.Z. Chadovich obtained 8, 40 and 37 thermal conductivity values from core samples from the Nagurskaya, Hayes and Severnaya boreholes, respectively. Samples of terrigenous rocks gave values varying from 1.94 to 3.51 W/mK. Studies of samples from Franz Josef Land and elsewhere show that thermal conductivity values mainly depend on the same rock characteristics which determine density and wave velocity. Thermal conductivity values increase in a clay-silt-sand series with an enrichment in carbonate material and an increase in the level of diagenesis downwards. In addition, allowance must be made for the presence of carbonaceous material, a high concentration of which markedly lowers the thermal conductivity value. Increases in the density of terrigenous rocks in the contact zone to igneous bodies and through stress should also raise the value. Temperature logging was carried out in all the boreholes, and temperatures were measured during fluid testing. In the Nagurskaya and Severnaya boreholes, the temperature curve was recorded in obviously unstable conditions. The preliminary rest time in these boreholes was, respectively, 10 and 6 days, i.e. evidently insufficient to restore the temperature regime in the zone disturbed by drilling. Temperature data may be presumed to be close to natural conditions only in the Hayes borehole, which rested for 158 days. Geothermal gradients, calculated from thermal logging records, vary from 1.6 to 5.0°C/100 m. The most reliable data for the Hayes borehole are within 2.5–4.0° C/100 m.

Because of different approximations of the temperature measurements obtained to true values, no quantitative comparison can be made of the gradients calculated for the different boreholes. However, a comparison of the gradients within each individual borehole column is more valid, since it provides relative information. It showed that the gradient value in terrigenous rocks is higher than in carbonate, metamorphic and igneous rocks, which are characterised by higher thermal conduction. In the terrigenous rocks, maxima are recorded in essentially argillaceous deposits, and minima in primarily sandy rocks that have higher thermal conduction.

The lower boundary of permafrost was found by thermometer readings and apparent electrical resistance, determined by an increase in values for ice-saturated rocks. The depth to permafrost in the Nagurskaya, Hayes and Severnaya boreholes was 80, 170 and 410 m, respectively. It is probably dependent on the distance between the borehole and the coast, the size of the island, and the density of the heat flow rate. According to Ya.V. Neizvestnov (unpubl. manus.), frozen rock can now be observed on the coasts of Franz Josef Land islands as a result of freezing of the sea floor on which ice is frozen fast for much of the year when the depth is not less than 2–2.5 m. This frozen zone forms peculiar caps around the islands. These caps are 15–20 m thick at the edge of the water and tens or, possibly, hundreds of metres wide. Offshore from Alexandra Land, the cap width is 20–45 m (Dzhandzhgava et al. 1990). The density of the heat flow rate was estimated from data on thermal conductivity and temperature measurements taken in boreholes. Values which are closest to true values were calculated for the lower parts of borehole columns, which contain no unconsolidated or poorly cemented rocks, these being disregarded in laboratory measurements of thermal conduction. Moreover, geothermal gradients in the upper column can be skewed by a cooling effect from above, i.e. from the permafrost zone, and from the side of the Arctic Basin which is 200–300 km from the boreholes.

The densities of the heat flow rate in the Nagurskaya, Hayes and Severnaya boreholes were 148, 57.7, and 75.5 mW/m^2, respectively; these values were calculated from the geothermal gradient and thermal conduction. The value recorded for the Hayes borehole, i.e. 57.7 mW/m^2, can probably be regarded as closest to the true value because this borehole rested longer before thermometry than the other two. Levashkevich et al. (1992) published recalculations of the density of the heat flow rate. Values of 79.2, 78.8 and 80.2 mW/m^2 were given for the Nagurskaya, Hayes and Severnaya boreholes, respectively. Unlike the previous data, Levashkevich et al. (1992) estimated the heat conduction of the rocks by using logs, not only laboratory measurements of samples, and, when calculating weighted averages for the boreholes, they did not rule out data obtained from the upper parts of the columns. No matter which of these sets of data on the density of the heat flow rate are preferred, all of them (except 148 mW/m^2) are close to the values calculated for the Vassdalen borehole in Spitsbergen and higher than those calculated for boreholes on the islands of Kolguyev and Sverdrup on the southern shelf, and also on the coasts of the Barents and Kara Seas.

The relatively high density of the heat flow rate in Franz Josef Land, like elsewhere on the continental margin, is probably caused by thermal radiation emanating from basement rocks propagating sideways from upstanding blocks, not only upwards. For example, the basement of the upstanding block in the Nagurskaya borehole area may also raise the heat of sedimentary rocks in the adjacent block. If a folded area does exist north and northeast of Franz Josef Land, it served, and probably still serves, as an additional heat source. During the Mesozoic, the heat field was further complicated by magma injections.

The overall effect of these heat flows is reflected by the degree of carbonification of organic matter. Diagenetic zones, complicated by superposed anomalies, are distinguished by the degree of carbonification in the sedimentary cover. The above-described peculiarity of heat flow is probably responsible for the unusually small thicknesses of the diagenetic zones where carbonification of organic matter is at the stages of brown coal and long-frame coal.

6.4 MAGNETIC PROPERTIES – E.G. BRO († 1997) & V.D. DIBNER

Magnetic susceptibility (æ) and natural remanent magnetisation (In) were measured in samples from outcrops and drill core. Samples were taken on most of the Franz Josef Land islands (Table 6.3). Samples of sedimentary rocks derive mainly from the islands of Alexandra Land, Hayes and Graham Bell, and igneous rocks from other islands. The magnetic properties of metamorphic rocks were determined in core from the Nagurskaya borehole.

Sedimentary and metamorphic rocks may be considered nonmagnetic. Their magnetic susceptibility varies from 0 to 60.10–5 SI units. In this range, a direct relationship between magnetic susceptibility and the content of silty-clayey material is found in terrigenous rocks. This is because, during sedimentation and diagenesis, fine-grained sediments accumulate more elements and minerals that have high magnetic properties. Values up to 690.10–5 SI units, which are rare in terrigenous rocks, are mainly caused by higher contents of magnetite, iron hydroxides and fragments of basic igneous rocks in sandstone, and of siderite in mudstone. The range of magnetic susceptibility in carbonates is somewhat greater than in terrigenous rocks. Values of (6–12).10–5 SI units were obtained for the Upper Carboniferous limestone encountered in the Nagurskaya borehole, and ironstone concretions locally encountered in Triassic strata yielded values as high as 230.10–5 SI units.

Table 6.3 Measurements of magnetic susceptibility (æ) and natural remanent magnetisation (In) in rock samples.

Source	*Sampling site*	*Age of rocks*	*Number of measurements*	
			æ	*In*
Karasik & Dibner 1965	Outcrops on 18 islands	Upper Triassic-Cretaceous	365	331
Gusev 1971	Outcrops on more than 17 islands	Triassic-Cretaceous	2636	2636
Livshits et al. (unpubl. data, 1974)	Outcrops on Alexandra Land	Lower Cretaceous	78	–
	Outcrops on Graham Bell Is.	Upper Triassic-Jurassic	258	–
Piskarev & Kovaleva 1975	Outcrops on Alexandra Land	Lower Cretaceous	48	48
Tarakhovsky et al. (unpubl. data, 1976)	Outcrops on Graham Bell Is.	Upper Triassic-Jurassic	57	–
Verba et al. 1980	Nagurskaya borehole	Vendian, Carbon. Triassic	2095	20
Bro (unpubl. data, 1980)	Severnaya borehole	Middle & Upper Triassic	3135	28
Bro (unpubl. data, 1982)	Hayes borehole	Middle & Upper Triassic	1991	54

Remanent magnetisation was measured in 92 samples of Triassic terrigenous rocks from drill core. The values are within (0.2–544).10–3 A/m, often in excess of 20.10–3 A/m. Comparison of remanent magnetisation and structural and lithological features showed no clear petrophysical relationships. The orientation of core samples carried out in the VNIGRI laboratory indicates that both directly and inversely magnetised rocks are present in borehole sections.

The magnetic properties of igneous rocks vary greatly and are one or two orders of magnitude higher than those of sedimentary rocks. Most data concern basalts. The magnetic susceptibilities of basalt and dolerite are (160–9650).10–5 and (130–15090).10–5 SI units, respectively. Dolerite sometimes shows not only higher maximum, but also higher mean values which are usually within (1500–2500).10–5 SI units in both dolerite and basalt. Gusev (1971) explained the difference in magnetic susceptibility between basalt and dolerite by the fact that the latter contains larger grains of magnetic minerals. On the contrary, basalt exhibits higher natural remanent magnetisation. Values of 0.03 to 15.5 A/m and 0.12 to 46.6 A/m were recorded for dolerite and basalt, respectively. Mean values in basalt are twice those in dolerite.

Most samples with high remanent magnetisation were from dyke swells and related basaltic sheets and sills. Such magnetisation is especially characteristic of igneous bodies with pegmatoid schlieren, which are usually rich in magnetite. These peculiar bodies were discovered by V.D. Dibner in basaltic rocks and dyke swells on Alexandra Land, Scott-Keltie, Hooker and other islands. Similar schlieren were described by Lupanova (1953) in basalts on Rudolf Island. Dark grey, almost black schlieren stand out against the background of basic rocks. They form branching veins, rounded in cross section and up to 10 cm across. The veins are partly of hyalobasalt, partly of pegmatoid-type rocks. Hyaloschlieren show a porous structure. Pore (up to 2–3 mm in diam.) walls are covered by black, locally lustrous, graphite-like encrustations, which are probably compounds of carbon (including hydrocarbon) which exsolved from magma together with hydrothermals when the basaltic sheet was cooling.

Microscopy by B.I. Test showed that schlieren whose groundmass is particularly rich in glass are very fine-grained rocks. The finest laths of labradorite and xenomorphic granules of pyroxene were observed in vitreous masses. Rounded and extremely irregular palagonite aggregates (usually with calcite in the middle), locally showing a spherulitic structure, occur in the interstices of the laths.

Pegmatoid schlieren differ from the host rocks by being more coarse grained and showing ophitic, poikiolitic and, less commonly, intersertal textures. Plagioclase and clinopyroxene form the largest aggregates, as long as 5–7 mm. Grains of magnetite and other ore minerals are present, locally in abundance. Therefore, in some swells, for example, in the Rubini Rock swell and associated agglomerates on the slope of the Ciurlionis plateau, remanent magnetisation values are as high as 14.4 A/m. Similar high values were recorded in basaltic sheets for which the Rubini-Ciurlionis dyke could serve as a feeder. A northwestern continuation of this dyke is marked by a local, oval-shaped magnetic anomaly, elongate in the same direction (the easterly declination increases by as much as 31°), and by an anomaly at Cape Astronomic (west coast of George Land) revealed by aerial photography in 1953; samples show In values as high as 10.6 and 14.4 A/m.

Very high In values of 34.2 A/m were recorded in samples from the contact of one of several small swells of the Skvoznaya (Through) dyke in the central part of Hayes Island. Enhanced (8.0 A/m) values were noted in basalt samples from agglomerates in an explosion pipe in the western part of Hayes Island. The highest values were found in the lower sheet at Cape Vasiliev on Wiener-Neustadt Island, at the top of which they reach a maximum value of 46.6 A/m. In other basaltic sheets, In generally increases from the base to the top and decreases from lower to upper sheets. For instance, an In of 35.3 A/m was recorded in a sample from the top of a lower sheet in the Cape Albert Markham area on Hooker Island (sample 796b taken in 1953).

In four cases, In in excess of 10.0 was also noted in sills, but only those occurring in the vicinity of dyke swells and explosion pipes. Magnetite may have accumulated in schlieren and directly in groundmass on more than one occasion at the same localities. Gas-rich magma served as a carrier of metalliferous emanations and, because of its kinetic energy and emplacement near the surface, formed (in decreasing order) magnetite-rich dyke swells, apical parts of "normal" dykes, explosion pipes, sheets and sills.

Studies on alternating field demagnetisation of igneous rock samples (Gusev 1971) showed that basalt had high magnetic stability. High Q values (remanent-induced magnetisation ratio), the character of alternating field demagnetisation curves, and thermomagnetic analyses suggest the thermoremanent nature of most In. Viscous magnetisation of the rocks accounts for 15–30% of the In value. Thermomagnetic curves indicate the presence of titanomagnetite and magnetite. The vector direction of remanent magnetisation in basalt and dolerite is steady and coincides with the present magnetic field direction. The same In direction was found in six dolerite samples from core from the Nagurskaya borehole (V.V. Verba, unpubl. manus.).

Mass measurements of magnetic susceptibility are plotted on petrophysical diagrams of the boreholes (Fig. 6.1). The measurements arrange as an almost vertical band whose width is determined by the range of the commonest values for terrigenous rocks. Sporadic high values outside the band represent igneous rocks. The arrangement of points within the band follows the order of chemical elements with different magnetic properties, according to granulometric fractions and variations in the amount of siderite or, to be more accurate, accompanying ferric oxide minerals, in the rocks. The magnetic properties of sedimentary and metamorphic rocks are similar, but because the metamorphic basement contains far more intrusions than the sedimentary cover, the weighted average values are higher.

Discussion

The study of the physical properties of rocks has been irregular in Franz Josef Land, sampling for magnetic properties being most even. Most of the laboratory data stem from the islands of Alexandra Land, Hayes and Graham Bell, where they derive from both outcrops and boreholes, and these are of great value.

The gathering and systematisation of data were accompanied by investigations aimed at explaining why the physical parameters varied over time. This sometimes allowed us to distinguish anomalous, generally not representative data, and to predict trends of variations in physical properties away from the sites sampled. Correlation of the physical properties of terrigenous deposits with structural, lithological and other geological data supported petrophysically consistent patterns recognised elsewhere.

Density, wave velocity and thermal conductivity values are mainly functions of the same characteristics, reflecting the same natural processes; hence, these physical parameters are interrelated. At the same time, each of these parameters is caused by different properties of the rock. Unlike density and thermal conduction, the wave velocity is a function of the granulometric composition at early stages of post-depositional transformations only. The distinguishing feature of thermal conduction is that it is more sensitive, compared with other closely related physical properties, to the presence of organic matter in the rock. A collection of 77 samples of core from the Hayes and Severnaya boreholes gave a paired density-velocity correlation coefficient of +0.709, whereas another collection of 65 samples from core from the same boreholes and the Sverdrup borehole (17 samples) gave a paired density-thermal conduction correlation coefficient of +0.497.

In the boreholes studied, physical datum horizons, which can be traced through all or most of Franz Josef Land, are related to boundaries of sequences that have contrasting structures and lithologies, and to the boundary of a sharp decrease in the gradient of variations in physical properties. Three datum horizons have so far been recognised. The uppermost horizon determines the boundaries of Lower Cretaceous basalt and probably Upper Triassic terrigenous rocks. Beneath the upper contact, density, wave velocity, magnetic susceptibility and natural remanent magnetisation drastically decrease. Sharp decreases in the density and the velocity gradient were noted at the Upper/Middle Triassic boundary. A relatively high admixture of carbonate material in terrigenous deposits below the boundary probably causes an additional build up in the values of both physical parameters. The third datum horizon is marked by an increase in density, wave velocity and magnetic properties at the top of the basement.

As noted in section 6.1, increasing carbonification of organic matter with depth takes place ahead of a density increase in the Severnaya borehole column, which is probably closer to the presumed folded area in the north and northeast than the other boreholes. This cannot be considered fortuitous. The same was observed with respect to reservoir features estimated in samples from core and on the basis of the borehole columns. If the relatively young folded area does exist, then, as it is approached, the effect of stress should increase and differentiation of density, velocity and thermal conductivity values with respect to rock varieties and zones of diagenesis should weaken. Consequently, the Middle/Upper Triassic boundary would lose its acoustic sharpness.

7. TECTONICS – V.D. DIBNER & A.G. STARK

Franz Josef Land belongs to the East Barents Sedimentary Basin, which is composed of three subbasins, the South Barents, North Barents and Franz Josef Land subbasins, separated by fairly low, elongated domes. Franz Josef Land forms the northern closure of the East Barents Sedimentary Basin. In the first two subbasins, the cover attains 20 km or more in thickness (Gramberg 1987). In Franz Josef Land, the cover of Palaeozoic and, especially, Mesozoic deposits, along with volcanics and hypabyssal intrusions of the plateau-basalt rock association, varies greatly in thickness. This is a function of the mosaic tectonic pattern (Fig. 7.1) that originated early in the geological history of the area, was inherited during Early Cretaceous rifting, and has since been reflected in the relief.

7.1 TECTONIC SETTING AND DEEP-SEATED STRUCTURE

Gravity mapping has delineated two elongate ENE-WSW trending zones in the Franz Josef Land subbasin. These are separated by the Ziegler flexure zone. The northern one, the Alexander zone, characterised by gravitational (Bouguer) anomalies of 40 to 90 mGal, is the result of a regional rise of the folded basement and its relatively thin cover which, calculations suggest, almost nowhere exceeds 4–5 km. The southern one, the Wilczek zone, results from regional subsidence of the folded basement, especially in the central-northern part of the zone. The cover in the Wilczek zone attains 7–8 km in thickness in local (now inverted) lows. The seismological data mentioned above suggest that this value may be underestimated. A more precise estimate can be anticipated to result from deep seismic work planned for Franz Josef Land.

Results of seismological investigations (deciphering of PS waves) obtained from measurements at the Arkticheskaya Station (Severnaya Zemlya) and the Hayes Station (Franz Josef Land) have enabled Avetisov & Bulin (1974) to construct the following section: 1) Mesozoic sandy-clayey deposits are 1.5–4.0 km, Vo (layer velocity) 3.2 km/s; 2) older deposits (limestones and other rocks) are 1.5–4.0 to 7–10 km, Vo 4.8 km/s; 3) "granitic" layer is 7–10 to 15–17 km, Vo 5.7 km/s; 4) "basaltic" layer is 15–17 to 23–25 km (Moho discontinuity), Vo 6.7 km/s.

The results of a small-scale gravity survey performed in 1990, with allowance made for preliminary seismic profiling, were used by A.G. Stark to construct geological-geophysical profiles (Figs. 7.2 and 7.3) and the following crustal section: 1) Palaeozoic (Wenlockian-Ludlovian) and, predominantly, Mesozoic terrigenous and volcanic rocks, from a few hundred metres to 7.0–8.5 km; 2) low-grade Vendian and, possibly, Palaeozoic metamorphic rocks (Llandoverian-Wenlockian?), 0 to 5–6 km; 3) granitic and metamorphic ("granitic") layer (Archaean+Early Proterozoic), 0 to 17 km; 4) granulitic-basic ("basaltic") layer; 5) asthenospheric lens, the locally most low density part of the asthenosphere (Vo < 7.0 km/s) situated directly beneath the Moho discontinuity and inducing its local rise, 0 to 15 km (for more information on asthenospheric lenses, see Golovkov 1978, Artyushkof 1983, Dibner 1989, 1995).

Comparison of these two crustal profiles reveals some differences in sedimentary cover thicknesses: on Figures 7.2 and 7.3, the maximum composite thickness is under 8.5 km, whereas the seismological section shows 14 km, i.e. the value which, as shown below, is in better agreement with geological data for the maximum thicknesses of the cover on Franz Josef Land and, by extrapolation from the seismological measurements, in the more southerly part of the East Barents Sedimentary Basin. Figure 7.2 and, especially, Figure 7.3 indicate a lenticular layer with velocity not exceeding 7.0 km/s directly underlying the Moho discontinuity. This suggests that the lightest part of the upper mantle has risen up to the base of the crust. As was mentioned above, it may represent a thin (no more than 10–15 km) asthenospheric lens exceeding 280 km across. The folded basement embraces: 1) the crystalline (Proterozoic-Archaean?) basement underlying depocentres on crustal blocks stabilised at the end of the Proterozoic and which later underwent recurrent, lengthy subsidence (Krasny 1978), and 2) the folded basement of rift-related structures, only met with in the Nagurskaya borehole (section 3.1). It should be remembered that greenschist-facies phyllites and fine-grained schists were found there at a depth of 3204–2555 m where they were overlain by quartzites from 2555–1895 m. The assemblage of acritarchs and trichomes (taken at depths of 3095, 3094, 3045 and 3015 m) dates the lower strata as Vendian. The age of the metamorphism and, hence, orogeny was determined in 1980 at the Komi Branch of the USSR Academy of Sciences using the K-Ar method on quartz-sericite schist taken at a depth of 3046 m. The date ob-

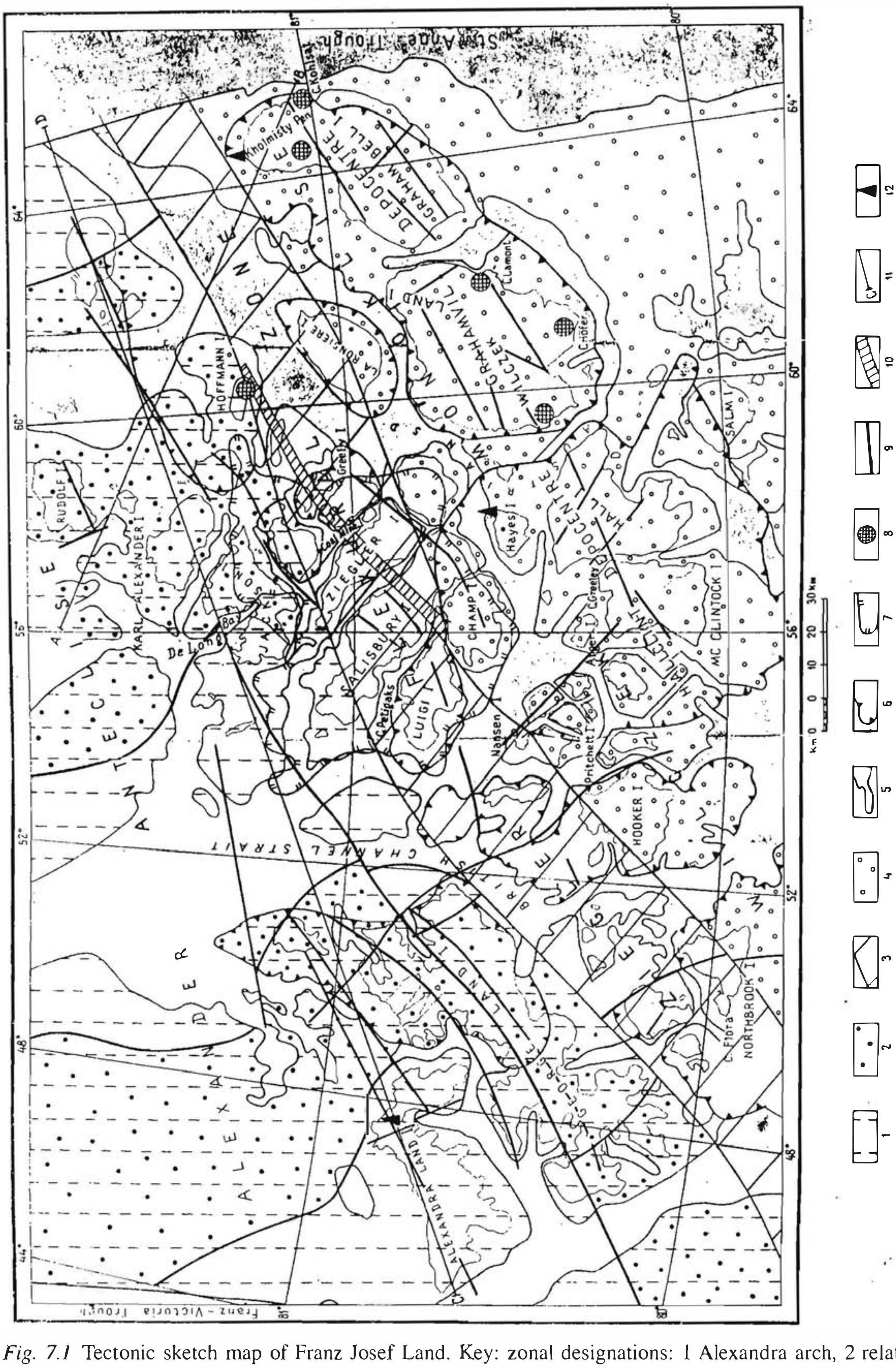


Fig. 7.1 Tectonic sketch map of Franz Josef Land. Key: zonal designations: 1 Alexandra arch, 2 relatively subsided parts of the arched area, 3 Ziegler flexure, 4 Wilczek monocline; other designations: 5 secondary rifts, 6 local inverted lows on crustal blocks, 7 outlines of the area with the most intense magnetic field (more than 1000 nT), suggesting maximum (more than 500–550 m) thicknesses of the sedimentary-volcanic sequence, 8 diapiric features, 9 ordinary faults, 10 deep-seated fault zone, 11 location of profiles AB and CD (see Figs. 7.2 and 7.3).

tained, 360 ± 18 my, exactly corresponds to the Devonian/Carboniferous boundary according to the time scale used by Harland et al. (1982). This points to the late-Caledonian, Svalbardian orogenic phase, defined in central Spitsbergen where the Devonian strata were unevenly deformed and then unconformably overlain by Carboniferous beds (Vogt 1928, Orvin 1940, Harland et al. 1993). Similar events may have taken place at the same time on Alexandra Land where the Lower Carboniferous also unconformably overlies strata deformed and metamorphosed at the Devonian/Carboniferous boundary (see section 3.1).

7.2 STRUCTURE OF THE SEDIMENTARY AND VOLCANIC COVER

According to data given in section 3.3, the boreholes drilled on the islands of Alexandra Land, Hayes and Graham Bell revealed sharp differences in cover thickness. The composite thickness is only 1900 m in the borehole on Alexandra Land (geophysical data indicate only a few hundred metres of sedimentary cover below the ice cap in the centre of Alexandra Land), whereas the boreholes on Hayes Island and Graham Bell Island gave apparent thicknesses of 3344 m and 3529 m, respectively. The overall thickness of the cover on Alexandra Land comprises the thicknesses of Lower Cretaceous basaltic sheets, Middle and Lower Triassic strata, and Upper and Lower Carboniferous strata, resting on highly deformed Vendian (possibly partly Palaeozoic – see below) quartzites, phyllites and schists. The other two boreholes (with very similar logs) penetrated the Upper Triassic and reached the Middle Triassic, but did not pass through all of the Anisian.

Let us try to extrapolate the cover thicknesses, including those of deposits beneath the beds penetrated by the boreholes. To the 3.5 km penetrated by the borehole on Graham Bell Island we add: 1) 300 m for the lower, not penetrated, part of the Anisian (650 m were drilled, and the overlying Ladinian deposits of the same duration of sedimentation are 300 m thicker); 2) 3.0 km for the

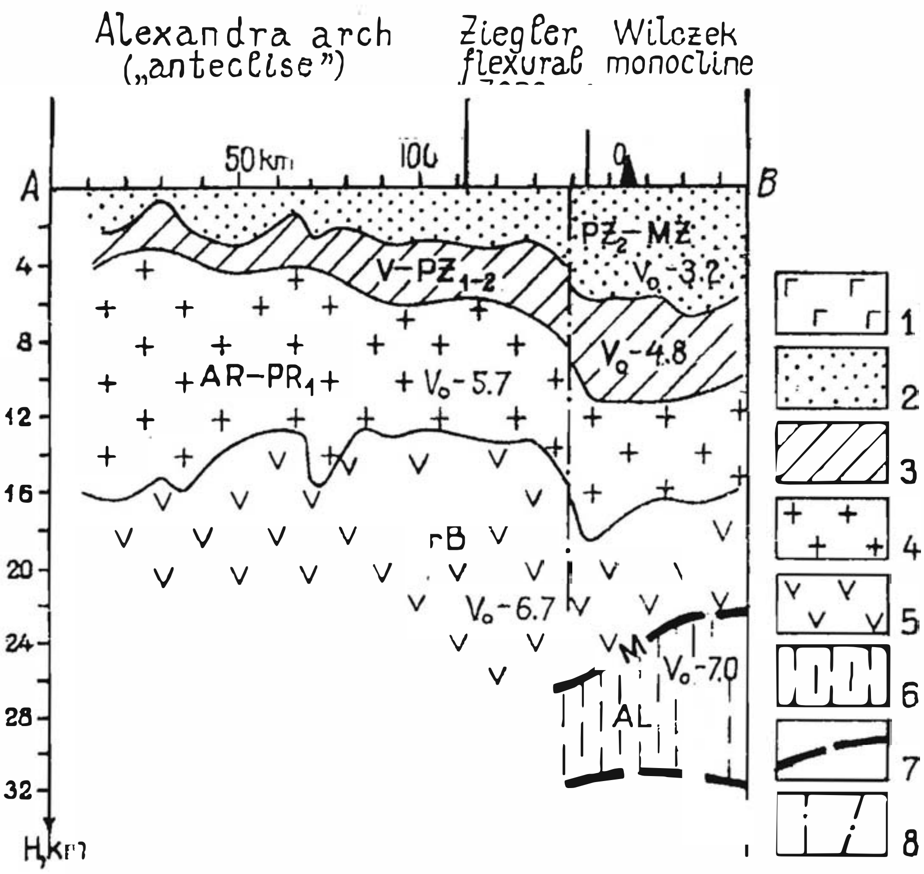


Fig. 7.2 Profile AB (for location see Fig. 7.1). 1 basic magmatic rocks (on Fig. 7.3), 2 Mesozoic and Palaeozoic sedimentary and volcanic rocks, 3 metamorphosed Vendian and Palaeozoic sedimentary rocks, 4 "granitic" layer, 5 basic granulites ("basaltic" layer), 6 possible asthenospheric lens, 7 Moho discontinuity, 8 faults.

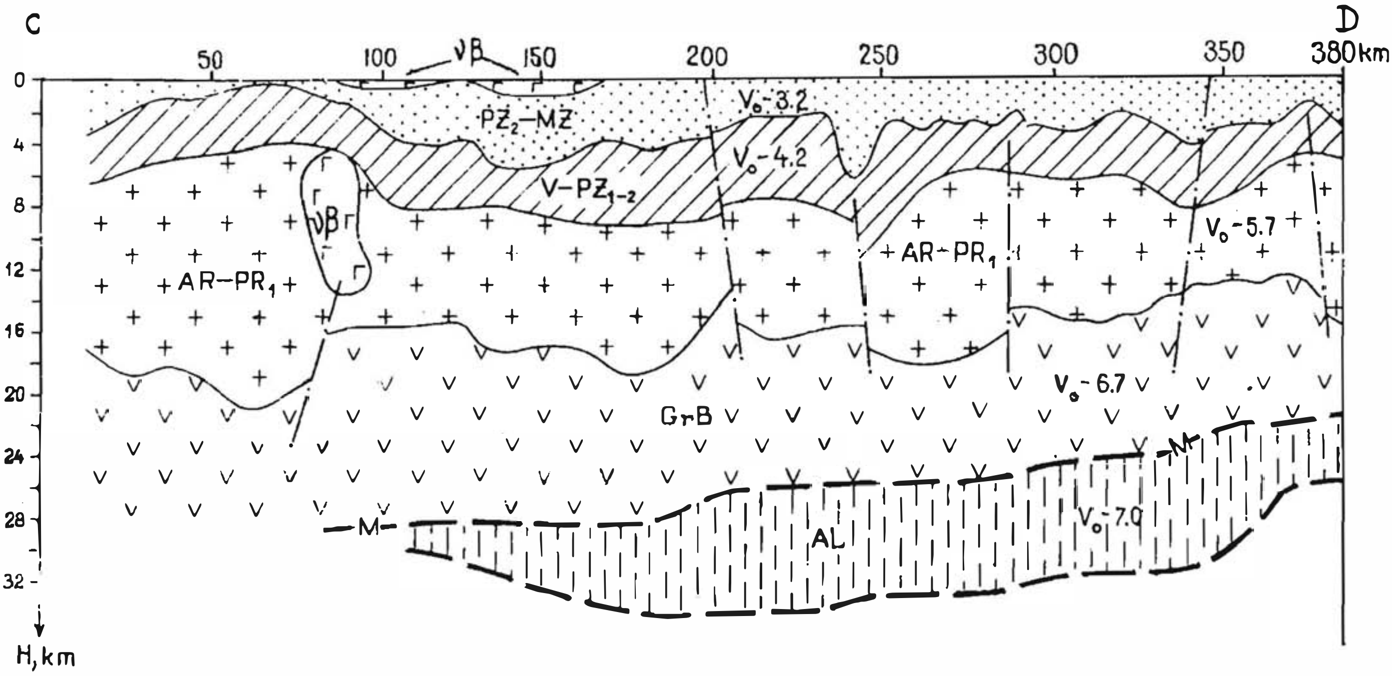


Fig. 7.3 Profile CD (for location see Fig. 7.1); see Fig. 7.2 for explanation of symbols).

Lower Triassic and Upper Permian deposits which are 3 km thick in the North Barents Subbasin; 3) 3.0 km for the underlying Lower Permian and Middle and Lower Palaeozoic, essentially carbonate deposits, which also attain this thickness in the North Barents Subbasin. This amounts to 9.8 km, this being a minimum estimate since some islands also have post-Triassic strata, namely Lower Jurassic deposits (in part encountered by the Severnaya borehole on Graham Bell Island), Middle-Upper Jurassic and Lower Cretaceous (Berriasian-Hauterivian) sandy-clayey deposits, Barremian-Albian sedimentary-volcanic sequences, and Upper Cretaceous and Cenozoic terrigenous deposits. Geological observations and seismic measurements from near the southwestern and southeastern islands of Franz Josef Land enable us to estimate their composite thickness at no less than 1.0–2.0 km. Thus, the cover partly drilled by the boreholes on Hayes and Graham Bell islands can attain a total maximum thickness of 11–12 km. However, these great thicknesses are not developed everywhere. In the vicinity of the Nagurskaya borehole, located in the northwest-trending graben, the thickness of the sedimentary-volcanic strata is an order of magnitude less. As mentioned in section 5.1, trachyandesitic basalts have been recognised in the Lower Cretaceous effusives. This is characteristic of rift magmatism (Piskarev & Kovaleva 1975). They could form a stock-like magmatic diapir(?), which was recognised on geophysical evidence below the borehole and was traced downwards as far as the near-basal zone of the granitic-metamorphic layer. In the interval 4.5–16 km below sea level, it contains multiple intrusions of basic igneous rock. All this suggests that the present "Nagurskaya graben" originated in response to rifting and, hence, the intrusion can be considered a product of intense rift-related heat and mass transfer. The process may be genetically related to the above-mentioned asthenospheric lens from which the subcrustal material derived to be intruded along a fault (or faults) through the basaltic layer (being contaminated in the process), to be concentrated in the near-basal part of the granitic-metamorphic layer, excess material forming the diapir-like intrusion injected along the Nagurskaya rift (Fig. 7.3).

The Nagurskaya graben is responsible for part of the intricately ramifying system of linear, negative physical features (valleys, sounds, etc.) which break up the Franz Josef megaplateau. These features are secondary rift grabens (Dibner 1989) which inherited primary rifts formed in the Caledonian basement. This may have taken place in the early Neocomian, prior to the formation of the volcano-sedimentary sequence which was deposited on intensely block faulted, very unevenly eroded, pre-Neocomian deposits. Thus, the Franz Josef Land Subbasin started to form in late-Caledonian time. It was divided by folds into separate blocks of different sizes. These folds were later inherited by rift-related structures. Thus, fragments of ancient cratogenic structures, which have not been reworked by a later orogeny, were formed. This peculiar megastructure of Franz Josef Land, which in outline resembles a gigantic stockwork, may be termed a "stockwork structure" (Fig. 7.1).

The crustal, or tectonic, blocks may be placed in one of two categories, uplifted and subsided. The subsided blocks, referred to as Pannonian-type blocks, or median masses (Zabrodin et al. 1970), are characterised by great thicknesses of infilled sedimentary and volcanic deposits. The crust of these blocks is thin. Although the data are inadequate to ensure reliable interpretation of the megastructure of Franz Josef Land as a whole, a good fit exists between the largest negative gravity anomalies and the largest infilled depressions or depocentres, "Grahamwil" and "Hallclint". Other negative gravity anomalies permit the recognition of many other crustal blocks of various sizes, and their depocentres, which previously had mainly been interpreted on the basis of structurally-related features in the surface relief (Fig. 8.1).

In places (in the western part of the Hallclint depocentre, in the vicinity of Bruce and Northbrook islands, at De Long Bay and elsewhere), relatively narrow rift grabens form triangular systems. They are typical of the early stage of rifting and are located on uplifting and, hence, extending and fracturing arches (Cloos 1939). In Franz Josef Land, such minor rift systems dissect different-order crustal blocks (generally minor ones), unlike larger rift grabens, which usually flank large crustal blocks.

Two regional tectono-sedimentary stages (series of formations separated by regional unconformities) are recognised. The lower one is mainly represented by Triassic, Jurassic and Neocomian deposits, and the upper one by a sedimentary-volcanic sequence of Barremian-Albian age (the younger beds are only found locally). The lower stage consists of two varieties: 1) an intrarifting stage consisting of relatively thin epi-Caledonian deposits which fill the rifts and rest on strata deformed during the Caledonian orogeny; they were not entirely removed by subsequent erosional events because they occur in the Nagurskaya rift graben and probably other unidentified rifts of similar type mostly concealed on the floors of straits and sounds or beneath outlet glaciers on islands and offshore, 2) depocentric stages associated with subsided crustal blocks and distinguished by very great thicknesses of sediment fill proved by logging of the Hayes and Severnaya boreholes and by seismographic sections; moreover, these boreholes also show that the Hallclint and Grahamwil depocentres have complete syntectonic sedimentary sequences (Fig. 7.4), although we have no information about the syntectonic nature of other depocentres shown on Figure 7.1.

There were three breaks in the intrarifting structural stage: 1) between the Lower and the Upper Carboniferous; 2) between the Upper Carboniferous-Asselian and the Induan (lowermost Triassic), 3) between the lower Olenekian and the upper Ladinian (Triassic). The depocentric structural stage displays many stratigraphical breaks, especially in the Jurassic and Cretaceous, which we will take up in Chapter 9.

The upper structural stage mainly consists of the sedimentary-volcanic sequence. These strata rest on beds belonging to the lower structural stage, which had been dissected by rift grabens and in places strongly eroded prior to the onset of the upper structural stage since particular beds rest on strata of different age and there is a major disconformity from Volgian to Norian-Rhaetian. This regional, essentially basaltic, armour rests disconformably or unconformably upon both the depocentre and the various varieties of rifts belonging to the early structural stage (Fig. 7.4). The beds of the upper structural stage (Barremian-Albian) are most completely developed in a wide NE-SW trending zone in the west of Franz Josef Land, on Alexandra Land, most of George Land and the underwater Alexandra plateau, as shown by the magnetic field T intensity ranging from 100 to 700 nT. However, the greatest thicknesses of strata from this structural stage have been preserved in a zone (also NE-trending) occupying the central part of Franz Josef Land. This is confirmed by direct geological observations and also because it is here, over the northern part of the central group of islands, that the most complicated and intensive magnetic fields, typical of basic effusives, have been recorded. The field is most intensive over the islands of Luigi, Salisbury, Champ, Ziegler and Jackson (T 700 to 1000 nT), and somewhat less intensive in the southwest over Hooker, Nansen, Bromwich and other islands, and in the northeast over Greely, Payer, Rainer, Karl Alexander, Rudolf and other islands. The present data suggest that on this central group of islands the present aggregate thickness of the sedimentary-volcanic sequence can exceed 500-550 m.

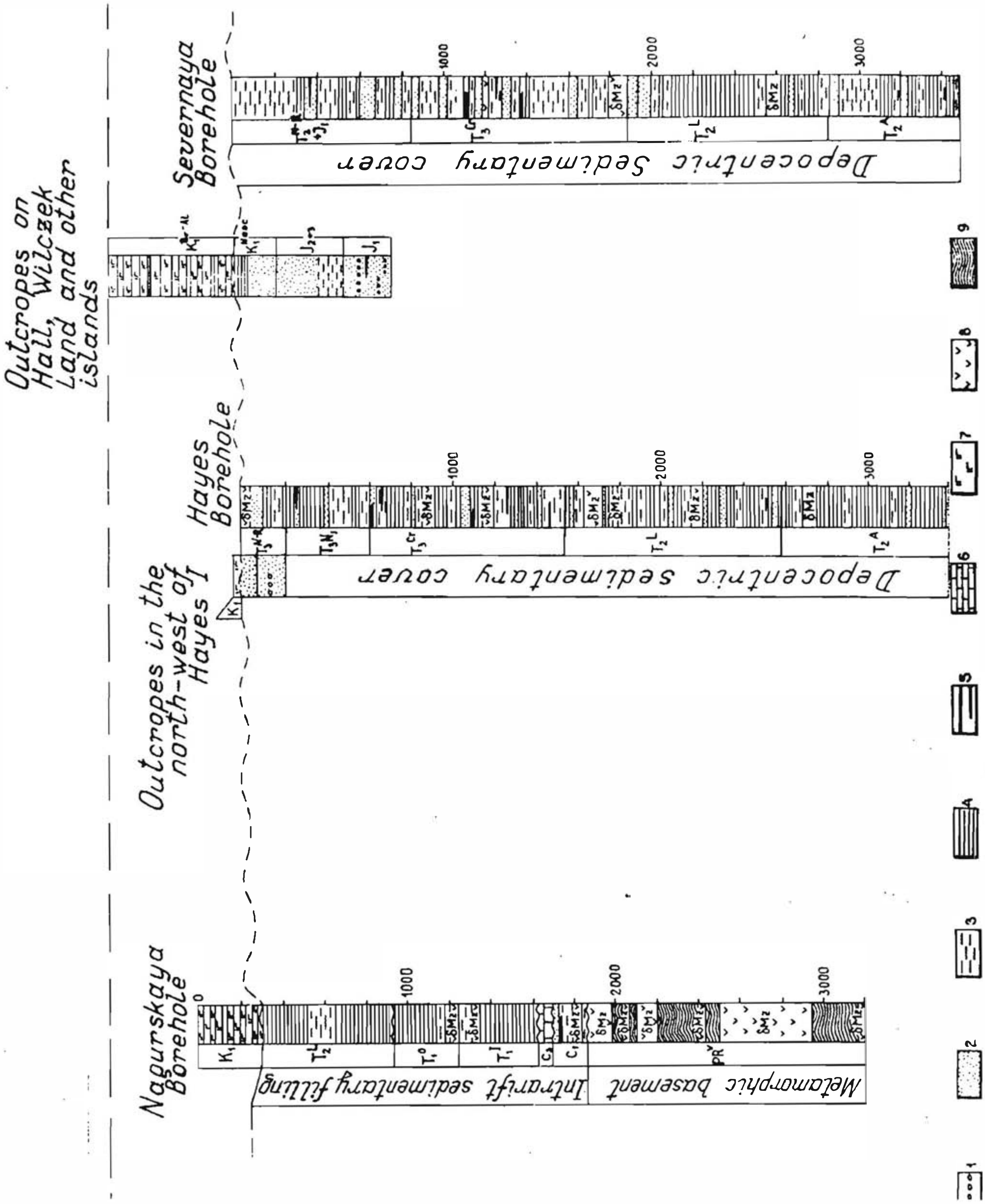


Fig. 7.4 The lower (Triassic and Jurassic) and upper (Lower Cretaceous) structural stages. 1 pebbly gravel and conglomerate, 2 sand and sandstone, 3 silt and siltstone, 4 clay and mudstone, 5 coal seams, 6 limestone, 7 basaltic sheets, 8 dolerite and coarse-grained dolerite, 9 quartz-sericite schists and quartzite.

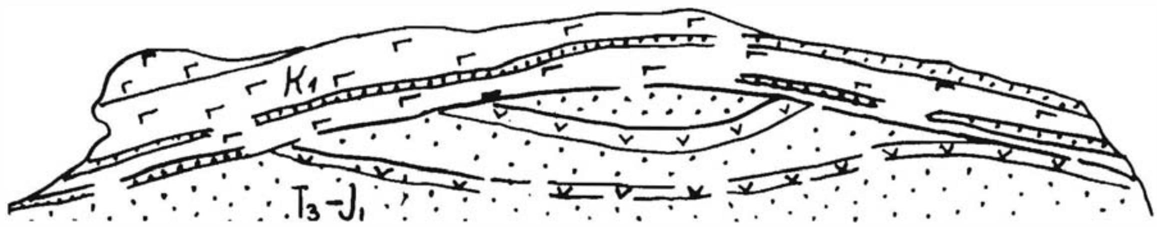


Fig. 7.5 Section across Cape Brice on the northwest end of Ziegler Island showing Upper Triassic deposits of the lower structural stage intruded by sills and then gently folded, subsequently eroded and still later overlain by Lower Cretaceous basaltic sheets and sediments.

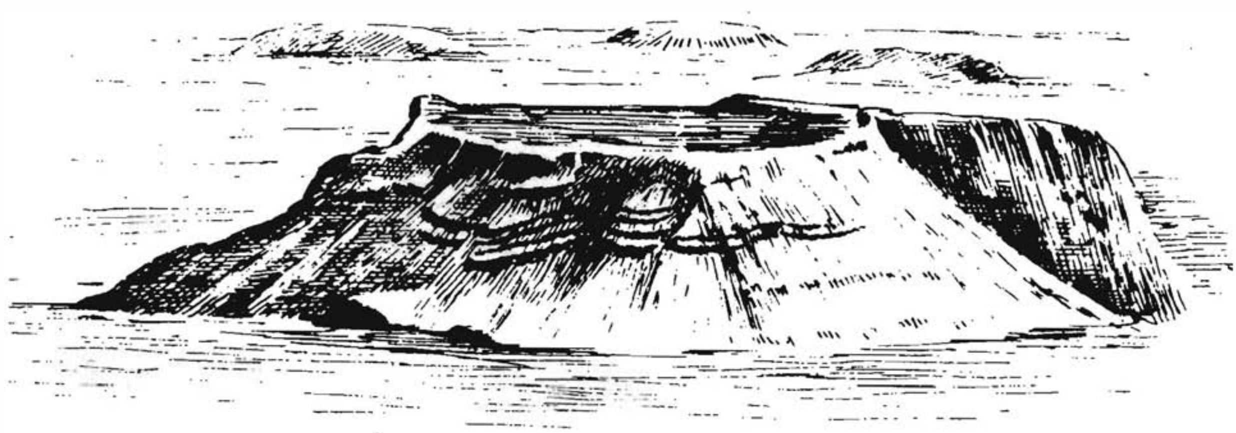


Fig. 7.6 Basaltic sheets flexured and faulted on the northern cape of Pritchett Island. Sketched from an aerial photograph by V.D. Dibner in 1953.

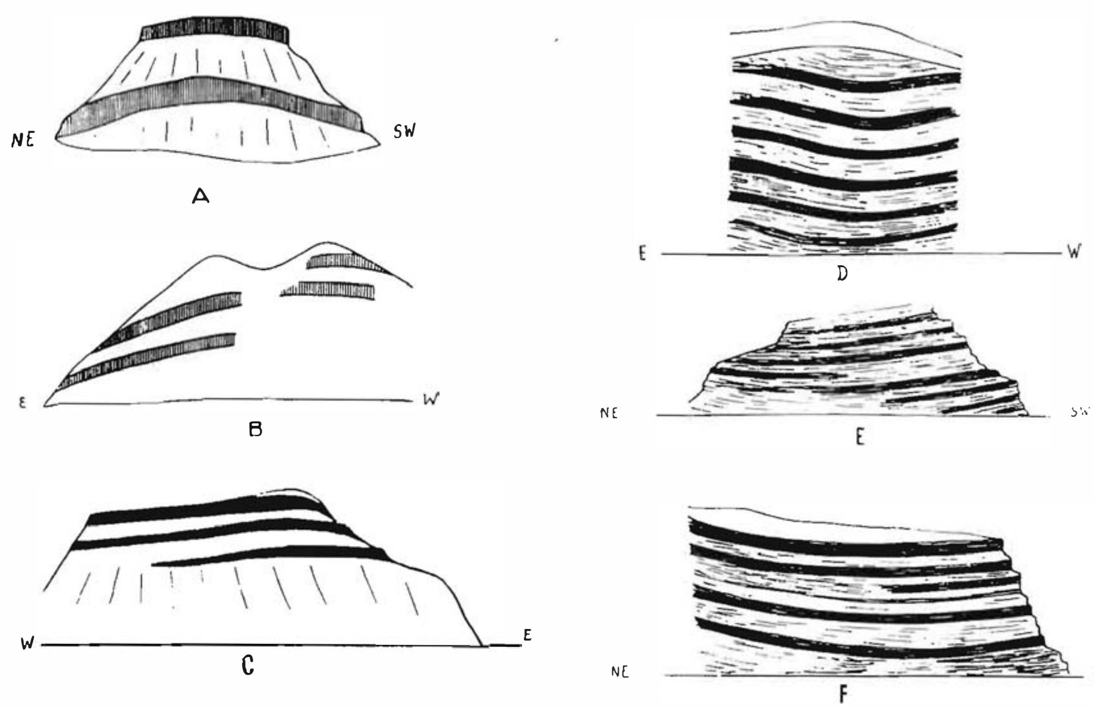


Fig. 7.7 Local anticlines and synclines picked out by flexures in doleritic sills: A northwestern cape of Coal Mine Island, B a cape on the north coast of Salisbury Island, C Cape Petigaks, Luigi Island, D northern cape of Pritchett Island, also showing basaltic sheets of the sedimentary-volcanic sequence, E Cape Greely, McClintock Island, F north end of Alger Island.

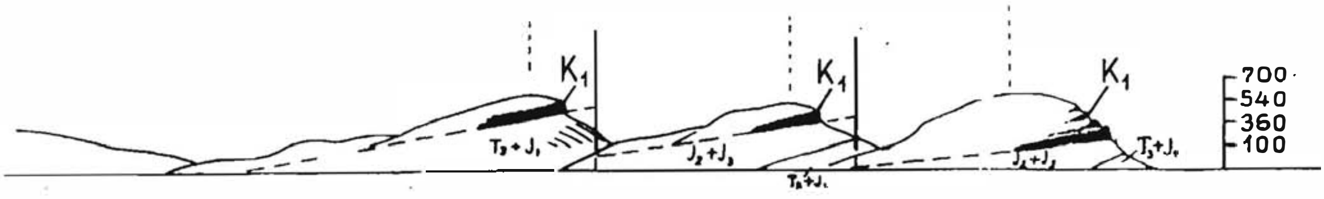


Fig. 7.8 Faulting in the southwest part of Northbrook Island. 1 Cape Gjertrud, 2 Hally Rocks, 3 Cape Flora. Sketch by R. Koettlitz in 1898.

Folding is observable to varying degrees in the strata of the two structural stages. In the lower one, deformations are best known in the Upper Triassic and Jurassic depocentric strata, which are well exposed. Folding and related fracturing is most easily seen in sills. Folds are gentle with wavelengths of 0.2–0.3 to 2–3 km and limbs dipping at angles of 3–5° to 14–16°. The steepest dips are, on average, about 8.0°, and are most commonly seen in Upper Triassic-Liassic deposits. The overlying strata, with few exceptions, are much more gently folded. The basaltic sheets, locally alternating with terrigenous deposits, constituting the upper, sedimentary-volcanic, structural stage are practically horizontal, or follow the erosional surface at the top of the lower strata (Figs. 7.5–7.7).

There are numerous, and locally very large, faults in the Franz Josef Land area. Straight sea cliffs, submarine scarps and the deep channels of straits and sounds are mainly subparallel to faults transecting the sedimentary-volcanic strata. These faults, observable in outcrops and shown by terrestrial and offshore topographical features, form a system composed of structures trending, respectively, E-W, N-S and diagonally. A group of NNW-SSE trending listric faults in the Cape Flora area on Northbrook Island has created topographical blocks, partly representing horsts. These faults were first observed by Nansen (Pompecky 1900) and Koettlitz (1898) who stated that the asymmetrical block forming Cape Gjertrud had been uplifted relative to similar blocks forming Galley Rocks and Cape Flora, the faults having throws of 40 m and 200 m, respectively (Fig. 7.8). A similar example is observed on the west and east slopes of the Stremitelny Glacier valley (Wilczek Land) where a number of faults vertically displace a sill into separate blocks, the faults having throws of 20–80 m (Fig. 7.9). The faults on both sides of the valley are also distinct on aerial photographs, which show that they trend ENE-WSW, parallel to the north coast of Wilczek Land. To the west, along the same coast, major faults trending ENE-WSW and NNW-SSE are clearly seen on Cape Schmarda and Cape Heller. Almost E-W faults with vertical displacements of 35 m transect a sill exposed on the eastern sea cliff of Hayes Island (Fig. 7.10). A large, almost E-W fault is observed in the northwest part of Hooker Island where the Rubini and Antirubini subvolcanic swells, associated with the same dyke, are displaced relative to each other. Aerial photographs and direct observations indicate the presence of strike-slip faults with horizontal displacements of 80 m on the islands of Hayes and Bolshoi Komsomolsky.

Most faults trend NW-SE and basic dykes have been intruded along the majority, as shown by A.N. Tarakhovsky on Hayes Island. NE-SW trending fractures are fewer in number and are typically joints.

Some deep-seated, NE-SW trending fault zones have been recognised through sharp shifts in the position of different types of anomalies revealed in aeromagnetic data. The largest of these fault zones runs across the islands of Champ, Salisbury, Ziegler, Greely, Becker and Hoffmann. NW-SE

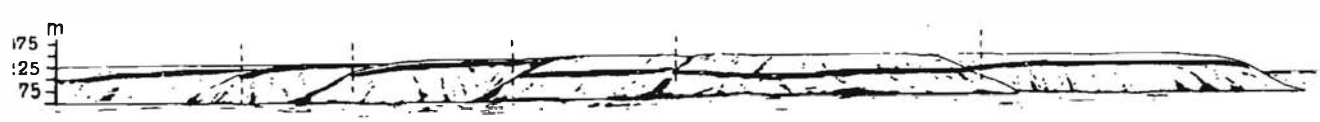


Fig. 7.9 Faulted sill (throws of 20 to 80 m). West slope of Stremitelny Glacier, Wilczek Land. Sketch from photo by V.D. Dibner.

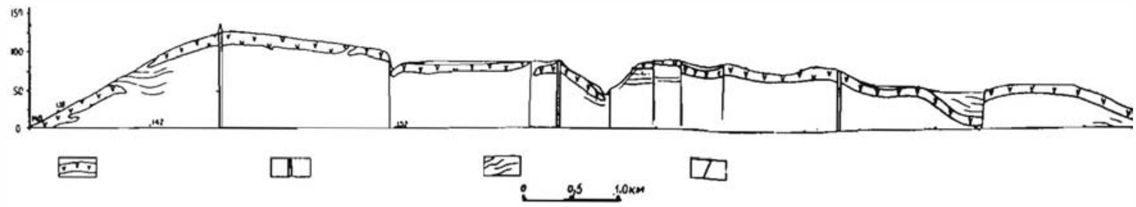


Fig. 7.10 Coarse-grained doleritic sill faulted into separate blocks (after A.N. Tarakhovsky). Southeastern sea cliff of Hayes Island. 1 sill, 2 dykes, 3 sedimentary rocks, 4 faults.

trending feather faults, coinciding with hollows on Salisbury Island and Ziegler Island and on sea cliffs on the northwest coast of Greely Island, tend to be located in this zone. A negative magnetic anomaly was recorded about 15 km southeast of this fault zone, indicating, according to D.V. Levin (unpubl. manus.), an ultrabasic intrusion, which also suggests the existence of the NE-trending deep-seated fault (Fig. 7.1).

With its extraordinary degree of dissection, Franz Josef Land represents a mosaic of subsided and uplifted (with amplitudes up to 1000 m or more), large and small blocks (10 x 3 km on Alexandra Land), that is unique on the Arctic shelf of Eurasia.

7.3 DIAPIRIC FEATURES – V.D. DIBNER

Diapiric features in Franz Josef Land include dyke-like forms consisting of injected, liquefied sedimentary rocks, dyke-like structures forming diapiric cores, diapiric domes and folds with unexposed cores. Specific diapiric features are considered below in this order.

"Neptunian dyke" – a dyke-like feature composed of sedimentary rocks. On the western-central part of the Kholmisty Peninsula on Graham Bell Island, V.K. Razin found a dyke-shaped remnant of claystone-like limestone. Microscopic examination showed that it resembles the lower Norian limestone on Cape Hansa. It is located in a position coinciding with a narrow, NW-SE oriented doleritic dyke which cuts psammites of the Vasiliev Formation (upper Norian-Rhaetian as suggested by palynological data). The impure limestone "dyke" yielded a spore and pollen assemblage consisting of older forms than those in the Vasiliev Formation. The assemblage is dominated by ferns of the family *Matoniaceae*. This assemblage, together with the presence of Permo-Triassic forms of spores and pollen, suggests a pre-Norian-Rhaetian age for the limestone "dyke" (Dibner & Sedova 1959). Recent examination of the same sample has yielded the following ostracods: *Cyterella* (?) *gurimiskensis* Lev, *C.*(?) *orbiculata* Lev, *Ogmonchella* cf. *ordinata* Gerke et Lev and *O. tchajdahensis* Gerke et Lev. According to N.V. Kupriyanova (unpubl. manus.), these species derive from Late Triassic marine deposits. This is in agreement with a Carnian age obtained from spore and pollen analysis by N.A. Pervuninskaya (Dibner 1960, 1970). We are probably dealing with a relatively rare variety of mixed, magmatogene-sedimentogene diapirism where the initial driving force may have been an intrusion of basic magma in the form of a doleritic dyke which squeezed out and lifted up the dyke-like block of sedimentary rock.

Diapiric cores Cape Kohlsaat is a rock picturesquely towering above the low raised beach on the east coast of the Kholmisty Peninsula and rising more than 100 m above sea level. Cape Kohlsaat cannot be regarded as a monadnock since as high as the middle of its slope it is composed of psammites of the Vasiliev Formation, similar to surrounding ones, and still higher it is built up of intercalated sand, sandstone, clay and mudstone that are more prone to denudation. This geological and geomorphological situation suggests that such an inappropriate, upstanding feature may be explained by diapirism.

The slope of Cape Lamont is built up of fossiliferous, lower Volgian siltstones interrupted about 50 m above sea level by slightly calcareous, poorly consolidated sandstones which form low, dyke-like features. The sandstones show horizontal lamination dipping gently east-southeastwards and dissected by cleavage dipping eastwards at 30°. The sandstone dykes, reaching 3 m in height, are exposed over an area of a few tens of m^2. At the western edge, the sandstones are lenticular and are

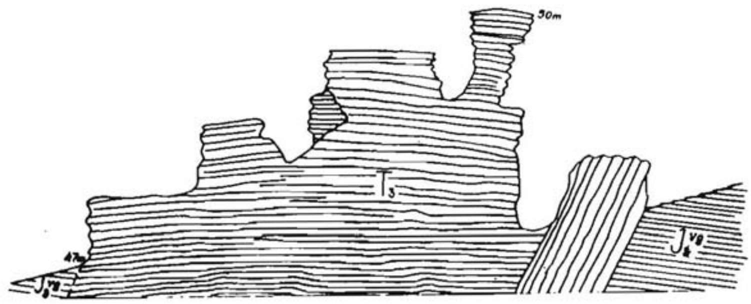


Fig. 7.11 Upper Triassic diapiric stock (sandstone dyke) cutting lower Volgian siltstone. Cape Lamont, Wilczek Land.

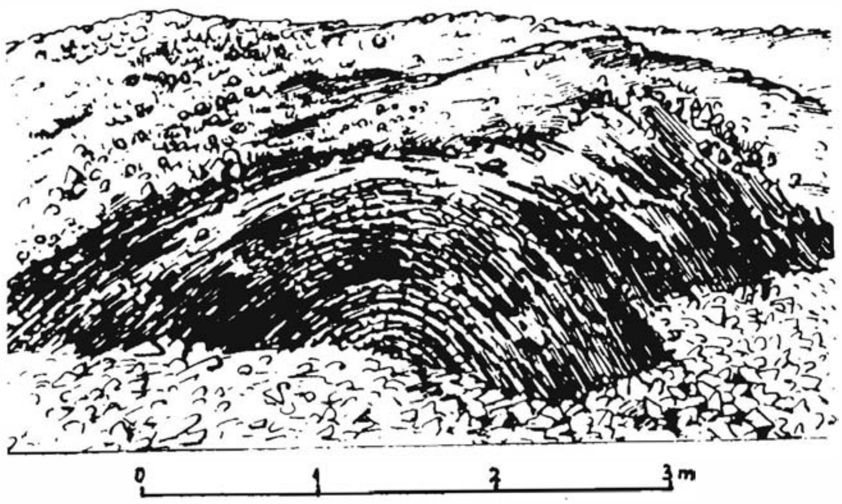


Fig. 7.12 Diapiric fold in Neogene deposits, Cape Sugrobov, Hoffmann Island.

in a subvertical position (Fig. 7.11). Because of the friable nature of these rocks, the features cannot be regarded as denudation remnants, and cleavage, boudinage and the locally subvertical position suggest that they are derived from some depth by diapirism. Results of palynological analysis remove all doubts about this. Sample 1n yielded abundant spores and pollen. The assemblage is dominated by spores of *Dictyophyllum* sp. and pollen of *Piceites* sp.; spores of *Coniopteris* sp., *Osmunda* sp. are also rather common, and spores of *Lycopodium* sp., *Matonia* sp., *Chomotriletes anagrammensis* K.-M. and pollen of *Caytoniales* and *Cycadaceae* are sporadic. According to V.D. Korotkevich, the assemblage probably indicates an Upper Triassic age, in contrast to the lower Volgian age of the country rocks.

Dome-shaped "swell" At Cape Hansa on Wilczek Land, cleaved calcareous siltstone and limestone yielding a lower Norian fauna are exposed within the area of terrigenous deposits (essentially siltstone) of the Wilczek Formation (upper Norian) (see section 3.3). The deposits form a local dome-shaped structure which is curved in plan view. It occupies an area of 1.5–2.0 km^2. The structure may have formed through some stock-like cores uplifting the lower Norian limestones, but not cutting through them (Fig. 3.3.4).

For the description of the skeleton of a plesiosaur broken by possible diapirism at Cape Hofer on Wilczek Land, see section 3.4 (Fig. 3.4.11).

Diapiric folds Neogene deposits on Cape Sugrobov on Hoffmann Island surprisingly display sharp anticlinal folds (Fig. 7.12). These are probably local manifestations of diapirism (Cenomanian beds exposed a few kilometres away are very gently dipping).

8. GEOMORPHOLOGY AND PRESENT-DAY GLACIATION – V.D. DIBNER

The Franz Josef Land islands, straits and adjacent shelf form a sedimentary-volcanic megaplateau bounded in the west and east by the Franz-Victoria and St. Anna troughs, in the south by an unnamed shelf trough trending almost E-W approximately between latitudes 79 and 80°, and in the north by the edge of the Barents Sea shelf.

The Franz Josef megaplateau, and particularly the archipelago proper, is extremely fragmented (Fig. 8.1). The major, nearly N-S straits, British Channel and Austrian Strait, divide it into western, central and eastern groups of islands. The width of these and many other straits varies from hundreds of metres to tens of kilometres. The most compact group of islands, separated by very narrow NW- and NE-trending straits, forms the northern part of the central group from Champ Island (in the south) to Karl Alexander Island (in the north) inclusive. In the remainder of the archipelago, straits and their relatively deep axial channels, differing in size, stretch chiefly along the same trends; N-S and particularly E-W straits are far fewer. Wide straits bound two large island groups in the extreme west (Alexandra Land and George Land) and east (Graham Bell Island, Wilczek Land, La Ronciere Island). The rest of Franz Josef Land is represented by smaller groups composed of many islands and both related and isolated submarine plateaus.

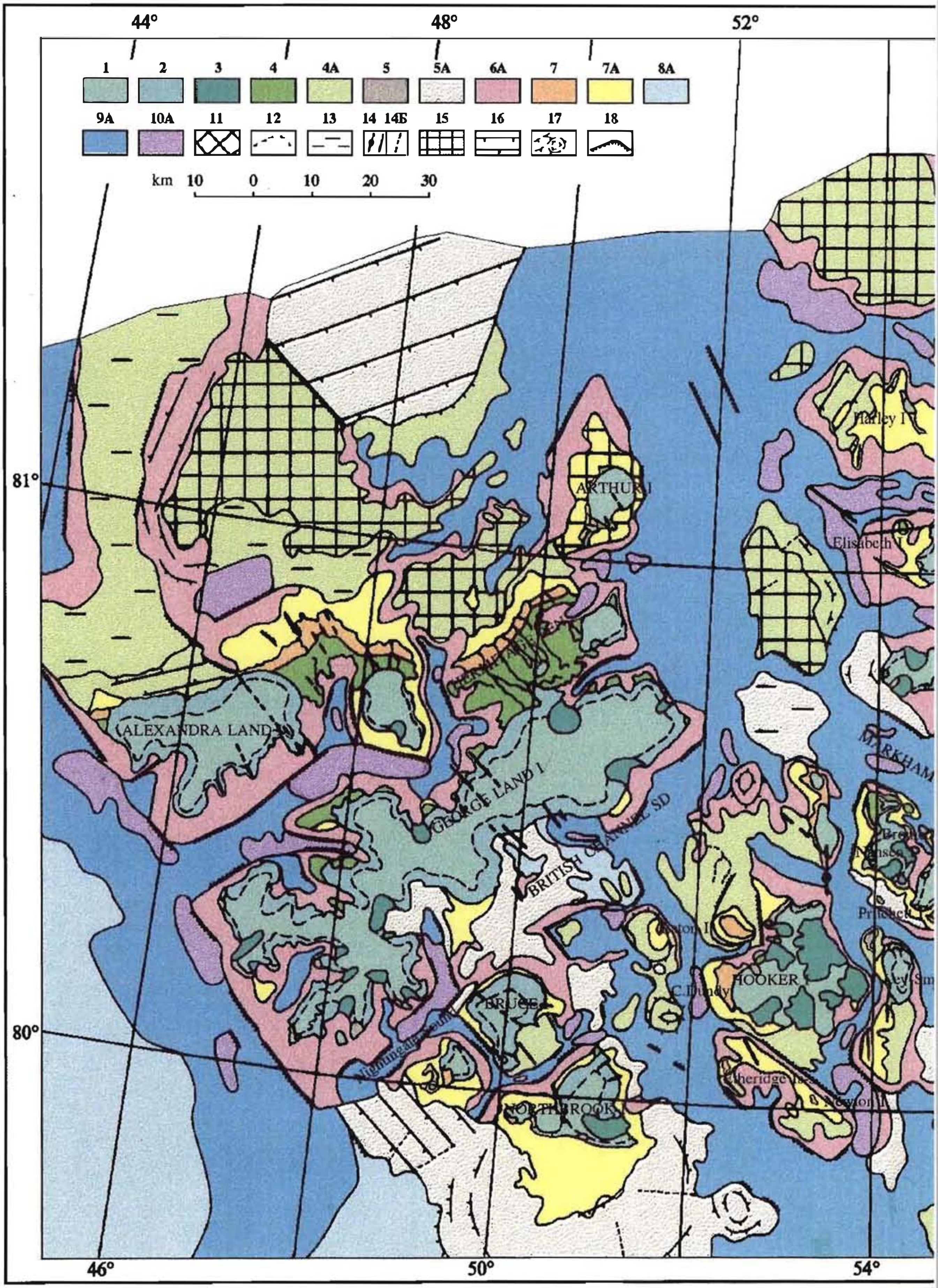
8.1 GEOMORPHOLOGY

The bedrock of the archipelago as a whole and of most of the individual islands is very dissected. Franz Josef Land extends 360 km from east to west and 230 km from north to south and consists of 191 islands. However, airborne radio-location surveying by the Polar Marine Geological Research Expedition (unpubl. manus.) indicated that some large ice caps (up to 500 m thick) completely conceal several islands; hence, the total number of islands may be larger.

The total area of the islands is 16,365 km^2, 2400 km^2, or 14.9%, of which is ice free land. Only the islands of George Land, Wilczek Land, Graham Bell and Alexandra Land exceed 1000 km^2 in area. The area of 22 islands is in excess of 100 km^2, 19 islands range from 100 to 10 km^2, and the remaining 146 islands are under 10 km^2 each (Vinogradov & Psareva 1965). A comparable archipelago consisting of such a large number of primarily small islands or even islets in such a restricted area is known nowhere else in the Euroasiatic Arctic. Moreover, some islands consist of separate areas of bedrock linked by low bars (no more than 20–30 m above sea level) formed only a few thousand years ago by glacio-isostatic uplift.

With a few exceptions, the coastline of the islands, formed by ice (63%), bedrock and Quaternary deposits, is poorly defined. In plan view, its delineation, in spite of being partly concealed by ice sheets which protrude into the sea, is generally angular in character. Direct geological observations and geophysical evidence suggest that this is related to fractures which are also responsible for the orientation of major landforms on the islands themselves. Most distinct is the NW-SE trend along which almost all the northern and some southern islands of the central group are oriented. A NE-SW trend is most obvious in the orientation of Alexandra Land and George Land. A N-S trend is shown by the orientation of Austrian Strait and most of the coastline along the eastern and southern periphery of Franz Josef Land (Wilczek Land, Hall, McClintock and other islands), as

Fig. 8.1 (pages 158-159) Geomorphological map of Franz Josef Land, compiled by V.D. Dibner and drawn by M.A. Agafonova and T.Yu. Babich. I. Ice topography: 1 caps on plateau summits, 2 sheets on faulted bedrock topography and plateau slopes, 3 outlet glaciers and "areas of subsidence" (marginally heavily fissured zones of ice sheets). II Topography formed by erosion of bedrock: 4, 4A on armouring layers of plateau basalts, 5, 5A in sedimentary rocks, 6, 6A talus, and snow and ice slopes, 7, 7A wave-cut platforms and wave-cut/built platforms (4, 5, 6, 7 are on land, 4A, 5A, 6A, 7A are on the sea floor). III Wave-cut/built topography on the interinsular and peripheral shelf: 8A shelf floor and confluent surfaces, 9A floors of shelf troughs, 10 separate lows within troughs. IV. Miscellaneous: 11 hummock-and-hollow topography, 12 thalwegs of flooded river valleys, 13 bottomset beds levelling off subaerial bottom relief, 14A rocky ridges of dykes and other remnants of solid rocks on land and sea floor, 14B dyke ridges under glaciers, 15 subhorizontalsurfaces, 16 sloping surfaces, 17 arched and trough-shaped features, 18 fault-controlled scarp slopes.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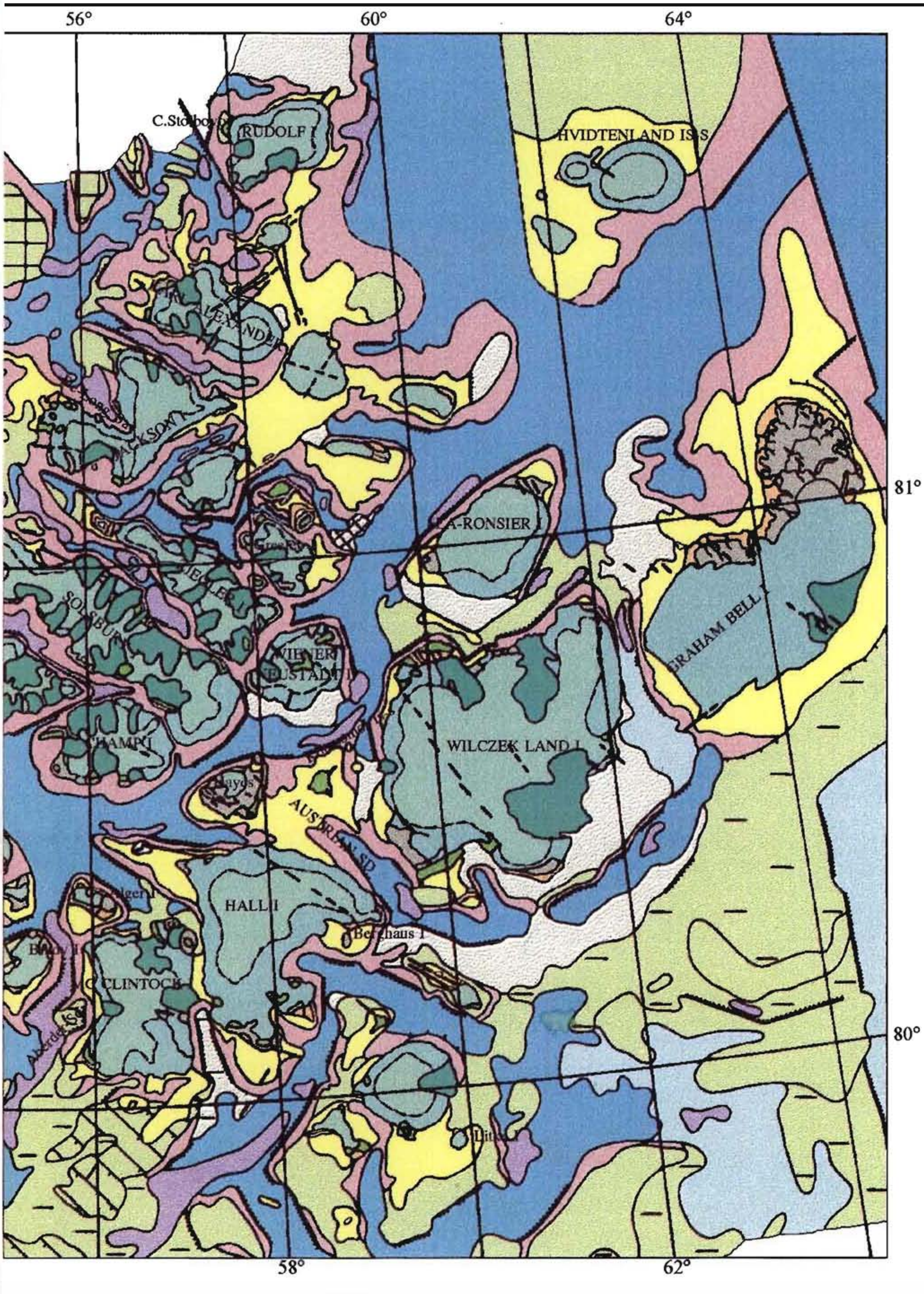
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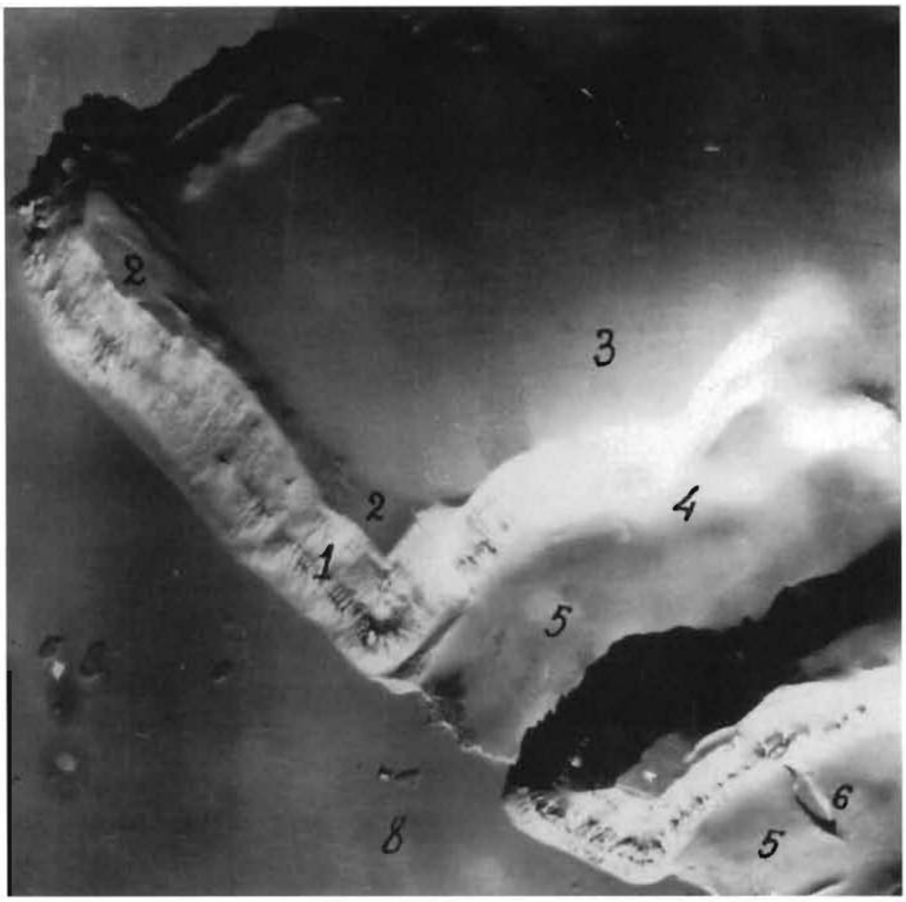

Fig. 8.2 Characteristic portion of coastal topography and glaciers in the southwest part of George Land. 1 shore cliffs and capes built of basaltic sheets, 2 ice-free parts of plateaus, 3 ice sheets, 4 cirques, partly buried by firn and ice, 5 outlet glaciers, 6 bergschrund (up to 100 m wide) separating the glacier reservoir from the outlet glacier proper, 7 snow-filled shore cliffs formed by talus, 8 sea ice with small icebergs frozen into it.

well as that of the submarine Franz-Victoria and St. Anna troughs which delimit the archipelago in the west and east.

The main feature of the physical geography of the Franz Josef Land islands is the present-day glaciation. The topography of the islands is therefore chiefly formed by glaciers and to a much lesser extent by ground protruding from the ice as capes, nunataks and cliffs. Where the glaciers reach the sea, the coastline does not protrude into the straits (unlike some large capes), but is in line with adjacent portions of the ice barrier (Fig. 8.2).

Tray- or pan-shaped plateaus are a notable feature of the topography of some large islands (e.g. Alger Island). However, some islands or their separate capes form gently-sloping domes (Graham Bell and La Ronciere). This, and not least direct geological observations, indicate that the topography of the islands follows the gentle folding of the strata and also reflects the fracturing. Thus, some islands resemble fragments of faulted brachy-synclines, brachy-anticlines and domes.

The largest ice-free sites are remarkable for their location along the western and eastern peripheries of Franz Josef Land, whereas many relatively small islands and intervening deep straits occupy its central parts. In this connection, the average elevations of Franz Josef Land are lower in its centre than around its periphery and, since glaciation is also most developed in the centre, the megaplateau appears to be a gigantic inverted pan with the cracked central part being ice filled.

The area where most land is free of glacier ice (Alexandra Land and the Armitage Peninsula on George Land) consists of relatively low, gently northwestward-sloping basaltic platforms divided by the Arkhangelsky Strait graben into two unequal parts. The southern part, Central Land, is as high as 50–60 m and gradually reaches sea level northwards. The larger, eastern, part of the platform, the Armitage Peninsula, has a similar relief. In eastern Franz Josef Land, the Kholmisty (Hilly) Peninsula has a dome-shaped hummocky surface, reaching an altitude of about 100 m. It is made up of Upper Triassic sand and sandstone and is dissected by a radial system of little incised streamlets.

Most of the Franz Josef Land islands, particularly those of the central group, are plateaus, ranging in height from 100 to 500–600 m. They were formed on flat-lying sedimentary and volcanic

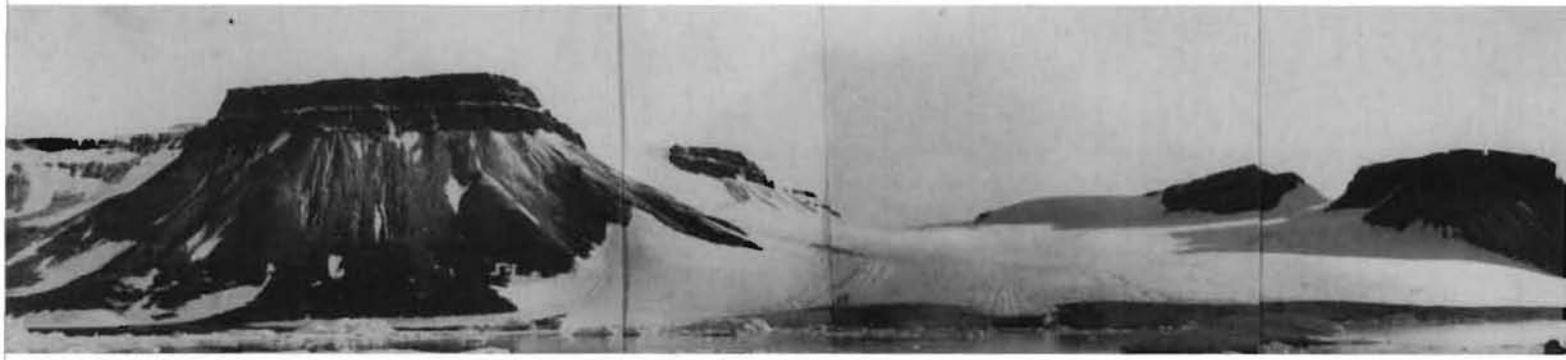

Fig. 8.3 Cape Tirol, Wiener-Neustadt Island, a typical form of the two-stage structure. Photo: V.K. Razin.

rocks of mostly Mesozoic age. The lower and upper structural stages described in Chapter 7 are strongly reflected in the relief of Franz Josef Land.

Basaltic sheets and, less commonly, sills armour separate, residual plateaus, capes and islets. The plateaus are generally dissected by many cirques and short, but deeply entrenched troughs, now partially buried beneath ice caps and locally flooded and turned into small bays, such as the southern bays of George Land, De Long Bay on Jackson Island, and many other inlets. The lower stage is seen as scarps dipping at angles up to 40°. They are formed of poorly cemented sediments, commonly hidden by basaltic and doleritic talus derived from the upper stage (Fig. 8.3). Capes, nunataks and cape-nunataks (Fig. 8.4), whose armours are fragmented, are dome- or cone-shaped.

As stated in Chapter 5, many nunataks and capes are formed by doleritic dykes, some of them bifurcating or with swells (Figs. 5.13 & 5.15). It is not unusual to observe dykes penetrating relatively thin ice caps, such as the Skvoznaya (Through) dyke beneath the Hydrographers Glacier (Fig. 5.10). Sills also project from the ice, predetermining sharp bends in the glacier where crevasses are common.

The maximum elevations (500–620 m) are found on nunataks on islands in the central parts of the central and eastern groups of islands, the highest ones being on Wiener-Neustadt, Wilczek Land, Hooker, McClintock, Graham Bell, Champ and Hall. On Wilczek Land, they are formed by dykes (Wullerstorff Mountains) and on the remaining islands by basaltic sheets (Fig. 8.5). Other islands have maximum elevations below 500 m, half of them being below 400 m.

Capes and shore cliffs are rimmed by narrow terraces of boulders, blocks and stones usually up to 25–35 m high which, as stated above, in some cases form isthmuses linking former islands to the main part of an island (e.g. the Rubini Rock on Hooker Island and Cape Stog (Stack) on Bromwich Island). Some of these raised beaches form small, low headlands on islands which are otherwise entirely covered by ice (e.g. Hvidtenland, Arthur and Litke), or whole islets which have quite recently risen from beneath the sea (e.g. Eaton, Dead Seal and Harley).

Fig. 8.4 Alpine capes and nunataks, Wiener-Neustadt Island. Photo: V.K. Razin.

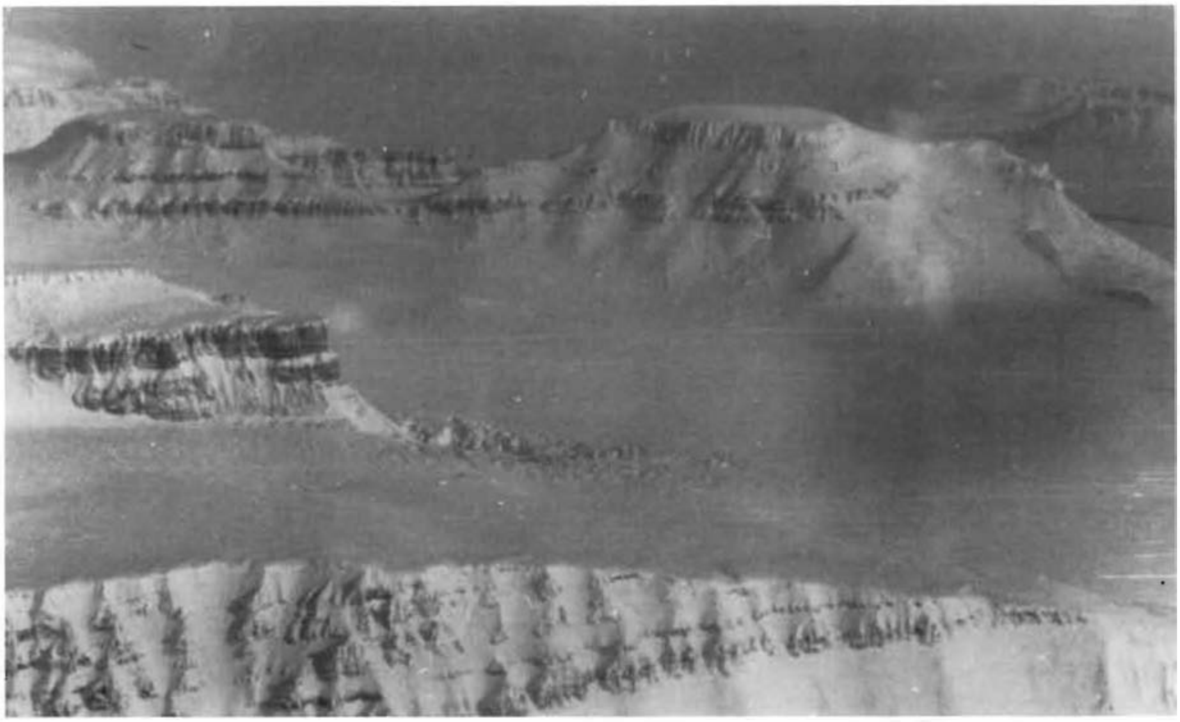

Fig. 8.5 Nunataks (composed of sedimentary-volcanic rocks) typical of the central group of islands. Photo: D.V. Levin.

On the islands of Franz Josef Land, the drainage system and, hence, the water-eroded surface, is in the earliest stage of development, and linear runoff has just been initiated. This is partly because areas of flat ground are small and have only recently risen from beneath sea level or been freed from ice, and partly to the very short and cold "summers" characterised by low precipitation and maximum meltwater occurring when the soil is still completely frozen, thus preventing erosion. More or less permanent watercourses are known to occur only on Central Land on the island of Alexandra Land, the Armitage Peninsula, Hayes Island and the Kholmisty Peninsula. The largest streams on Alexandra Land and the Armitage Peninsula spring from tiny lakes in hummocky terrain eroded by Pleistocene glaciers. Other streams on Alexandra Land and the Armitage Peninsula are typical outwash streams whose drainage systems are formed anew on ice caps every year. They are only slightly incised, permanently shifting and bifurcating watercourses on the surface. Such glacial outwash streams occur on Cape Dundy on Hooker Island, and also on Nansen and other islands.

The erosional dissection of the Kholmisty Peninsula is of a special nature. Outwash streams draining glacial meltwater to the western and eastern coasts of the peninsula are only found in the immediate vicinity of the glacier. None of them reach the centre of the peninsula as most of it has acquired radial dissection because of recent dome-like uplift. Hayes Island has a similar drainage system. In the northwest, the system radially dissects a growing domal structure. Complex ravine dissection has created badland topography there.

Lakes occurring on some islands may be classified under two groups, depending on their origin. 1. Basins formed by glacial erosion during the late Pleistocene glaciation (the Dezhnev Bay area on Alexandra Land). These are the most stable lakes. 2. Lagoonal lakes separated from the sea by shore bars and preserved owing to extremely severe frost conditions on raised beaches as high as 20 m and even 25–30 m (Govorukha & Simonov 1965).

8.2 MORPHOLOGY AND DYNAMICS OF PRESENT-DAY GLACIATION

The present-day glaciation was described in some detail by Groswal'd (1963), Vinogradov & Psareva (1965) and Groswal'd et al. (1973) which give the results of fundamental glaciological research done by an expedition organised by the Institute of Geography, USSR Academy of Sciences, in 1957–1959.

Fig. 8.6 Ice crest on the Richthofen nunatak, Alger Island. Photo: A.N. Radygin.

The total glaciated area in Franz Josef Land is about 13,730 km^2 (85.1% of the total area of the islands), and the volume of glacier ice is about 2250 km^3. The main forms of glaciers are ice caps and ice sheets, outlet glaciers and small glaciers. Ice-covered coasts are mainly represented by glacier barriers, which make up 63% of the shoreline. The glaciation of Franz Josef Land is more strongly developed in eastern and southeastern parts due to an extremely severe temperature regime (the average temperature in July-August is close to zero), combined with the penetration of the North Atlantic depressions into this part of the archipelago.

Observations from the air and analysis of aerial photographs have enabled us to study the influence of bedrock relief and, hence, geological structure on the morphology and dynamics of the glaciation.

Most islands in Franz Josef Land are partially covered by glaciers which, when incompletely developed, approximate the "cover net" glaciation of Groswal'd et al. (1973) and in their maximum form of development are close to "mountain ice sheets" (Flint 1957) in type. Other islands mainly have two stages of glaciation, each associated with different stages in the development of the structurally related relief. The two-stage development is most characteristic of the central group of islands, whereas islands in the extreme east and west only have glaciers related to the upper structural stage. In other words, the distribution pattern of contemporary glaciers is predetermined by major features in the bedrock structure.

The simplest form of the upper stage glaciers is an ice cap developed in the central, unbroken part of a plateau, away from which it usually gives way to an ice sheet whose morphology reflects bedrock relief. Another form is isolated ice caps, which may, in turn, be classified into two types.

The first type comprises ice caps that almost completely cover islets and are situated on low plateaus, or flat hills, no more than 50–75 m above sea level and standing 20–100 m high (e.g. on one of the Oktyabryata Islands and on the Adelaida Islands). At first sight, the existence of ice caps on such low islands seems unexplainable since it is not unusual to find that they neighbour similar or much higher, completely ice-free terrain (e.g. Elizabeth Island adjacent to the Harley Island ice cap, and Shenau Island adjacent to the Litke Island ice cap). Dibner (1965a) suggested that this could be explained using the concept of the "inertia of glaciation" developed by Tronov (1956). According to this, two levels should be distinguished for the base of the "hionosphere" (the layer

Fig. 8.7 Transitional glacier between ice crests and niche glaciers on the top and north slope of Cape Fiume, Champ Island.

of the atmosphere where frost is permanently present), namely, the "geohionobase" and the "cryohionobase" for rock surfaces and glacial surfaces, respectively. As applied to Franz Josef Land, this means that ice caps covering very low islands are relics of an extensive ice sheet developed under climatic conditions that were more favourable to glaciation than those of today, but which have survived owing to a more severe microclimate and, correspondingly, a low cryohionobase and cryohionosphere, as a whole. A subsequent warmer period was responsible for the fragmentation of ice sheets, mostly those whose base lay below sea level, as a result of more intense abrasion and the activity of currents. During recent decades, only low island ice caps have started waning, since they "tore away" from their cryohionobase level whose inertia up to then had been promoted by the underlying ice surface. However, the inertia of glaciation makes itself felt to the present day. Therefore, over the vast majority of islands, low ice-free land is represented only by raised beaches formed during the Holocene by glacio-isostatic and, possibly, tectonic uplift. This has led to the most extensive areas of low-lying, ice-free land only being formed on the western and eastern peripheries of Franz Josef Land, which are washed by shallow water. On the Antarctic coast, such ice-free areas are named "oases". The "Terra nova" may have been formed there in a similar way.

Tiny ice caps and their embryos, "ice ridges", represent a quite different variety of isolated, small glaciers. The ice ridges are shaped like dunes, suggesting their formation from perennial snow accumulations. They are

Fig. 8.8 Stremitelny Glacier, one of the largest outlet glaciers; north coast of Wilczek Land. Aerial photograph.

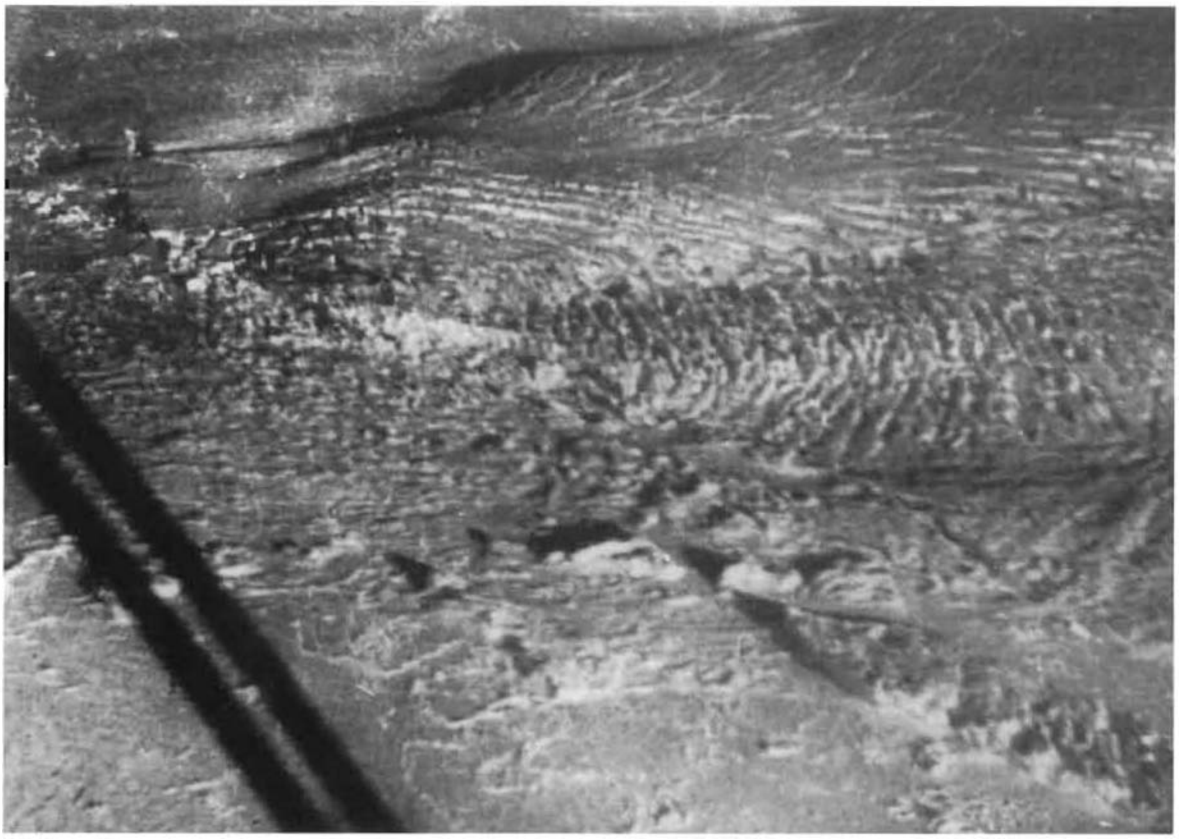

Fig. 8.9 Typical area of ice subsidence with numerous criss-crossing crevasses. Oblique aerial photograph of a glacier margin on George Land.

up to 200–300 m across and are situated in relatively high positions (about 300–350 m in absolute height). The first ice ridges were found at Mount Richthofen on Alger Island (Fig. 8.6), Cape Kopland on McClintock Island, one of the capes on Champ Island, and at some other localities when L.I. Perkis was doing aerial surveying in 1953. According to other observations in 1953, made by the geographer A.N. Radygin (unpubl. manus.), ice ridges also occur on the margins of high plateaus where they form from snow cornices. These small glaciers are probably unstable. For instance, a small plane glacier with three radial, ridge-like lobes observed by V.D. Dibner in 1953 on the plateau of Bell Island had waned greatly by the summer of 1956 (B.I. Kuznetsov, pers. comm.). This suggests that more or less long-term snow névé can also form on rock surfaces at heights of only 300–350 m and upwards under the present-day climatic conditions on Franz Josef Land with snow-drifting, gale-force winds. In other words, 300–350 m marks the upper level of the hionosphere base where the hionosphere can be in contact with not only the ice surface, but also the bedrock. It is interesting that a snowline observed on large ice caps on the islands in 1954 by A.N. Radygin and in 1960 by Govorukha & Simonov (1961) lay approximately at the same height (300–330 m). Accumulation and ablation now occur above 300–350 m and below 300 m above sea level, respectively.

Embryonic ice caps fixing the upper level of the lower hionosphere (geohionobase), and relict ice caps fixing its lowermost level (cryohionobase), can also be distinguished on other Arctic islands. This helps to give a more complete understanding of the conditions supporting the existence of present-day glaciation in the Euroasiatic Arctic and of the limits of its wider distribution in the recent geological past, and allows us to gain some insight into the common laws of the evolution of high-Arctic glaciation in its progressive and regressive stages (Dibner 1961g, 1965a).

Small glaciers, formed through the transformation of perennial snows, have developed in hollows on the plateaus of some islands (e.g. Cape Säulen on Rudolf Island, Windworth and other islands) and are therefore named niche glaciers here (Fig. 8.7).

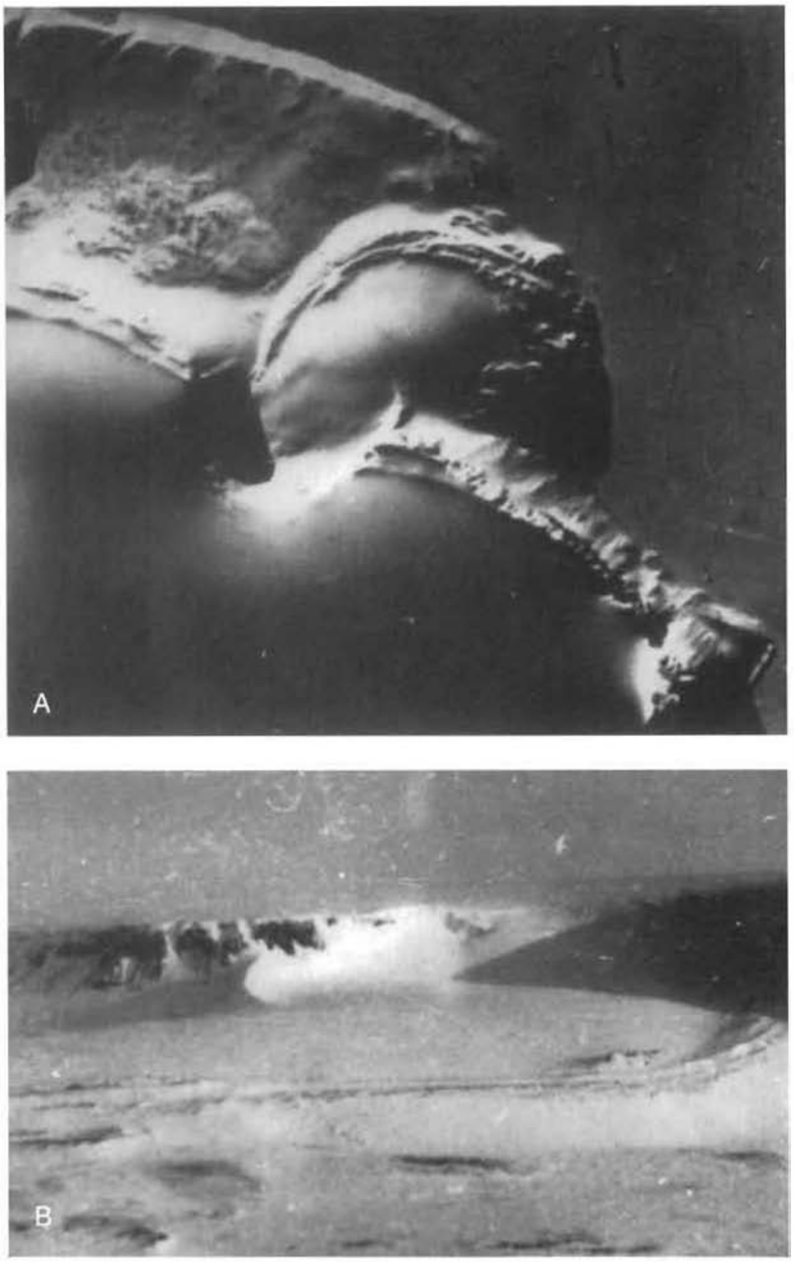

Fig. 8.10 Parasitic ice stream flowing down a narrow gap onto the low coast of Cape Willas, Wilczek Land, where its lobe expands and is rimmed by ridges of terminal moraine. Vertical (A) and oblique (B) aerial photographs.

Lower stage glaciers are developed away from generally elevated plateaus. They include, first and foremost, ice sheets whose surface follows irregularities in the bedrock surface. In addition, outlet glaciers (about 500 in Franz Josef Land) are in part similar to valley glaciers of mountain regions. They originate in cirques and then occupy related troughs which deeply dissect plateau slopes (Fig. 8.8). They very actively calve into the straits, sounds and offshore areas of Franz Josef land (see Figs. 8.17, 8.18 & 8.19 at the end of the chapter). A number of transitional varieties are recognised here. They form along the margins of partially collapsed ice sheets and are notable for their numerous crevasses, reflecting many irregularities in the underlying surface, and are here called "areas of subsidence" (Fig. 8.9). They are are larger and broader equivalents of linear outlet glaciers, also called "bleeding basins" (Groswal'd & Krenke 1962, Groswal'd et al. 1973).

Like valley glaciers, most outlet glaciers are convex in transverse section. This is explained by high friction and, hence, lower rates of ice motion at the boundaries with trough valley slopes, as well as by intense ablation in the same areas where they are overloaded with till. Along the edges of ice streams, between a marginal moraine and the ice, meltwater scours deep marginal channels containing some narrow lakes and bays. When a marine transgression takes place, and following the retreat of a glacier into the mouth of a valley, the sea penetrates most deeply inland along the

Fig. 8.11 Reticular glaciation of orthogonally dissected bedrock topography; central part of Champ Island. Photo: V.D. Dibner, 1953

former marginal channels, thus causing the coastline to become lobate, typical of fjärd coasts in southern Scandinavia. Good examples of this are seen in the southern part of George Land.

Another type distinguished here is named parasitic ice streams. These "illegally" force their way to the coast across relatively unfavourable terrain. Unlike normal outlet glaciers, which flow along large depressions in the bedrock topography, parasitic ice streams use isolated gullies at the plateau edges, permitting the removal of "excess" ice which cannot be removed by trunk ice streams. Because they are too thin, it is not unusual to find that parasitic ice streams do not descend to the sea, but form anomalously wide lobes framed by the arcs of terminal moraines on low coasts (Fig. 8.10).

On islands with highly irregular topography, present-day glaciation forms reticular glacial complexes, which are characterised by having isolated ice-free areas on the wind-blown upper parts of glacial troughs and close to the edges of plateaus. The plateau summits generally have more or less large ice caps feeding outlet glaciers. Reticular glacial complexes can be divided into two subtypes. The first is characteristic of islands with radially broken terrain, which produces ice-free capes and nunataks around their periphery. Glacier reservoirs are situated in the centre of such islands, where they form small ice caps, either on elevated plains or in central saucer-like hollows. This subtype is most pronounced on the islands of Hooker, Nansen and Alger. Another, more widely developed subtype of reticular glacial complex is observed on some northern islands in the central group (e.g. Salisbury and Ziegler) where the terrain is deeply dissected in an orthogonal pattern caused by diagonal fault systems (Figs. 8.11 & 8.12).

Cirque glaciers (including hanging ones) are also classed with the older, lower stage glaciers. They are situated on steep, ice-free slopes, generally below the geohionobase, and are relatively small (up to 0.5–1.0 km^2). As a rule, they occur on the sides of large nunataks, residual plateaus and capes. They are especially numerous on islands in the central group. Some cirque glaciers (e.g.

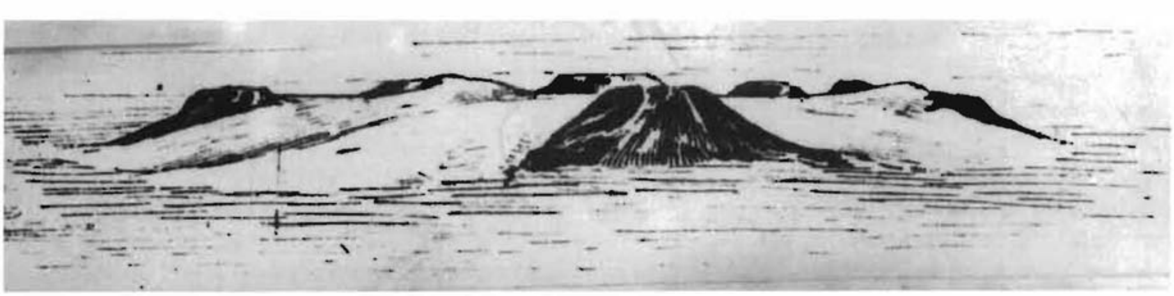

Fig. 8.12 Reticular glaciation in radially dissected topography, with outlet glaciers radiating from a common glacier reservoir in the centre of Alger Island.

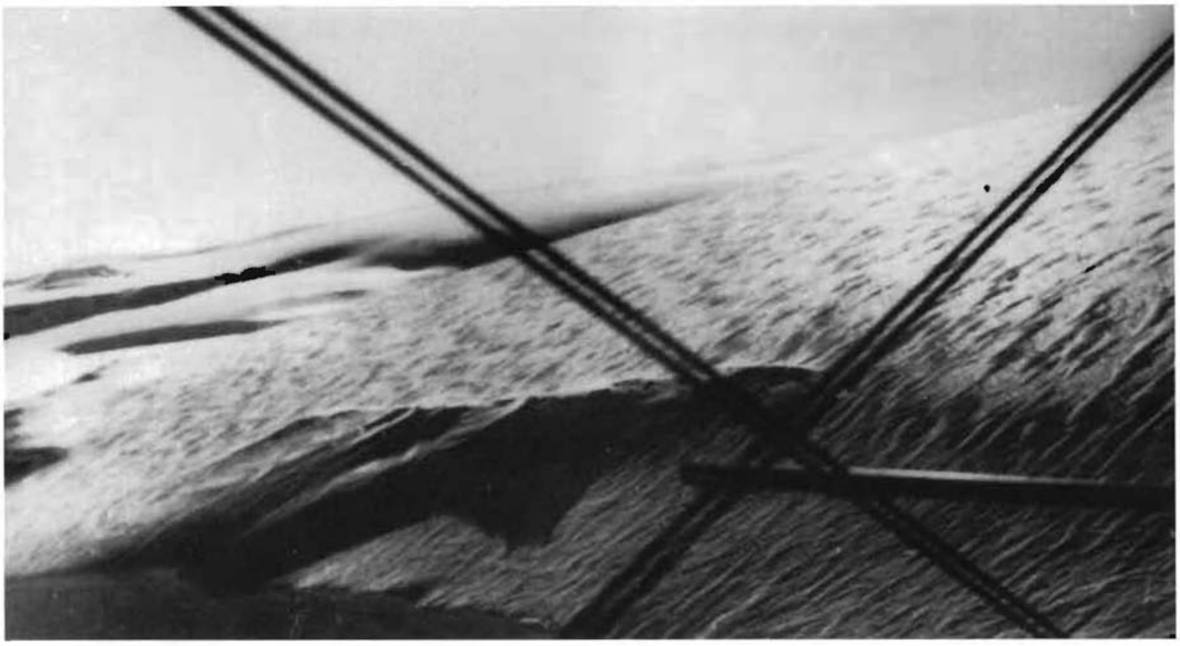

Fig. 8.13 Relict wall-sided glacier separated from the ice cap by the plateau edge, George Land. Photo: L.N. Fokin.

that in the Teply (Warm) cirque) end on land where, like parasitic glaciers, they are rimmed by horseshoe-shaped terminal moraines. A hanging variety of cirque glaciers is exemplified by a small glacier in the steep-sided Molchaniya valley on Hooker Island. A.N. Radygin observed small hanging glaciers on Brice Island and at Cape Bergen on McClintock Island. A cirque-valley glacier, probably the only one of its type in Franz Josef Land, was observed by V.D. Dibner in 1957 at Cape Tirol.

Wall-sided, or cliff-foot glaciers, located on steep, coastal slopes, where they locally stretch for 10–15 km, represent a distinct and common variety of the lower stage glaciers in Franz Josef Land, occurring on Cape Nansen and Cape Johansen on George Land, Cape Dundy on Hooker Island and elsewhere. The fronts of these glaciers generally lie on offshore shallows and both their termini often connect with outlet glaciers, thus turning the capes where they occur into near-coastal nunataks. In places, some wall-sided glaciers of adjacent near-coastal nunataks coalesce with internunatak ice streams to form piedmont glaciers. These usually occur on shores facing relatively wide sounds without strong currents, where the ice cap can advance far into the sea, partly as grounded ice and partly as a tongue floating down a gentle (1.5–2.5°) gradient (e.g. the east coast of Wilczek Land, the southeast end of Salisbury Island, the south coast of Wiener-Neustadt Island and the east coast of Greely Island). Franz Josef Land displays all kinds of transitions, from separate wall-sided glaciers to glaciers only isolated from the caps by plateau edges (Fig. 8.13). Wall-sided glaciers arranged in two or three steps are formed on slopes with well-defined steps. Groswal'd & Krenke (1962) put forward some weighty arguments for the relict nature of wall-sided glaciers. In particular, they emphasised their occurrence on slopes of different aspect and in places sometimes far removed from locations that are always favourable for snow drifting.

Two varieties of wall-sided glaciers, drift and relict glaciers, are inferred. Drift glaciers form in places protected from the wind and when they spread out they can coalesce with upper stage glaciers. Relict wall-sided glaciers originate as slope glaciers formed when extensive ice sheets become fragmented due to thawing at the plateau edge and separation from the ice sheet front.

It should be emphasised that in the high-Arctic maritime climate of Franz Josef Land the accumulation of snow and, later on, firn and ice is even promoted by constructions which offer effective protection from the wind, allowing snow drifts and embryonic glaciers to start forming as early as the first winter season. The house built of planks by the second Leigh Smith Expedition members, and still intact at the northern end of Bell Island, is the only exception to this rule.

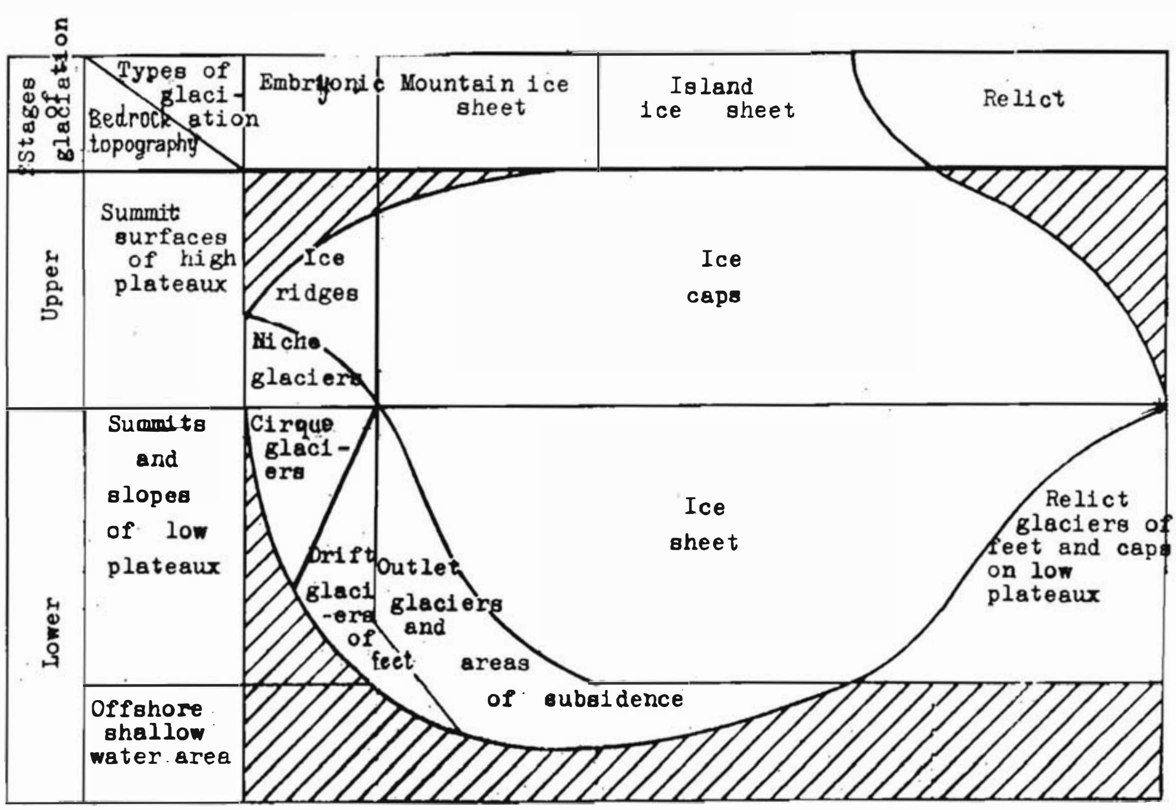

Fig. 8.14 Types of glaciers and glaciation on the islands of Franz Josef Land.

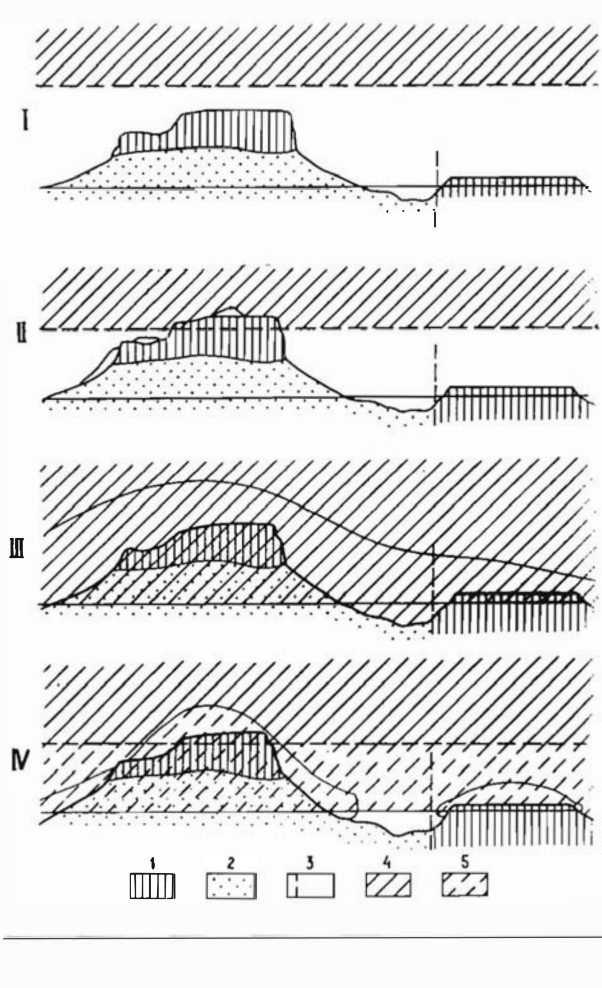

Fig. 8.15 Stages of glaciation evolution on the islands of Franz Josef Land during a single climatic cycle. Hypothetical schematic diagram. Key and explanation: I geohionobase above the plateau – no glaciation; II geohionobase comes into contact with plateau summits – emergence of ice ridges, drift and cirque (orographic) glaciers on leeward slopes; III geohionobase lowers to sea level – formation of a solid ice field; IV geohionobase rises to the plateau edges, but the cryohionobase remains at sea level. In this instance, erosion of the ice field in the straits causes the formation of contemporary insular ice and relict ice caps. 1 basalt, 2 sedimentary rocks, 3 faults, 4 hionosphere above geohionobase, 5 hionosphere between geohionobase and cryohionobase.

Fig. 8.16 Glacial complexes of Franz Josef Land after M.G. Groswal'd (Groswal'd et al. 1973). Key: 1 ice-free ground, 2 upper stage glaciers (ice caps and sheets), 3 areas of subsidence and outlet glaciers, 4 glacier boundaries on land

The morphology of glaciers in Franz Josef Land and their relations with the hionosphere and bedrock relief are shown schematically in Figure 8.14. This depicts (from left to right) types of glaciation, distinguished by genesis and evolutionary stage, and together forming a complete cycle presumably undergone by any island in Franz Josef Land during a profound macroclimatic change under relatively stable orographic conditions similar to those of the present. These types of glaciation now co-exist on various islands in Franz Josef Land, being related to different positions of the hionosphere over time. The main topographic steps and appropriate glaciation stages are arranged vertically. The diagram shows elementary glacial forms (ice caps, ice sheets, cirque glaciers, etc.), thus displaying glacier types, their interrelations and their association with some type of glaciation. For instance, at the embryonic stage, cirque and probably wall-sided glaciers emerge first on plateau slopes and niche glaciers on the upper surface of the plateau. At the same stage, when the hionosphere is further lowered, ice ridges, later growing into ice caps, develop on the plateau. Progressive spreading of the ice caps is conducive to the development of the partial cover variety of glaciation, with a simultaneous independent existence of lower stage glaciers still being characteristic. Snow redeposition from the ice caps starts gaining in importance through the alimentation of the ice caps and thus wall-sided glaciers grow substantially. An ice field is then formed by the confluence of upper and lower stage glaciers. Steps in the formation of the main types of glaciation in Franz Josef Land during a climatic cycle are shown in Figure 8.15.

A reduction in an ice sheet caused by an overall rise of the hionosphere induces no essential changes in its morphology because of its great inertia. Hence, where both stages of bedrock relief are present, the glaciation of Franz Josef Land can remain as ice caps or mountain ice sheets (partial cover glaciation) until it disappears completely (Fig. 8.16).

8.3 BOTTOM TOPOGRAPHY OF STRAITS, SOUNDS AND SURROUNDING OFFSHORE AREAS

The many straits and sounds in Franz Josef Land form a network of varying mesh size separating islands and groups of islands (Figs. 7.1 & 8.1). The pattern continues on the shelf surrounding the archipelago, where the straits and sounds are represented by the St. Anna, Franz-Victoria and other troughs and the islands by underwater plateaus.

Straits and sounds

The morphology of the floor of straits and sounds can be divided into two parts, the peripheral area with a relatively large number of shoals and the central area. The central area is a fairly deep channel with a maximum depth exceeding 500 m. The 200 m isobath roughly separates this from the shallow-water periphery.

Like the coastline of separate islands (see above), underwater features throughout Franz Josef Land trend NW-SE, NE-SW and in part N-S. The NW-SE orientation predominates and is typical of major straits separating the northern islands of the central group and the sides of submarine depressions and highs. They include the steep submarine slope off the southwestern extremities of George Land and Alexandra Land, the Hercules Scarp, traced about 50 km into the Victoria Sea northwest of Cape Mary Harmsworth. This scarp defines a rapid increase in depth to 250–350 m only a few hundred metres from the southwest coasts of George Land and Alexandra Land. The same trend is also found for: 1) the submarine slope off the northeast end of George Land, which merges southeastwards with the southwest flank of Markham Strait; 2) the Ekholot slope and the De Bruyne Sound channel between the islands of Northbrook and Bruce and the Nakhimovtsev submarine plateau south of Hooker Island; 3) Bates Sound whose northeast flank can be traced northwestwards for 30 km across Nightingale Sound into Essen Bay on George Land; 4) the southeast slope of the rolling submarine area, Andromeda, stretching 120 km southeast of Cape Cecil Harmsworth to where it joins the Weber slope (the southeastern slope of the Aurora plateau); 5) one of the bends of Lavrov Sound (off the east coast of Hall Island) and some other negative forms in the submarine topography.

NE-SW trending submarine slopes, although relatively pronounced in places, are much less extensive than the transverse, NW-SE trending features. This orientation is displayed by Cambridge Bay, separating Alexandra Land and George Land, both trending in the same direction, and by Nightingale and Miers sounds, separating the islands of Bell, Mabel and Bruce from George Land and Northbrook Island. Weyprecht Bay (Alexandra Land), Gray Bay, Geographers Bay and Somerville Bight (George Land) trend in the same direction. The channels in the bays are abruptly interrupted when they meet the steep, unbroken Hercules Scarp. A still more pronounced break is shown by the Nightingale Sound channel which meets the Hercules Scarp and the southwestern flank of Bates Sound between the islands of Bruce and Mabel) in the northeast and southwest, respectively. The channel of British Channel clearly follows the northeasterly trend.

A N-S and E-W system of submarine highs and depressions is less common. It is most pronounced on the eastern periphery of Franz Josef Land where a leading part is played by N-S and feathering E-W fractures which have also predetermined the St. Anna Trough, the largest negative feature on the Arctic shelf of Eurasia. In the central and western areas of Franz Josef Land, the N-S structurally-related features include the channel along Arkhangelsky Sound (trending parallel to the Armitage Peninsula and Arthur Island), a submarine bar separating Smithson Sound (between Hooker and Leigh Smith islands), the Hecla submarine rise, the underwater Eaton chain (including the island of the same name) and the Robert Peel Sound (between Nansen Island and Koettlitz Island).

Deep vertical dissection among the islands of Franz Josef Land is responsible for greater depths there compared with adjacent offshore areas to the north and south. The maximum depth known (655 m) is in the Cambridge Channel, the southwest and northeast ends of which are marked by the 400 m isobath. Similar, but less deep, depressions are situated at the entrance to Shirshov Bay (540 m), the southern part of Nightingale Sound (over 400 m) and its extension in the British Channel (532 m), a horseshoe-shaped channel framing the northern part of the Eaton chain (380 m), Robert Peel Sound (380 m), Ommaney Channel (over 500 m), and some other straits and sounds. All the bottom depressions are clearly closed by transverse uplifts in neighbouring areas. Specific features in the morphology of the channels in Franz Josef Land point to the substantial role played by glacial ploughing in their formation, whereas the orientation in certain directions, rectilinear and steep slopes definitely indicate a primary relationship between the channels and the complicated system of neotectonic (Neogene-Pleistocene) fractures inherited from older structures.

8.4 PLATEAUS ON THE SHELF IMMEDIATELY SURROUNDING FRANZ JOSEF LAND

Northwest of Alexandra Land, the sea floor is a basaltic plateau that slopes very gently down to 100–150 m. Similar structures are the Salm and Lamont plateaus southeast of Franz Josef Land, the Aurora plateau southwest of the islands of Leigh Smith, Brady, McClintock, Hall and Wilczek, and the islets of Borisyak, Lyuriky and Aagaard, formed of basalt which rises above sea level. Unlike the Alexandra plateau, the topographical pattern, sea-floor grounds and geological structure of adjacent islands suggest that the bedrock forming the Aurora plateau is slightly deformed into a NE-SW trending syncline whose axis is situated in the area of the Aagaard and Borisyak islands).

Similar deformation is distinctly seen on a plateau at Persej Bay, where it is a natural extension of the structures along the south coast of Wilczek Land. Elsewhere, there are isolated isometrical, dome-shaped submerged plateaus a few tens of kilometres across. They include a basalt plateau (50 m deep in the centre and up to 100 m around the periphery) north of Alexandra Land, the Hecla basalt or dolerite(?) plateau (100–200 m deep) in the British Channel, and the extensive Chapiteau plateau south of the islands of Bell, Mabel, Bruce and Northbrook, presumably formed of Upper Triassic and Liassic sand and sandstone (down to a depth of 200 m). Together with these islands, the Chapiteau plateau forms a major dome whose central part rises up to 300 m above sea level. On the northwest and northeast, the dome is cut off by faults which also form troughs predetermining Nightingale and De Bruyne sounds and traversing the central part of the dome.

A similar dome-shaped and faulted terrestrial and underwater plateau is formed by the islands of Nansen, Pritchett, Bromwich, Bliss and Brice, situated on a common submarine platform, also sharply bounded by the 200 m isobath from surrounding, relatively deep, straits and sounds. The

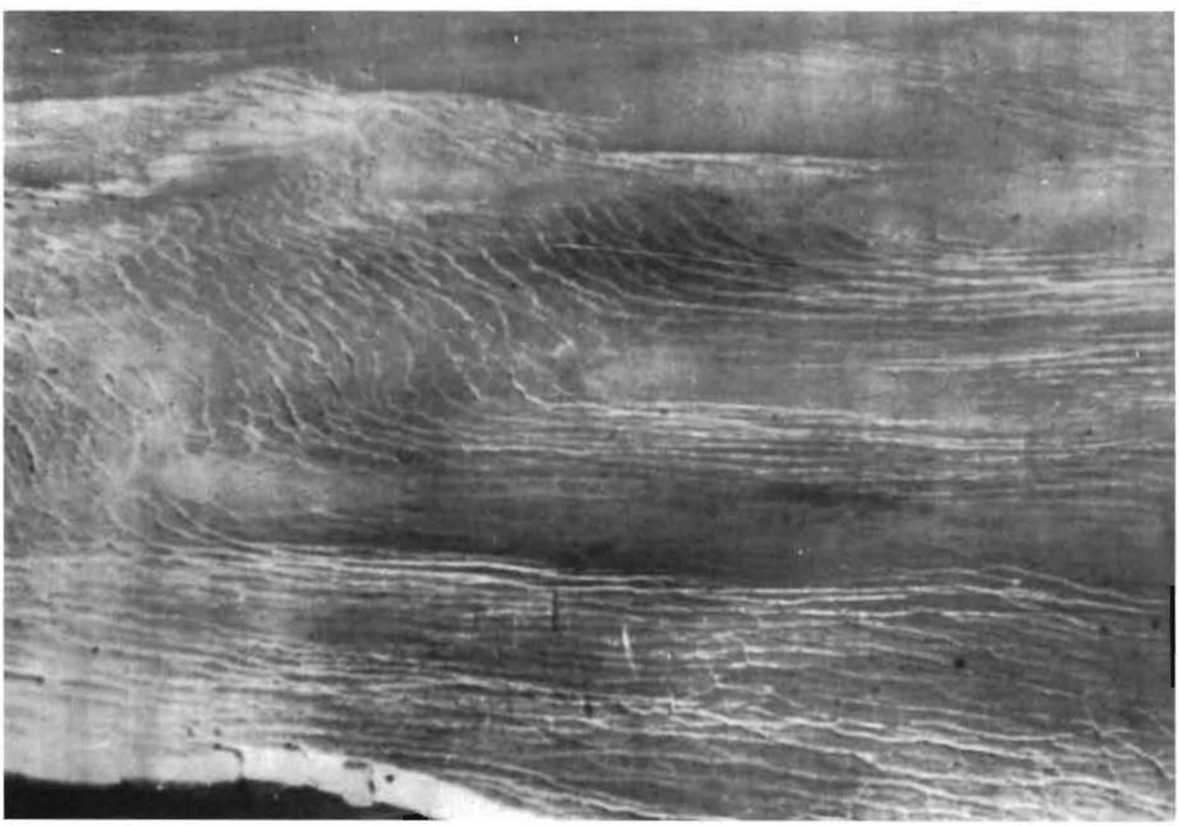

Fig. 8.17 Crevassed margin of an ice sheet, a permanent source for icebergs. Oblique aerial photograph by A.N. Radygin.

Fig. 8.18 Icebergs (up to 1 km long) calving from the barrier of an outlet glacier on the south coast of Wilczek Land. Vertical aerial photograph, 1953

Nakhimovtsev basalt plateau, locally rising above sea level as low islets of basalt, such as Etheridge, May and Newton, is situated south of Hooker Island. A peculiar feature of this plateau is its gently rolling surface, submerged to 30–50 m below sea level, or occasionally deeper, and sloping steeply towards the surrounding deeper (200 m and more) sea floor. The slopes which are rectilinear (faulted) to the northeast and dissected by cirque-like depressions on other sides make the Nakhimovtsev plateau similar to nearby Hooker Island. A similar topography is typical of the Zenith dolerite plateau in the northwest part of Franz Josef Land, which rises above sea level as Harley Island in the east.

Fig. 8.19 Grounded iceberg in Austrian Strait. Photo: V.D. Dibner, August 1957

The complex Andromeda high in the eastern part of the British Channel is extensively fragmented by trough valleys into numerous plateau- and dome-shaped peaks with very steep (up to 45°) slopes.

A very intricate pattern of horizontal dissection of relatively shallow underwater topography, revealed even by small-scale bathymetric charts, is also observed on the Aurora plateau south of Leigh Smith and Brady islands.

The underwater Alexandra (100–150 m), Voronin (200–250 m) and Johansen (250–300 m) plateaus are situated north of the Franz Josef Land islands and the edge of the Brusilov continental slope. Dredged bottom samples indicate that these plateaus are composed of Middle-Upper Carboniferous and Upper Triassic-Lower Jurassic deposits and Lower Cretaceous basaltic sheets, as well as hypabyssal doleritic intrusions. The Schilling plateau, broken by troughs and similar in the pattern of its isobaths to the two-stage plateaus on the islands, is situated off the southern islands of Franz Josef Land, separated from them by a chain of narrow troughs.

Hence, the bathymetrical evidence for the presence on the sea floor of submerged plateaus with bluffs on their upper slopes, trough valleys, dome-shaped highs, dyke ridges and other features strongly suggest that the submarine and terrestrial topographies of Franz Josef Land form a coherent entity. Faulting and folding reveal themselves better in the submarine topography than on land because below sea level they are not veiled by subaerial denudation processes. Tectonic, erosional and glacial dissection features formed when the present sea floor lay above sea level, or when it was below sea level but covered by a thick ice sheet, are almost entirely protected by deep water.

9. SUMMARY OF THE GEOLOGICAL HISTORY OF FRANZ JOSEF LAND – V.D. DIBNER, T.M. PCHELINA, E.N. PREOBRAZHENSKAYA & Z.Z. RONKINA

9.1 VENDIAN TO LATE DEVONIAN – V.D. DIBNER

Strata from parts of this long period are only known from the Nagurskaya borehole. The oldest rocks recorded in the drilling log are of Vendian age, dated by acritarch and trichome remains. At that time, sandy and silty flyschoid sediments accumulated in a geosynclinal trough across Alexandra Land. These rocks were later overlain by quartz-rich silty sand and more fine-grained sediments, including argillo-quartzose silt. At the Devonian/Carboniferous boundary (360 m.y. ago), the Vendian and overlying sequences were deformed and metamorphosed in the greenschist facies. As a result, the Vendian strata were transformed into quartz-mica and carbonate-mica schists and phyllite. The younger, probably also Vendian, deposits became fine-grained, sericitic feldspathic quartzites.

9.2 CARBONIFEROUS TO PERMIAN

9.2.1 Tournasian-early Serpukhovian (360–325 m.y.) – E.N. Preobrazhenskaya & V.D. Dibner

The late-Caledonian, Svalbardian tectonic phase resulted in the geosynclinal trough sediments in the vicinity of the Nagurskaya borehole being folded and faulted in a horst, uplifted and subsequently partially eroded. In common with the rest of the northern West Barents Shelf, following a long break, deposition took place on a platform (Gramberg 1988). Sandy, silty and clayey sediments, locally rich in organic matter, accumulated on a lacustrine-alluvial plain in a quiet tectonic setting. The climate was tropical. Abundant vegetation and favourable burial conditions resulted in the formation of coal. A vast land area which formed on the western and northern margins of the Barents Shelf after the completion of the Caledonian orogeny served as a source for the terrigenous material. This land area was not high, as suggested by the small thicknesses of sediments accumulated through its erosion, both in southeast Spitsbergen and Franz Josef Land which were then a province of the Euroamerican palaeofloristic region.

The eroded strata may have consisted of sedimentary rocks, as suggested by the composition of the terrigenous material which is entirely represented by a suite of highly stable minerals, both the abundant quartz and the accessory minerals, zircon, rutile and tourmaline.

Some indirect data on the Palaeozoic stage of development are also available from depocentres, where cover rocks which were synchronous with or even predated the Svalbardian orogenic phase may be present on the Archaean-Proterozoic basement. Of primary interest in this context is evidence from the oldest coal occurrence in the Grahamwil depocentre, represented by a unique, Middle Devonian, cuticular leptobiolith (a clast in the Upper Triassic conglomerates).

9.2.2 Late Carboniferous-Early Permian(?), Gzelian-Asselian (288–277 m.y.) – E.N. Preobrazhenskaya

Sedimentation began after a break (Middle Carboniferous sediments are lacking). An extensive transgression which took place in Spitsbergen as early as the Middle Carboniferous, manifested itself in Franz Josef Land in the Late Carboniferous, possibly during its second half, i.e. in the Gzelian. At that time, and perhaps at the beginning of the Asselian (Early Permian), a single shallow-water marine basin covered Franz Josef Land and most of the Barents Shelf. Thin calcareous, silicio-calcareous and argillo-calcareous muds and bio-accumulated detrital limestones, almost with no admixture of terrigenous material, were laid down in a shallow, warm basin. Foraminifera, brachiopods and bryozoans lived in the basin.

The very beginning of the Gzelian (288 m.y.) was marked by the oldest eruptions of basic rocks (porphyritic basalts), as suggested by K-Ar datings of xenoliths from the Inaccessible Rocks subvolcano.

9.2.3 Sakmarian-Tatarian(?) (277–248 m.y.)

In post-Asselian, Early Permian and Late Permian time, marine sedimentation may have been gradually replaced by lagoonal and continental deposition over most of the Barents Sea shelf. As this took place, the Franz Josef Land area underwent overall uplift; post-Asselian deposits in the area surrounding the Nagurskaya borehole may have been removed by this and/or subsequent erosion. Eruption of porphyritic basalts also took place during the Tatarian, a xenolith from the Inaccessible Rocks subvolcano having yielded a K-Ar age of 252 m.y.

9.3 TRIASSIC

The palaeogeography of the Early Triassic can be judged from deposits preserved in the Nagurskaya rift graben, which was formed much later.

9.3.1 Early Triassic, Middle Triassic and Carnian – T.M. Pchelina & V.D. Dibner

Induan (248–246.5 m.y.)
This marks the onset of the first Triassic transgression, during which a sequence of essentially clayey and silty-clayey sediments with thin layers of clayey and argillaceous limy mud formed. Benthic foraminifers, rare bivalves and fish inhabited the Induan sea. Thin layers of fine-grained sand containing vegetable detritus and remains of large plants appeared in clayey silts during a regressive stage at the end of the Induan.

Olenekian (246–243 m.y.)
A uniform sequence of mainly clay and clayey silt with intercalations of argillaceous limy mud continued to form during the Olenekian. During the Induan and Olenekian, sediments accumulated in a quiet basin. In the eastern part of Franz Josef Land, in the Hallclint and Grahamwil depocentres, the Lower Triassic and lower Anisian deposits were not reached by the stratigraphic boreholes. However, the great aggregate thickness (no less than 8 km on geophysical evidence) of the post-Archaean-Proterozoic cover in the depocentres suggests continuous sedimentation throughout the Early Triassic.

Middle-late Anisian (248–238 m.y.)
The logs of the Hayes and Severnaya boreholes suggest that the Hallclint and Grahamwil depocentres were areas infilled by shallow-water sediments. A rhythmic sequence of clayey and poorly sorted, silty-clayey and silty-sandy sediments with thin layers of bioturbated argillaceous limy muds was formed along with intercalations of intraformational conglomerates and breccia. The bulk of the psammitic-psephitic material was deposited in the Grahamwil depocentre which was closer to the provenance. Another eruption of porphyritic basalt (as suggested by a 240 m.y. old xenolith from the Inaccessible Rocks subvolcano) occurred in the mid-Anisian.

Ladinian (238–231 m.y.)
During the Ladinian, the whole archipelago was covered by a shallow sea. A clayey and silty-clayey sequence accumulated in the area surrounding the Nagurskaya borehole with a regressive unit of silts deposited in the centre. Shallow-water clayey and clayey-silty sediments with beds of limy and argillaceous-limy mud were deposited in the Hallclint and Grahamwil depocentres. The Middle Triassic sea was inhabited by abundant bivalves, echinoderms and other invertebrates, including rare ammonoids. During the Ladinian, the regime of stable marine sedimentation came to a close in the east of Franz Josef Land.

Carnian (231–225 m.y.)
In the Hallclint and Grahamwil depocentres, Carnian sediments were deposited in a progressively shallowing marine basin, as offshore-onshore and lacustrine-alluvial facies. A rhythmic, essentially silty and, to a lesser degree, sandy and clayey sequence was formed which contained coal in its upper part. Structures indicating sediment slumping, erosion and bioturbation are common. In the Carnian, like in the Middle Triassic, the main provenance was situated just east of the Grahamwil depression where various schists and igneous rocks were eroded. In the vicinity of the Nagurskaya borehole, Carnian and younger Upper Triassic deposits are absent (the upper Ladinian is overlain by a Barremian-Albian sedimentary-effusive sequence).

9.3.2 Norian and Rhaetian – V.D. Dibner, T.M. Pchelina & Z.Z. Ronkina

Early Norian (225–223 m.y.)

The early Norian witnessed a gradual downwarping of the basin floor and the formation of a unit of silt and sand. Further subsidence led to a brief transgression. Clay containing ammonoids, bivalves and foraminifers formed in a shallow sea. At Cape Hansa, deposits of clay and silt with intercalations of silty-limy mud containing lower Norian ammonoids probably also correspond to this time interval. At the end of the early Norian, a brief transgression was followed by regression when intercalating clay, silt, sand and gravel, characterised by poor sorting and the presence of crushed shells of bivalves and ammonoids, accumulated in an offshore environment.

Middle(?) Norian (c. 223–221 m.y.)

A new transgression resulted in the accumulation of mainly silty and, to a lesser extent, psammitic and psephitic sediments (Wilczek Formation). The composition of pebbles and sand suggests that the provenance consisted of rocks rich in highly broken down quartz (possible derived from granite-gneiss), fresh acid plagioclase, orthoclase, as well as quartzite, acid effusives, various metamorphic schists and siliceous rocks. The quartz-chalcedony composition of flint-like pebbles suggests a Palaeozoic age for those. Granitoids and related pegmatitic veins were present in the provenance. Moreover, readily broken down clinopyroxene in association with ore minerals and the heavy mineral fraction indicates that some local source areas containing intrusions of basic rocks, so far undated, were present around the western periphery of Franz Josef Land. At the end of the middle Norian, when another regression took place, the Franz Josef Land area was a lacustrine-alluvial plain covered by conifer-ginkgo-bennettite forest with ferns in the undergrowth, suggesting a warm, temperate climate.

Late Norian-Rhaetian(?) (c. 220–215 m.y.)

The Vasiliev Formation accumulated during this period. The very variable composition of the whole formation and, in particular, its variegated unit, distinguished by poor sorting and the presence of silty and clayey intercalations containing a marine microfauna and, at the same time, the appearance of coal seams, suggests considerably more intense fluctuations in sea level than occurred when the Wilczek Formation was being deposited. As before, material came from the east, as suggested by an increase in pebble size and the preferential occurrence of unconsolidated sedimentary rocks on the eastern islands of Franz Josef Land, as well as predominantly westerly and southwesterly dipping cross beds.

Like in early to middle Norian time, quartzites and acid effusives continued to be transported from the main source area, but eventually cherts, radiolarites and jaspers were exposed, to occur among the pebbles in mainly quartz-rich rocks. At the same time, mica schists with staurolite, epidote, kyanite, chloritoid and glaucophane (Ronkina & Vishhnevskaya 1982), as well as granitoids and associated granite and quartz-porphyry dykes were exposed in those parts of the Vasiliev terrigenous deposits that were derived from the most deeply eroded provenance areas, indicating an age range of 320–255 m.y. for all the above rocks (Dibner & Krylov 1970, Dibner 1978). The data suggest the destruction of the northern extension of Novaya Zemlya, situated east of Franz Josef Land on the site of the present St. Anna Trough (Dibner & Krylov 1970, Dibner 1978), which was formed as a secondary rift during the neotectonic stage of the development of Franz Josef Land.

In late Norian-Rhaetian(?) time, the area comprising the present Franz Josef Land was covered by coniferous, primarily araucarian, forests with some bennettitions and ginkgos; neocalamites and other equiseta, lycopods and pteridophytes grew in the lower storey. Seams of allochthonous, banded brown coal formed in lakes and peat bogs where some water flowed and the water table fluctuated (Dibner & Krylova 1963). The Vasiliev Formation conglomerates contain scarce limestone pebbles, yielding a Middle-Upper Palaeozoic macro- and microfauna. The fauna and a micaceous sandstone occurring in a section at Cape Goristy on Champ Island suggest the existence of a local provenance. On the other hand, the presence of abundant Upper Triassic coal debris in the light-mineral fraction of the Vasiliev Formation sand and sandstone indicates the recurrent reworking of these deposits. This implies that the Upper Triassic lacustrine-alluvial plain underwent relatively intense oscillatory movements, particularly when the variegated unit was deposited, simultaneous with a regional subsidence.

9.4 JURASSIC – V.D. DIBNER & Z.Z. RONKINA

9.4.1 Lower Lias (c. 210–200 m.y.)

This period saw the deposition of the Tegetthoff Formation. The Early Jurassic transgression, which led to an intense outwash of small particles leaving behind concretions containing *Neoschizodus*, may have taken place at the very onset of the Jurassic. It was followed by an almost complete epoch with a continental regime. The main provenance area moved away from Franz Josef Land, as suggested by the monomineralic composition of the light fraction of sands and sandstones. Micaceous quartz sandstones, the mica of which is 320 m.y. old and indicates the outwashing of Lower and Middle Carboniferous rocks (Dibner & Krylov 1970), quartzitic sandstones and flints, fine-grained quartzites and biotite schists, similar to those that gave rise to the Vasiliev Formation, were transported from the main provenance area. The heavy mineral fraction contains rare grains of glaucophane (for the first time) and garnet. Younger acid effusives, radiolarites and jaspers had probably already been removed by that time. The thickness of the conglomeratic intercalations in the Tegetthoff Formation, and the size of their clasts, similar to those of the Vasiliev Formation conglomerates, decreased from east to west. However, like the Late Triassic, the Early Jurassic saw the occasional appearance of separate local provenances (so characteristic for local depocentres), as suggested by highly differing compositions of the heavy mineral fraction in separate Lower Lias outcrops. In the early Lias, bennettite-ginkgo-conifer forests became still more extensively developed across the area studied, providing material for coal accumulation.

The Sinemurian saw the onset of intrusions of plateau-basalt magma. At intervals varying from 1 to 97 m.y., they can be traced from the early Lias to the Oligocene (section 5.5). In the late Lias (Toarcian), after the deposition of the main, continental, part of the Tegetthoff Formation, the sea transgressed in the Bell Island area and deposited littoral sand containing spores and pollen directly upon deposits of the Vasiliev Formation.

9.4.2 Middle-Late Jurassic (c. 188–145 m.y.)

This period was one of multiphasal transgression separated by periods of erosion taking place at different times in different parts of the Franz Josef Land area. No fewer than ten transgressions, namely, early Aalenian, late Aalenian, early(?) Bajocian, early Bathonian, middle to late Bathonian-Callovian, early Oxfordian, late Oxfordian, early Kimmeridgian, late Kimmeridgian and lower to middle Volgian, invaded the islands of Graham Bell, Wilczek Land (Grahamwil depocentre), Hayes and Berghaus (Hallclint depocentre), Champ, Hooker, Northbrook and Rainer (minor depocentres).

The composition of the heavy fraction of the upper Aalenian deposits exposed on Hooker Island points to erosion of basic rocks which had probably formed by that time in an area situated in the immediate vicinity of Franz Josef Land. Bajocian and lower Bathonian marine clayey deposits exposed at Cape Fiume indicate that the central part of Franz Josef Land was then a shelf somewhat removed from the provenance area. Late Bathonian clays containing fossils and phosphatic nodules were deposited in the Cape Flora area at depths of 30–300 m. Sections at Cape Medvezhy suggest that the sea existed throughout the Callovian and that the transgression reached its peak as early as the onset of the period. The predominance of plagioclases in the light fraction and pyroxenes and ore minerals in the heavy fraction of Callovian pelites suggest the same source area as in Aalenian time. Angular grains of fresh, zoned, basic plagioclases found in samples from Hooker Island indicate that basic effusives were probably present in the provenance area.

In central Franz Josef Land, at Cape Fiume, purely argillaceous deposits laid down during the Middle to Upper Jurassic transgression phases are traced from the lower Aalenian to the lower Oxfordian inclusive (with breaks occurring in the late Aalenian, middle to late Bathonian and middle Callovian). At Cape Hofer, a transgression represented by "brown clays" is also recognised in the late Oxfordian. The Kimmeridgian-Volgian palaeogeography has been studied in the southeastern part of Franz Josef Land, in the Grahamwil and Hallclint depocentres. The facies of the Kimmeridgian deposits (Cape Hofer) can be related to an open shelf basin. The end of the late Kimmeridgian was marked by the commencement of regression, shown by an increase of sandy material in carbonate mud on Berghaus Island and the formation of leptochloritic sand at Cape Hofer. After a short break, the regression caused the accumulation of lower to middle Volgian "dark" and "light sands" at Cape Lamont. This is a thick (280 m in aggregate apparent thickness) accumulation of Jurassic littoral deposits with a plesiosaur skeleton preserved in its lower part. In the Volgian, the rate of sedimentation was about 70–80 m per million years. At Berghaus Island, a sand sequence of the same type, about 250 m thick, accumulated at a rate of 120–130 m per million years in the middle Volgian. During the Middle and Late Jurassic, marine sediments were deposited around the periphery of a vast sea embracing the shelves of the Barents, Norwegian and North Seas (Shulgina & Burdykina 1992).

9.5 CRETACEOUS AND LOWER TERTIARY – V.D. DIBNER

9.5.1 Neocomian (c. 144–122 m.y.)

A terrigenous sequence was deposited from Berriasian to early Barremian time (144–122 m.y.). A gradual transition to continental conditions, accompanied at the peak by the initial manifestations of ash volcanicity, proceeded throughout the Neocomian. After a break in the late Volgian, the early Berriasian (at Cape Lamont) saw the re-appearance of a shallow sea, marked by fossiliferous beds, crowning the "light sand" strata. This sea may have existed throughout the Berriasian and, in places, the lower Valanginian (Klagenfuhrt Island). A short break was followed by the recommencement of sedimentation in the middle-upper Valanginian. At that time, "variegated", coal-bearing strata were formed under humid, subtropical conditions. In the area of Salisbury and Champ islands, the strata contain ash, the precursor of plateau-basalt volcanism, which was widespread in the region at the close of the Neocomian. Brackish lagoons (Cape Hofer) were formed at the very end of the Valanginian or in the Hauterivian. Eventually, the Hauterivian to the Barremian saw the return of continental conditions, as suggested by red psammites containing a brown coal seam at the base (Cape Dzegudze, Alger Island).

The heavy fraction throughout the Jurassic-Neocomian sequence contains glaucophane in association with kyanite, staurolite, garnet and epidote. Thus, starting from the Lias, outwashing of low- to medium-grade metamorphic rocks took place in the main provenance area. The rocks are similar to the glaucophane-bearing rocks of Vestspitsbergen (A.A. Krasilscikov, pers. comm.). The composition of the light fraction and of conglomerates proves that the provenance was situated directly off the eastern margin of Franz Josef Land.

9.5.2 Barremian-Albian (122–97.5 m.y.)

This was the period when the sedimentary-volcanic sequence was formed. At the very onset of the Barremian, or possibly in the Hauterivian, a regional uplift of Franz Josef Land and the surrounding area took place. This event, grandiose in scale, was related to the emplacement of a gigantic asthenospheric lens (or lenses) close up to the Moho discontinuity. This resulted in upwarping and erosion of the overlying crustal arch, its fracturing and, ultimately, the development of intense, rift-related, multichannel transfer of heat and mass, with basic volcanicity serving as its main agent. Thus, the sedimentary-volcanic sequence was deposited on the unevenly fractured and eroded surface of underlying rocks. On most of the present-day islands, both the Neocomian and Upper to Middle Jurassic deposits were eroded, but the Tegetthoff Formation was preserved in places. The Vasiliev Formation has been much better preserved and generally serves as the base of the sedimentary-volcanic sequence, which formed a vast volcanogenic plate overlying all the depocentres and separating secondary rifts and grabens.

The formation of the Barremian-Albian sedimentary-volcanic sequence started with outbursts of ash and minor basaltic lava flows, accompanied by the formation of agglomeratic (Hayes Island) and pelitic-psammitic (Hooker Island and others) tuffs intercalated with thin flows and sheets filling depressions in the pre-volcanic topography. A brief subsidence to below sea level may then have taken place, as suggested by the composition of the lowermost sheet on Hooker Island, represented by a rock resembling spilite (Lupanova 1953), and by the fact that wood, occurring there between the lower basaltic sheets, is calcified, unlike silicified wood at sites where younger sheets are exposed. Subsequent, more intense, eruptions produced basaltic flows and tuffs, filling in valley-shaped depressions to level off the pre-volcanic relief. During breaks between eruptions, structural plains were again generated. Each eruption was accompanied by isostatic lowering of the land, bringing it close to sea level and thus causing a slowing down of the erosional processes, which kept it flat until it was buried under a subsequent lava flow. This is vividly shown in outcrops, where, with a few exceptions, the base and top of the sheets appear as parallel, generally horizontal lines. The flatness of these recurrent basaltic plateaus was beneficial to the formation of a laterite-type weathering crust on slightly uplifted parts of the land under the warm climatic conditions and to the accumulation of coal-bearing palustrine-lacustrine or, less commonly, lacustrine-alluvial deposits in slight depressions. The lithology of the deposits, dominated by clinopyroxenes and heavy minerals, leaves no doubt that during the time interval between basaltic flows and sheets sedimentation of material derived from the erosion of basic effusives took place. At Inaccessible Rocks, a shield subvolcano built of lava breccia was exposed to erosion, which also affected parts of the sedimentary-volcanic sequence.

Wood remains, which are abundant in talus and bedrock in the sedimentary-volcanic sequence, suggest a virulent growth of vegetation. The Barremian-Aptian part of the sequence (Tikhaya Bay Formation) was dominated by pteridophytes and ginkgoaceous plants, mainly accompanied by conifers. In the Aptian-Albian strata (Salisbury Formation), the flora is very rich in cycadophytes and large-leaved conifers. These forests gave rise to brown coal beds accumulated in very flooded peat bogs with poor water circulation in which terrigenous material was only represented by a minute quartz fraction (Dibner & Krylova 1963). On some of the basaltic plateaus, the processes of weathering and continental sedimentation were supplemented by the action of siliceous, thermal springs, resulting in dense opal-chalcedony rocks and siliceous tuff containing fragments of plant tissues, as well as leaves, needles, cones, etc. The same springs are responsible for the silicification of branches and entire trunks. When a subsequent extrusion of lava took place, flints and silicified wood were inundated by the new basaltic sheet, forming peculiar basal horizons which, like continental sedimentary deposits or weathering crusts, serve as reliable evidence of breaks in volcanic activity.

9.5.3 Lower Cenomanian (97.5–94.0 m.y.)

The lower Cenomanian witnessed a new transgression which deposited sediments on Hoffmann Island, that are typical of a littoral zone. Their lithology, with the heavy fraction minerals represented by zircon, tourmaline and rutile, points to redeposition of Upper Triassic-Lower Jurassic terrigenous sediments.

9.5.4 Late Cretaceous and Lower Tertiary (94–25 m.y.)

Apart from the youngest sill, intruded into basaltic sheets on Alexandra Land during the Oligocene (34 m.y. ago), this period forms a gap in the geological record of Franz Josef Land.

9.6 UPPER CENOZOIC (NEOGENE AND QUATERNARY) – V.D. DIBNER

9.6.1 Miocene(?)

Judging from available palynological data, littoral silty-psammitic deposits with shell debris, exposed at Cape Sugrobov on Hoffman Island, indicate the last of the known pre-Quaternary transgressions.

9.6.2 Pliocene(?)

Intensive faulting took place as a rejuvenation of late-Neocomian rifts and grabens. It led to the formation of deep channels in the straits and determined the major features of the topography of the islands.

9.6.3 Quaternary

The distribution and petrographical composition of erratics, as well as the orientation of drumlinoids on Alexandra Land and the Armitage Peninsula, point to the former complete overriding of the islands, straits and sounds of the archipelago by a single ice sheet whose centre was located somewhere southeast of Franz Josef Land at the peak of the Late Pleistocene glaciation (Dibner 1962a).

According to Groswal'd (1983), the present glaciation of the archipelago is a remnant of the Late Pleistocene ice sheet which occupied the entire Barents-Kara shelf. The destruction of this vast ice sheet began about 11,000 years ago. Troughs bordering the western and eastern peripheries of Franz Josef Land were deglaciated 9000 years ago, and the shelf off the archipelago became ice free shortly afterwards, although ice sheet remnants survived for some time.

The overall deglaciation led to gradual thawing at the margins of plateaus and the formation of terraces on their slopes during the isostatic upwarping of the archipelago. According to Dibner

(1965), the uplift started about 15,000 years ago with the formation of a 250 m high wave-cut platform. Each raised beach, 250 m to 55 m inclusive, marks a brief episode of glacial advance accompanied by a slowing down of the isostatic upwarping. It is natural to assign the last major glacial advance to the end of the formation of a 35–40 m raised beach and the onset of the formation of a 20–25 m raised beach, i.e. around 8500–7500 years ago (second half of the Boreal and commencement of the Atlantic substages). From this time on, a slow glacial retreat has taken place. The single ice sheet became separate ice caps and outlet glaciers in glacial troughs, which formed as early as the initial stage of glaciation. Consequently, periodic glacial advances did not occur over the entire front, but by the spreading of separate glacier lobes and ice streams. The overall isostatic recovery from 8000 years ago to the present day is characterised by a much lower rate of uplift, averaging about 3 m per 1000 years compared to about 30 m per 1000 years during the preceding stage (15,000–8000 years ago).

In the period from 5000 to 6000 years ago, corresponding to the warmest part of Atlantic time, the species diversity in the marine invertebrate fauna increased and the purely Boreal *Mya arenaria* L. appeared. The remains of Greenland whales are especially abundant at this time, suggesting that the southern boundary of winter drift ice passed through Franz Josef Land, not far to the south as it does today. In the same period, the islands became inhabited by reindeer which probably migrated from Novaya Zemlya.

The formation of an 8–10 m raised beach (almost as widely developed as the 20–25 m one) marked some revival of glaciers, roughly synchronous with a minor glaciation around 4350–3300 years ago. This cold period resulted in the almost complete disappearance of Boreal invertebrate forms and a decrease in the whale population.

A 3–5 m terrace and beach ridges at the same height formed during a new, relatively cold period, when there was a worldwide revival of glaciers about 2600 years ago. This cold period caused the disappearance of reindeer from the islands of Franz Josef Land.

The oscillations of the present-day glaciation have been recorded by expeditions visiting Franz Josef Land in the 19th and 20th centuries. The glaciers advanced between 1875 and about 1900. After 1900, they began to retreat, a process which was intensified after the 1920's, especially in the 1930's and 1950's. 1/700th of the entire mass of glacier ice disappears every year (Groswal'd & Krenke 1962, Groswal'd et al. 1973).

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